1) The case for stochastic orbital migration
2) Open Exoplanet Catalogue

Hanno Rein @ UoT St. George Campus, March 2013
Extra-solar planet census
All discovered extra-solar planets

869 confirmed extra-solar planets

- Super-Jupiters
- (Hot) Jupiters
- Neptunes
- Super-Earths
- Earth-like planets

Open Exoplanet Catalogue (Rein 2012b)
All multi-planetary systems

327 confirmed planets in multi-planetary systems

- Multiple Jupiters
- Densely packed systems of Neptunes and (Super)-Earths
- 1 Solar System
- Some systems are deep in resonance

Open Exoplanet Catalogue (Rein 2012b)
Radial velocity planets

Cumulative period ratio in multi-planetary systems

- Periods of systems with massive planets tend to pile up near integer ratios
- Most prominent features at 4:1, 3:1, 2:1, 3:2

Kepler candidates

2740 planet candidates

- Probing a different regime
- Small mass planets
- A lot of planets
Kepler candidates with multiple planets

Kepler multi-planetary systems

- Small mass planets
- Hierarchical systems
- Densely packed
- Not many are in resonance

Open Exoplanet Catalogue (Rein 2012b)
Kepler's transiting planet candidates

- **KOI planets**
  - Period ratio distribution much smoother for small mass planets
  - Deficiencies near 4:3, 3:2, 2:1
  - Excess slightly outside of the exact commensurability

- **RV planets**

Stochastic orbital migration
Migration - Type I

- Low mass planets
- No gap opening in disc
- Migration rate is fast
- Depends strongly on thermodynamics of the disc

2D hydro code Prometheus (Rein 2010)
Migration - Type II

- Massive planets (typically bigger than Saturn)
- Opens a (clear) gap
- Migration rate is slow
- Follows viscous evolution of the disc

2D hydro code Prometheus (Rein 2010)
How does a real protoplanetary disk look like?

Image credit: NASA/JPL-Caltech
Why think about stochastic migration?

- Angular momentum transport
- Magnetorotational instability (MRI)
- Density perturbations interact gravitationally with planets
- Stochastic forces lead to random walk
- Large uncertainties in strength of forces

Animation from Nelson & Papaloizou 2004
Random walk in all orbital parameters

- **pericenter**
- **eccentricity**
- **semi-major axis**

**time**

Rein & Papaloizou 2009
Analytic growth rates for 1 planet

\[(\Delta a)^2 = 4 \frac{Dt}{n^2}\]

\[(\Delta \varpi)^2 = 2.5 \frac{\gamma Dt}{e^2} \frac{1}{n^2 a^2}\]

\[(\Delta e)^2 = 2.5 \frac{\gamma Dt}{n^2 a^2}\]

Analytic growth rates for 2 planets

\[
\frac{(\Delta \phi_1)^2}{(p + 1)^2} = \frac{9\gamma_f}{a_1^2 \omega_{lf}^2} D t
\]

\[
(\Delta (\Delta \varpi))^2 = \frac{5\gamma_s}{4a_1^2 n_1^2 e_1^2} D t
\]
Multi-planetary systems in mean motion resonance

- Stability of multi-planetary systems depends strongly on diffusion coefficient
- Most planetary systems are stable for entire disc lifetime

Rein & Papaloizou 2009
The formation of Kepler-36
Kepler-36 c as seen from Kepler-36 b

- Would appear 2.5 times the size of the Moon
- Very close orbits, near a 7:6 resonance
- Very different densities
Formation of Kepler-36

- Migration rate and mass ratio determine the final resonance
- Higher order resonances require faster migration rates
- Higher mass planets end up in lower order resonances
- Once in resonance, planets often stay there for the rest of the disc lifetime
Problem with Kepler-36

<1000 years

Need extremely fast migration rate to capture into a high order resonance.

Unrealistically fast.

Planets are not large enough to migrate in Type III regime.

