- Multi-planetary systems
- Binaries
- Single Star and Single Planetary Systems
Terrestrial planets: Habitable Zone

• Zone around a star where liquid water can exist on the surface of such a planet

• This zone depends on:
  – the spectral type, the mass, the age, ... of the star
  – the orbit of the planet
  – the mass, the composition, the atmosphere, ... of the planet
  – the parameters of other planets in this system (mass, orbit, ...)

Size of the habitable zone of a planetary system

based on the definition given by Kasting et al. (1993).
Types of Habitable Zones:

1) Hot-Jupiter type
2) Solar system type
3) + (4) giant planet type: habitable moon or trojan planet
Stability maps

Inner region  (Solar system type)

Outer region  (Hot-Jupiter-type)
Computations

Distance star-planet: 1 AU
Variation of:
- $a_{tp}$: [0.1, 0.9] [1.1, 4] AU
- $e_{gp}$: 0 – 0.5
- $M_{gp}$: 0 and 180 deg
- $M_{tp}$: [0, 315] deg

Dynamical model:
restricted 3 body problem

Methods:
(i) Chaos Indicator:
  - FLI (Fast Lyapunov)
  - RLI (Relative Lyapunov)
(ii) Long-term computations
  - $e$-max
Chaos Indikatoren

Fast Lyapunov Indicator (FLI)
C. Froeschle, R.Gonczi, E. Lega (1996)

MEGNO
RLI
Helicity Angle

Lyapunov Characteristic Exponent (LCE)
The Fast Lyapunov Indicator (FLI)  
(see Froeschle et al., CMDA 1997)

a fast tool to distinguish between regular and chaotic motion

length of the largest tangent vector:

\[ \text{FLI}(t) = \sup_i |v_i(t)| \quad i=1,\ldots,n \]

(n denotes the dimension of the phase space)

it is obvious that chaotic orbits can be found very quickly
because of the exponential growth of this vector in the chaotic region.
For most chaotic orbits only a few number of primary revolutions is needed to determine the orbital behavior.
Long-term numerical integration:

Stability-Criterion:
No close encounters within the Hill sphere

(i) Escape time
(ii) Study of the eccentricity: maximum eccentricity
Figure 2: The FLIs for orbits started at \( d_0 \) between 0.24 and 0.256. The solid line shows the results after an integration time of 1000 units; the dashed line with crosses is for 40,000 time units; the dashed line with stars for \( t=100,000 \) units and the dotted line shows the results after 1 mio. periods of the binary.
ANIMATION
How to use the catalogue

**HD114729:**
- $m_p = 0.82$ [Mjup]
- $a_p = 2.08$ AU
- $e_p = 0.31$
- $\mu = 0.001$
- HZ: 0.7 – 1.3 AU
\( \mu = 0.005 \)

**HD10697:**
- \( m_p = 6.12 \ [\text{Mjup}] \) (1.15 Msun)
- \( a_p = 2.13 \ \text{AU} \)
- \( e_p = 0.11 \)
- HZ: 0.85 – 1.65 AU
The **EXOCATALOGUE**: http://www.univie.ac.at/adg/

**Details:**

From the dynamical point of view there are four possible configurations for terrestrial like planets

1) The giant planet moves close to the central star.
2) Solar configuration:
3) Satellite configuration (e.g. Europa):
4) Trojan configuration:
...Like the Jupiter-Trojans
Two groups of asteroids close to L4 and L5

1. L₁, L₂ and L₃ (not stable) lie on a straight line connecting the primaries
2. L₄ and L₅ (stable for μ < 1:25) are at the third vertex of an equilateral triangle (Sun-Jupiter-Asteroid)
List of extrasolar systems with one giant planet in the HZ
(Single-planetary systems)

<table>
<thead>
<tr>
<th>Name</th>
<th>Spec.</th>
<th>mass $[M_{sot}]$</th>
<th>mass $[M_{jup}]$</th>
<th>a $[AU]$</th>
<th>ecc</th>
<th>HZ $[AU]$</th>
<th>partly in HZ $[%]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD101930</td>
<td>K1V</td>
<td>0.74</td>
<td>0.30</td>
<td>0.30</td>
<td>0.11</td>
<td>0.30-0.64</td>
<td>53</td>
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<tr>
<td>HD93083</td>
<td>K3V</td>
<td>0.70</td>
<td>0.37</td>
<td>0.48</td>
<td>0.14</td>
<td>0.28-0.60</td>
<td>100</td>
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<tr>
<td>HD134987</td>
<td>G5V</td>
<td>1.05</td>
<td>1.58</td>
<td>0.78</td>
<td>0.24</td>
<td>0.75-1.40</td>
<td>58</td>
</tr>
<tr>
<td>HD17051</td>
<td>G0V</td>
<td>1.03</td>
<td>1.94</td>
<td>0.91</td>
<td>0.24</td>
<td>0.70-1.30</td>
<td>100</td>
</tr>
<tr>
<td>HD28185</td>
<td>G5</td>
<td>0.99</td>
<td>5.70</td>
<td>1.03</td>
<td>0.07</td>
<td>0.70-1.30</td>
<td>100</td>
</tr>
<tr>
<td>HD99109</td>
<td>K0</td>
<td>0.93</td>
<td>0.50</td>
<td>1.11</td>
<td>0.09</td>
<td>0.65-1.25</td>
<td>100</td>
</tr>
<tr>
<td>HD27442</td>
<td>K2IVa</td>
<td>1.20</td>
<td>1.28</td>
<td>1.18</td>
<td>0.07</td>
<td>0.93-1.80</td>
<td>100</td>
</tr>
<tr>
<td>HD188015</td>
<td>G5IV</td>
<td>1.08</td>
<td>1.26</td>
<td>1.19</td>
<td>0.15</td>
<td>0.70-1.60</td>
<td>100</td>
</tr>
<tr>
<td>HD114783</td>
<td>K0</td>
<td>0.92</td>
<td>0.99</td>
<td>1.20</td>
<td>0.10</td>
<td>0.65-1.25</td>
<td>50</td>
</tr>
<tr>
<td>HD221287</td>
<td>F7V</td>
<td>1.25</td>
<td>3.09</td>
<td>1.25</td>
<td>0.08</td>
<td>1.10-2.30</td>
<td>100</td>
</tr>
<tr>
<td>HD20367</td>
<td>G0</td>
<td>1.05</td>
<td>1.07</td>
<td>1.25</td>
<td>0.23</td>
<td>0.75-1.40</td>
<td>76</td>
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<tr>
<td>HD23079</td>
<td>(F8)/G0V</td>
<td>1.10</td>
<td>2.61</td>
<td>1.65</td>
<td>0.10</td>
<td>0.85-1.60</td>
<td>35</td>
</tr>
</tbody>
</table>
Model parameters (initial conditions)

Eccentricity of the gas giant (GG) & the Trojan planet
\[ 0.00 < e < 0.3 \quad \Delta e = 0.05 \]

Mass ratio (\( \mu \))
\[ 0.001 < \mu < 0.04 \quad \Delta \mu = 0.001 \]

Stable region:
\[ 0.9 \text{ AU} < a < 1.1 \text{ AU} \quad \Delta a = 0.0025 \]
a is normalized to 1AU

Angular distance to the primary (M):
\[ 0° < M < 360° \quad \Delta M = 1° \]
Catalogue

Variation of:
$0 < e < 0.3$
$0 < \mu < 0.04$

Grid:
$\Delta \mu = 0.001$
Animation for ecc 0,05

Mass ratio →

Variation of
0 < μ < 0,21
Δμ=0,001

Integration-time
10^4 revolutions