On the existence of comet families in extrasolar planetary systems

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   -- escapes and new comets
   -- comet families ?
   -- selected examples of a capture orbit

4. INTERMEZZO
   Secular perturbation for e~0.9

5. Close encounters to the planets
6. The system 55 Cancri
7. Conclusion and Outlook
- The comets of the Oort cloud may have formed in a cluster of about a thousand of other stars, all packed together.

- Each young star then creates a huge number of small icy bodies around it in a disk from which planets gradually form.

- In our galaxy's early times, many of these icy objects got "ejected" from the planetary systems and eventually became comets.

- A few stayed near the Sun and formed the Oort cloud, about a light-year from the Sun.
The theory proposes that many comets may have formed in other Solar Systems: when our Sun was still a young star in its birth cluster, it may have gravitationally captured the Oort cloud comets formed in this big cluster.

This contradicts the earlier theory that most comets were born in the Sun's protoplanetary disk.
Two families of exocomets in the β Pictoris system

β Pictoris harbours active minor bodies

Spectroscopic observations of β Pictoris
-> a high rate of transits of small evaporating bodies
-> exocomets.

They produce a large amount of dust and gas through collisions and evaporation

Evaporating bodies observed in the β Pictoris system are analogous to the comets in our own Solar System.
<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral type</td>
<td>G1V</td>
</tr>
<tr>
<td>Apparent magnitude V</td>
<td>7.33</td>
</tr>
<tr>
<td>Mass</td>
<td>$1.06 \pm 0.05 , M_{\odot}$</td>
</tr>
<tr>
<td>Age</td>
<td>$4.3 \pm 0.5 , \text{Gyr}$</td>
</tr>
<tr>
<td>Effective temperature</td>
<td>$5911.0 \pm 19.0 , \text{K}$</td>
</tr>
<tr>
<td>Radius</td>
<td>—</td>
</tr>
<tr>
<td>Metallicity [Fe/H]</td>
<td>$0.08 \pm 0.01$</td>
</tr>
</tbody>
</table>
The 4 outer planets of HD 10180; there are more planets moving inside HD 10180 e, see http://www.exoplanets.eu

<table>
<thead>
<tr>
<th>Name</th>
<th>a [AU]</th>
<th>e</th>
<th>i</th>
<th>omega</th>
<th>Omega</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>10180 h</td>
<td>3.40</td>
<td>0.080</td>
<td>0.60</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>10180 g</td>
<td>1.4220</td>
<td>0.00010</td>
<td>0.80</td>
<td>1.0</td>
<td>1.0</td>
<td>181.0</td>
</tr>
<tr>
<td>10180 f</td>
<td>0.49220</td>
<td>0.1350</td>
<td>0.70</td>
<td>1.0</td>
<td>1.0</td>
<td>90.0</td>
</tr>
<tr>
<td>10180 e</td>
<td>0.270</td>
<td>0.0260</td>
<td>0.70</td>
<td>1.0</td>
<td>1.0</td>
<td>50.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>mass ([M_{Jupiter}])</th>
<th>(R_{\text{Hill}}) [AU]</th>
<th>(r_{\rho_1}) [AU]</th>
<th>(r_{\rho_2}) [AU]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10180 h</td>
<td>0.2095</td>
<td>0.1379</td>
<td>3.05E-04</td>
<td>2.42E-04</td>
</tr>
<tr>
<td>10180 g</td>
<td>0.0702</td>
<td>0.0400</td>
<td>2.12E-04</td>
<td>1.68E-04</td>
</tr>
<tr>
<td>10180 f</td>
<td>0.0786</td>
<td>0.0144</td>
<td>2.20E-04</td>
<td>1.75E-04</td>
</tr>
<tr>
<td>10180 e</td>
<td>0.0827</td>
<td>0.0080</td>
<td>2.24E-04</td>
<td>1.78E-04</td>
</tr>
</tbody>
</table>
The extrasolar system HD 10180

- HD 10180 b: (a=0.02 AU, P~1d, minimum mass ~ M_earth)
- HD 10180 c: (a=0.06 AU, P~5.4d, minimum mass ~ 13 M_earth ~ 0.04 M_jupiter)
INITIAL CONDITIONS:
100 comets from ~100 AU
0.9 < e < 0.99
0 < omega < 360 deg
0 < inclinations < 180 deg

Star + 4 outer planets
Integration for 1 Myrs – to 10 Myrs
escapes to infinity by close encounters ->
replaced by another ‘new’ comet
Initial conditions for the comet cloud in HD10180
Inclination = 0 deg, 100 different perihelion
Orbits for 100 initial conditions for 1 Myr

\[ e = 0.905 \]

Units AU
Orbits for 100 initial conditions
ca 1000 new comets

$e = 0.935$

Units AU
Orbits for 100 initial conditions for ca 5000 new comets
Temporary captures in the system HD 10180

Captured comets for i=0 deg

Captured comets for i=10 deg

**semimajor axis**
Temporary captures in the system HD 10180

Captured comets for $i=40$ deg

Captured comets for $i=50$ deg
captured comets of "Jupiter-family" in HD10180
EXAMPLE OF A CAPTURED COMET

distance to massive planet
inclination
\( a \)
10th of hill-sphere

semi-major axis
EXAMPLE OF A CAPTURED COMET

distance to massive planet

perihe|
Statement of the problem

The exact perturbing function:

\[ R = \mu_1 \left( \frac{1}{\Delta} - \frac{r \cdot \cos \psi}{r_1^2} \right) \]