Pardekooper, Rein & Kley (in prep)
Solution: Stochastic migration

\[ \tau_a = 20000 \text{ yrs} \]

- low order resonances
- high order resonances

- crossing of the 2:1 resonance
- convergent migration

Pardekooper, Rein & Kley (in prep)
A statistical analysis
Kepler's transiting planet candidates

- Period ratio distribution much smoother for small mass planets
- Deficiencies near 4:3, 3:2, 2:1
- Excess slightly outside of the exact commensurability

Testing stochastic migration: Method

- Architecture and masses from observed KOIs
- Placing planets in a MMSN, further out, further apart, randomizing all angles
- N-body simulation with migration forces

Rein 2012
Testing stochastic migration: Advantages

Comparison of statistical quantities
- Period ratio distribution
- Eccentricity distribution
- TTVs

Comparison of individual systems
- Especially interesting for multi-planetary systems
- Can create multiple realizations of each system

No synthesis of a planet population required
- Observed masses, architectures
- Model independent
Preliminary results

Observed KOI planets

Migration $\tau_a = 10^4$ years, $\alpha = 10^{-6}$
Migration $\tau_a = 10^4$ years, $\alpha = 10^{-5}$
Future expansions

- Physical disk model
  - 1D hydrodynamic simulation
  - Coupled to N-body simulations

- Completeness
  - Include planets missed by Kepler

- Other physical effects
  - Tidal damping
  - Evaporation

- GPU based integrators
  - Allows for much bigger samples
  - Wider parameter space exploration
Saturn’s Rings
REBOUND

- Multi-purpose N-body code
- Only public N-body code that can be used for granular dynamics
- Written in C99, open source, GPL
- Freely available at http://github.com/hannorein/rebound
Symplectic Epicycle Integrator

\[ H = \frac{1}{2} p^2 + \Omega (p \times r) e_z + \frac{1}{2} \Omega^2 \left[ r^2 - 3 (r \cdot e_x)^2 \right] + \Phi(r) \]

I/2 Kick \rightarrow Epicycle \rightarrow I/2 Kick

Rein & Tremaine 2011
Mixed variable symplectic (MVS) integrator

Rein & Tremaine 2011

Phase error vs. timestep $[2\pi\Omega^{-1}]$
Symplectic Epicycle Integrator: Rotation

- Solving for the orbital motion involves a rotation.
- Formally $\det(D) = 1$, but due to floating point precision $\det(D) \sim 1$ only.
- Trick: Use three shear operators instead of one rotation.
  \[
  \begin{pmatrix}
  \cos \phi & \sin \phi \\
  -\sin \phi & \cos \phi
  \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\tan \frac{1}{2}\phi & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & \sin \phi \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -\tan \frac{1}{2}\phi & 1 \end{pmatrix}
  \]

- $\det(D) = 1$ exactly for each shear operator, even in floating point precision.
- No long term trend linear trend anymore!
Saturn is a smaller version of the Solar System
Propeller structures in A-ring

Stochastic Migration

REBOUND code, Rein & Papaloizou 2010, Crida et al 2010, Pan, Rein, Chiang & Evans 2012
Motion is consistent with a random walk

Diagonalization

Pan, Rein, Chiang, Evans 2012
Observations

• Observational evidence for small scale structures
• Typical size \( \sim 100m \)
Close-up view of the viscous over-stability
Numerical simulations with REBOUND

Symplectic Epicycle Integrator
- Fast
- High accuracy
- No long term drifts (important)

Plane-sweep algorithm
- Fast
- $O(N)$ for elongated boxes

Direct particle simulations of Saturn's Rings
- Longest integration time ever done
- Widest boxes ever done

Rein & Latter (2013)
Non-linear evolution

time = 0.000 [orbits]

density

0 5000 10000 15000 20000

sink wavetrain source wavetrain

Rein & Latter (2013)
Long-term evolution

Rein & Latter (2013)
Open Exoplanet Catalogue
Why do we need another exoplanet catalogue?

