Dynamics of exoplanetary systems, links to their « habitability »

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★ A bit of perspective
★ A few words about tides
★ Planets around brown dwarfs
★ Kepler-186
★ A bit of perspective
★ A few words about tides
★ Planets around brown dwarfs
★ Kepler-186
Exoplanets discoveries

Planet orbiting a Sun like star

Rocky planet

Planet in the habitable zone
Habitable zone planets

«Habitable zone» region around a star in which a planet could potentially host surface liquid water.
Habitable zone planets

![Graph showing the habitable zone planets with a yellow arrow pointing to the year 1995. The x-axis represents period in days, ranging from 100 to 1000, and the y-axis represents mass in Jupiter masses, ranging from 0.01 to 10^2.](hzgallery.org)
Habitable zone planets

rocky
Outline

★ A bit of perspective
★ A few words about tides
★ Planets around brown dwarfs
★ Kepler-186
Constant time lag model

Mignard 1979; Hut 1981; Leconte et al. 2010
Constant time lag model

\[ \Omega_p = n_s \]

\[ \Omega_p < n_s \]

\[ \Omega_p > n_s \]
Constant time lag model

\[ \Omega_p = n_s \]

orbital distance of secondary \( a_s = r_c \)

corotation distance
Constant time lag model

\[ \Omega_p < n_s \]

\[ a_s < r_c \]
Constant time lag model

\[ \Omega_\star < n_{\text{HJ}} \]
\[ a_s < r_c \]

\[ \Omega_p \rightarrow n_s \rightarrow n_s \]

Hot Jupiter systems
Constant time lag model

\[ \Omega_p > n_s \]
\[ a_s > r_c \]
Constant time lag model

Earth-Moon system

Ω⁺ > n_{moon}

Ω⁺ → n_{moon} → a_{moon}

a_s > r_c

n_s
Tidal evolution

Constant time lag model

Star

Planet

Stellar tide
Tidal evolution

Constant time lag model

Planetary tide
Both tides need to be taken into account.
Tidal evolution

Stellar tide

★ planet inside corotation ➞ planet migrates inward

★ planet outside corotation ➞ planet migrates outward

★ eccentricity decreases

★ inclination of planet decreases
Tidal evolution

Planetary tide

Planet has low moment of inertia:
bulges get aligned quickly

Synchronization
Tidal evolution

Planetary tide

★ $e=0$: quick synchronization

★ $e \neq 0$: quick pseudo-synchronization

★ obliquity of planet decreases

★ eccentricity decreases

★ planet migrates inward
A bit of perspective
A few words about tides
Planets around brown dwarfs
Kepler-186

Tides
Climates
Planets around brown dwarfs

Diagram orbital distance vs stellar mass

Brown dwarfs

Distance Earth-Sun

Interesting zone!

Liquid water «Habitable zone»

0.08 M⊙
Evolution of brown dwarfs

Contraction ⇒ spin-up

Some BDs have rotation periods of $\sim 1$ hr

(Herbst et al. 2007)

Radius and rotation period of BDs of different masses

\[
\begin{array}{c|c|c}
\text{Radius } (R_\odot) & \text{Rotation period } (\text{hr}) & \text{Time } (\text{yr}) \\
\hline
1.0 & & \\
0.1 & & \\
\hline
& & \\
& & \\
\end{array}
\]

Baraffe et al. 2003

\[
R_{BD} = R_{BD}(t) \\
P_{BD} = P_{BD}(t)
\]
Planets around brown dwarfs

Aquability of an Earth mass planet

$M_{BD} = 0.04 \ M_{\odot}$

$M_p = 1 \ M_{\oplus}$

Orbit almost circular
no obliquity
no inclination

Bolmont et al. 2011
Planets around brown dwarfs

From aquability to habitability?

More time for life emergence, evolution and observability

Time spent in HZ (yrs)

BD mass ($M_{\text{Sun}}$)
Planets around brown dwarfs

Habitable zone

★ If planet is alone, when it reaches the habitable zone:

Danger for aquability: cold trap?