The approximate perturbing function for inner perturber:

\[ R = \frac{\mu_1}{r} \sum_{n=2}^{\infty} \left( \frac{r_1}{r} \right)^n P_n(\cos \psi) + \left( \frac{r_1}{r^2} - \frac{r}{r_1^2} \right) \cos \psi \]

Series developments of products of the form:

\[ r^a r_1^b \cos^c \psi \quad \text{with} \quad a, b, c \in \mathbb{Z} \]

Cometary expansions require low order \( n \) but high eccentricity \( e \)!
Most expensive (computational) part:

\[
\cos \psi = A(i, i_1, \omega, \omega_1, \Omega, \Omega_1) \cdot \cos f \cdot \cos f_1 + B(i, i_1, \omega, \omega_1, \Omega, \Omega_1) \cdot \cos f \cdot \sin f_1 + C(i, i_1, \omega, \omega_1, \Omega, \Omega_1) \cdot \cos f_1 \cdot \sin f + D(i, i_1, \omega, \omega_1, \Omega, \Omega_1) \cdot \sin f \cdot \sin f_1 \]

Classical expansions (around \(e=0\)) do not work, we start with Fourier series representation:

\[
r = a \left(1 + \frac{1}{2} e^2 - 2e \sum_{\nu=1}^{\infty} \frac{dJ_{\nu}(e)}{de} \frac{\cos(\nu M)}{\nu^2}\right)
\]

\[
r^{-1} = \frac{1}{a} \left(1 + 2 \sum_{\nu=1}^{\infty} J_{\nu}(e) \cos(\nu M)\right)
\]

\[
\cos f = 2 \frac{1 - e^2}{e} \sum_{\nu=1}^{\infty} J_{\nu}(e) \cos(\nu M) - e
\]

\[
\sin f = 2 \sqrt{1 - e^2} \sum_{\nu=1}^{\infty} \frac{dJ_{\nu}(e)}{de} \frac{\sin(\nu M)}{\nu}
\]

Inclinations, arguments of pericenter, ascending node longitudes, true anomalies:

\(i, i_1, \omega, \omega_1, \Omega, \Omega_1, f, f_1\)
Preliminary results

\[ H = H_S + H_r + H_p \]

Separate dynamics:
- secular evolution
- resonant evolution
- close encounters

**Emel'yanenko 1991:**
*Expansion of the secular and resonance parts of the perturbing function in the theory of motion of long-periodic comets.*

**Petrovsky, Broucke 1988:**
*Area preserving mappings and deterministic chaos for nearly parabolic motions*
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**Aim:** understand capture process on the basis of restricted three-body problem
Encounters within 1/10 of the Hill radius for 10180 h and 10180 g
Encounters within $1/10$ of the Hill radius for 10180 f and 10180 e
3 different scanaria of encounter
NEW (UNSTABLE) COMETS IN HD 10180
NEW (UNSTABLE) COMETS IN HD 10180 -- DETAIL
NEW (UNSTABLE) COMETS IN HD 10180 -- DETAIL

Stable region

eccentricity

inclination

Non-stable region
The 55 Cancri A planetary system\cite{20}[31]

<table>
<thead>
<tr>
<th>Companion (in order from star)</th>
<th>Mass</th>
<th>Semimajor axis (AU)</th>
<th>Orbital period (days)</th>
<th>Eccentricity</th>
<th>Inclination</th>
<th>Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>e (Janssen)</td>
<td>8.63 ± 0.35 $M_\oplus$</td>
<td>0.01560 ± 0.00011</td>
<td>0.736537 ± 0.000013</td>
<td>0.17 ± 0.04</td>
<td>83.4 ± 1.7°</td>
<td>2.00 ± 0.14 $R_\oplus$</td>
</tr>
<tr>
<td>b (Galileo)</td>
<td>0.825 ± 0.003 $M_J$</td>
<td>0.1148 ± 0.0008</td>
<td>14.6507 ± 0.0004</td>
<td>0.010 ± 0.003</td>
<td>~85°</td>
<td>—</td>
</tr>
<tr>
<td>c (Brahe)</td>
<td>≥0.171 ± 0.004 $M_J$</td>
<td>0.2403 ± 0.0017</td>
<td>44.364 ± 0.007</td>
<td>0.005 ± 0.003</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>f (Harriot)</td>
<td>≥0.155 ± 0.008 $M_J$</td>
<td>0.781 ± 0.006</td>
<td>259.8 ± 0.5</td>
<td>0.30 ± 0.05</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>d (Lipperhey)</td>
<td>≥3.82 ± 0.04 $M_J$</td>
<td>5.74 ± 0.04</td>
<td>5169 ± 53</td>
<td>0.014 ± 0.009</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
- Goal was to find comet families like in our SS
  - (Halley-types - Jupiter family comets)
  - (with C. Lhotka from IWF-secular perturbation theory for e~0.9)

- With M. Cuntz
- Transport of water to habitable zones by comets
- why comets (see first slide!)
- HD 10108, interesting also other systems
- Statistical approach (~10^6 comets) will show the probability of
  - Captures and impacts with planets
  - ‘LIFE of families ‘

Idea to look for early exosystems
When a comet collides with a planet in the habitable zone
(SPH collision computations Water? C-molecules?

All collisions are with respect to velocity of impact and impact angle
available – but many additional computations necessary and an
appropriate analysis of the huge amount of data during

CHECK OF ALL EXOPLANETS WITH OUTER GAS GIANT + PLANETS INSIDE
END