Open Exoplanet Catalogue

Open Exoplanet Catalogue

Catalogue

All extrasolar planets

Plots

Correlations plots
Bubble chart
Histograms
Python scripts for offline use

HD 178911

The planetary system HD 178911 hosts at least one planet. Note that the system is a multiple star system. It hosts at least 3 stellar components.

<table>
<thead>
<tr>
<th>Name</th>
<th>System parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 178911</td>
<td></td>
</tr>
<tr>
<td>Right ascension</td>
<td>19h 09m 03s</td>
</tr>
<tr>
<td>Declination</td>
<td>+34° 35' 59&quot;</td>
</tr>
<tr>
<td>Distance [parsec]</td>
<td>46.73</td>
</tr>
<tr>
<td>Distance [lightyears]</td>
<td>152.4</td>
</tr>
<tr>
<td>Number of stars in system</td>
<td>3</td>
</tr>
<tr>
<td>Number of planets in system</td>
<td>1</td>
</tr>
</tbody>
</table>

Architecture of the system
Common drawbacks of astronomical catalogues

Centralized
- Impossible to correct typos, add data without sending an e-mail to the person in charge
- Closed ecosystem

Web-based
- Website are badly written
- Requires flash or java plugin
- Need a constant internet connection
- Restricted to a very limited, predefined set of possible queries

Slow and outdated
- It can take days/weeks/months for new planets to be added
- Maintainer can be holiday or abandon the project

Old-fashioned formats
- Static tables are not adequate to represent diverse dataset
- Almost impossible to include binary/triple/quadruple systems
- Not flexible when adding new data
- Unintuitive to parse
Open Exoplanet Catalogue

Open source philosophy

- Unrestrictive MIT license
- Community project
- Everyone can contribute and modify data
- Everyone can expand it
- Distributed, no need for a server/website
- Private clones with confidential data

Ready to go

- 674 systems, 51 binary system, 870 exoplanets, 9 solar system objects, 2740 KOI objects
- ~10 million users

Hierarchical data structure

- Uses plain XML
- Can represent arbitrary configurations in systems with stellar multiplicity >1
- Extremely easy and intuitive to parse in almost any language
- Compresses extremely well
- size ~ 100KB

Based on git

- Distributed version control system
- Used by Linux kernel and most other open source projects
- Every single value, every change ever made is logged, verifiable

OpenExoplanetCatalogue.com, arXiv:1211.7121
Example of a system file: 42 Dra b

<system>
  <name>42 Dra</name>
  <rightascension>18 25 59</rightascension>
  <declination>+65 33 49</declination>
  <distance>97.3</distance>
  <star>
    <mass>0.98</mass>
    <radius>22.03</radius>
    <magV>4.83</magV>
    <metallicity>-0.46</metallicity>
    <spectraltype>K1.5III</spectraltype>
    <planet>
      <name>42 Dra b</name>
      <list>Confirmed planets</list>
      <mass>3.88</mass>
      <period>479.1</period>
      <semimajoraxis>1.19</semimajoraxis>
      <eccentricity>0.38</eccentricity>
      <description>42 Draconis is a metal poor star.</description>
      <discoverymethod>RV</discoverymethod>
      <lastupdate>09/03/23</lastupdate>
      <discoveryyear>2009</discoveryyear>
      <new>0</new>
    </planet>
  </star>
</system>
import xml.etree.ElementTree as ET, glob
for filename in glob.glob("*.xml"):
    tree = ET.parse(open(filename, 'r'))
    planets = tree.findall("./planet")
    for planet in planets:
        print planet.findtext("./name")
        print planet.findtext("./mass")
The case for stochastic orbital migration

- Stochastic migration is directly observable in Saturn’s rings.
- Protoplanetary disks are turbulent due to the MRI.
- Stochastic migration plays an important role for small mass planets.
- Resonances can easily get destroyed.
- Tendency to form high order resonance.
- Very soon, we will understand how most planets in the Kepler sample formed.

Open Exoplanet Catalogue

Use it!
Contribute to it!