★ What if the planet is part of a multiple system?
Planets around brown dwarfs

Tidal effects in multi-planet systems

Brown dwarf

Gravitational interactions between planets

No Resonances
Planets around brown dwarfs

Tidal effects in multi-planet systems

Brown dwarf

Jupiter

Planet 1

Planet 2

Planet 3

Io

Europa

Ganymede
Planets around brown dwarfs

Tidal effects in multi-planet systems

Tidal effect in Io $\rightarrow$ strong volcanism

Tidal heat flux is $\sim 3$ W/m$^2$ $\quad > \sim 40 \times$ Earth's flux (radioactivity)

Spencer et al. 2000 $\quad$ Pollack et al. 1993

Images from *New Horizons* showing volcano Tvashtar
Discussed in Barnes et al. (2010) for planets around M-dwarfs
Planets around brown dwarfs

Effect of tidal heating

Uniform temperature of a planet

\[ T_{\text{unif}}(a, e, A) = \left( T_{\text{eq}}^4 + \frac{\phi_{\text{tides}}}{\sigma_{\text{SB}}} \right)^{1/4} \]
Planets around brown dwarfs

Effect of tidal heating

$\sigma_p = 0.1\sigma_\oplus$

- $A=0$  
- $A=0.2$
- $A=0.6$
- $A=0.9$
- $A=0.999$

- $10^{-3} \text{ W/m}^2$
- $10^{1} \text{ W/m}^2$
- $10^{2} \text{ W/m}^2$

A contribution of tides
Planets around brown dwarfs

Effect of tidal heating

$\sigma_p = 0$

$A=0$

$A=0.2$

$A=0.6$

$A=0.9$

$A=0.999$

$\sigma_p = 0.1 \sigma_\oplus$

$\sigma_p = 1 \sigma_\oplus$

$\sigma_p = 10 \sigma_\oplus$

$log(T_{unif})$

0.00 1.00 2.00 3.00 4.00 5.00

SMA (AU)
Planets around brown dwarfs

- 1 planet: synchronized, no obliquity: $\Phi_{\text{tides}} = 0 \text{ W/m}^2$

- +1 planet: other dangers
  - $(\Phi_\star + \Phi_{\text{tides}})_{\text{avg}} < 300 \text{ W/m}^2$, **aquability**
  - $(\Phi_\star + \Phi_{\text{tides}})_{\text{avg}} > 300 \text{ W/m}^2$, **no aquability**

Several planets no resonances

Several planets resonances
A bit of perspective
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Kepler-186
Kepler-186f

Orbits of Kepler-186

Habitable Zone

Potentially habitable planets

Too hot for life

Planetary system comparison

Solar System

Kepler-186

Gliese 581

Incident flux (normalized to Earth)

100 10 5 2 1 0.5 0.25

M\(_\star\) = 0.48 M\(_{\odot}\)

Planets

1 < \(R_p/R_{\oplus}\) < 1.4

0.04 < a/AU < 0.4

Quintana et al. (2014)
Bolmont et al. (2014)
Kepler-186 Evolution

orbital plane

obliquity (deg)

Time (yr)
Kepler-186
Aquability of Kepler-186f?

Assuming Earth composition
Assuming Earth dissipation

Time (years)

<table>
<thead>
<tr>
<th>Rotation Period (hr)</th>
<th>Obliquity (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 hr</td>
<td>0</td>
</tr>
<tr>
<td>100 hr</td>
<td>23</td>
</tr>
<tr>
<td>2000 hr</td>
<td>60</td>
</tr>
<tr>
<td>80</td>
<td>80</td>
</tr>
</tbody>
</table>

orbital plane

ε

Assuming Earth composition
Assuming Earth dissipation
Kepler-186

Aquability of Kepler-186f?

Assuming Earth composition
Assuming Earth dissipation

\[ P_0 = 5 \text{ hr} \]
\[ P_0 = 100 \text{ hr} \]
\[ P_0 = 2000 \text{ hr} \]
\[ \varepsilon_0 = 23^\circ \]
\[ \varepsilon_0 = 60^\circ \]
\[ \varepsilon_0 = 80^\circ \]
Kepler-186

Aquability of Kepler-186f?

Assuming Earth composition
Assuming Earth dissipation
Kepler-186

- age ≳ 4 Gyr

★ Kepler-186 b, c, d and e are very likely to be pseudo-synchronized (P_{rot} > 3.75 days), and have equilibrium obliquities (∼0.1°)

★ Kepler-186 f might be in the process of pseudo-synchronization, its obliquity may have high values ➔ impact on its climate
Tides and climate

- Planetary tide $\sigma_p$
- Orbital distance
- Stellar tide $\sigma_*$
- Eccentricity
- Rotation period
- Tidal heat flux
- Obliquity
- Insolation
- Insolation $\pm$
- Cold trap e-seasons
- Cold trap seasons
- Neighboring planets
- If resonance
Thank you !