On the origin of stellar spin-orbit angle in extrasolar systems

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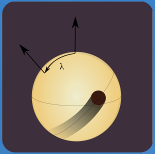
&
Jacques LASKAR, Daniel C. FABRYCKY

31th International Colloquium of the IAP
From Super-Earths to Brown Dwarfs: Who's who?



Source of stellar spin-orbit angle

Consequence of hot Jupiter formation

- high eccentricity migration [e.g., Rasio & Ford 96, Mazeh et al. 97]

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Stellar physics

- turbulent stellar formation [Bate et al. 10, Thies et al. 11, Fielding et al. 15]
- magnetic star-disk interaction [Lai et al. 11, Spalding & Batygin 14]
- modulation of the stellar envelope [Rogers et al. 12]

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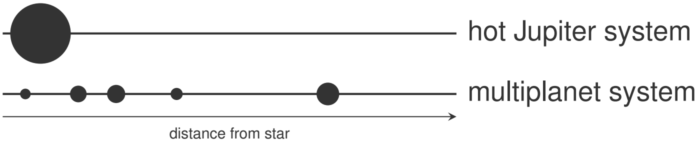
From hot Jupiters to low mass planets...



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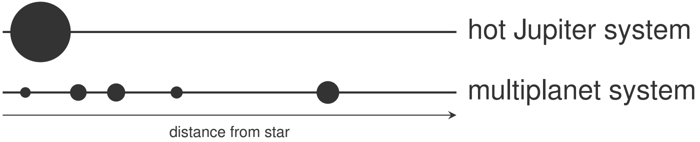
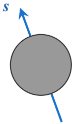


Source of stellar spin-orbit angle

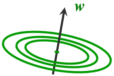
	HJ	multies	justification
formation (HEM)	✓	✗	compact system
ext. torque	✓	✗|✓	spin-orbit coupling strength
stellar phys.	✓	✓	
tidal dissip.	✓	✗	low planet masses

Spin-orbit and orbit-orbit couplings

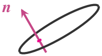
notation



spin-axis

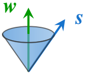


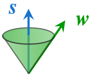
planet system

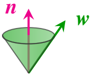


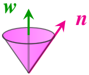
binary

- Equations of motion

$$\frac{d\mathbf{s}}{dt} = -\nu_1$$ 

$$\frac{d\mathbf{w}}{dt} = -\nu_2$$ 

$$- \nu_3$$ 

$$\frac{d\mathbf{n}}{dt} = -\nu_4$$ 

- Secular frequencies: $\nu_1, \nu_2, \nu_3, \nu_4$.
- Exact solution: Boué & Laskar (2006), Boué & Fabrycky (2014)

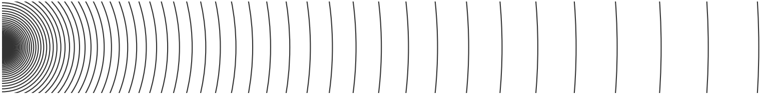
Archetype 55 Cancri

5 planets in a binary system

On the stellar spin-orbit angle

method	angle	ref.
theory	50°	Kaib et al. 11
	0°	Boué & Fabrycky 14
observation	70°	Bourrier & Hébrard 14
	undetected	Lopez-Morales et al. 14

Model 1: stars + disk



star parameters

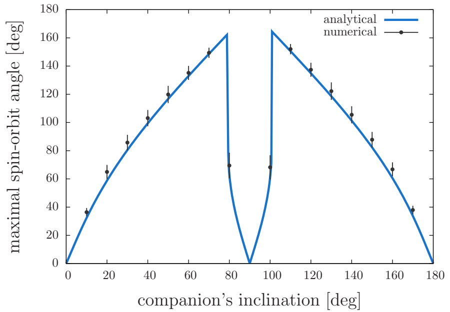
mass m_0 [$M_\odot$]	1
radius R_0 [$R_\odot$]	2
rotation period P_0 [d]	10
Love number k_2	0.028
moment of inertia I_0	0.09

disk parameters

mass [M_{Jup}]	10
inner radius a_{in} [au]	0.05
outer radius a_{out} [au]	50
number of rings N	100
surface density Σ	$\propto 1/r$

companion parameters

mass m_p [$M_\odot$]	0.27
semimajor axis a_p [au]	1250
eccentricity e_p	0.93



Secular periods

$P_1 \approx 6$ My , $P_2 \approx 900$ My , $P_3 \approx 10$ My , $P_4 \approx 3$ Gy .

About the formation of low mass planets

[Ogihara et al. 15]

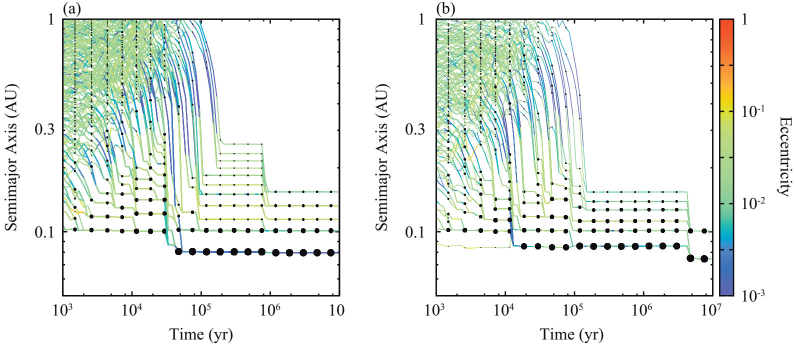


Figure: Time evolution of planets formation. The largest planets have masses $33M_{\oplus}$ and $35M_{\oplus}$ in panel a) and b), respectively.

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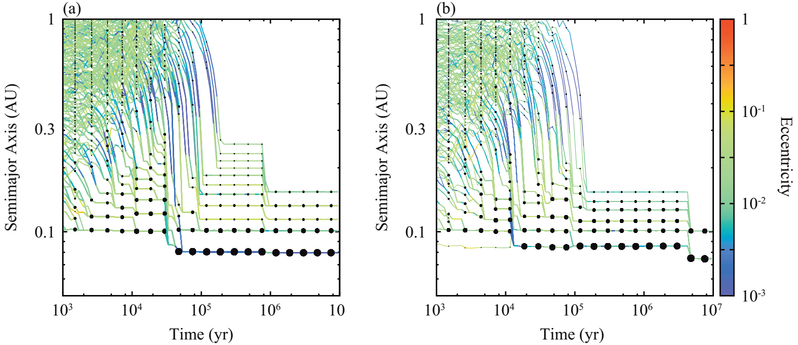

Figure: Time evolution of planets formation. The largest planets have masses $33M_{\oplus}$ and $35M_{\oplus}$ in panel a) and b), respectively.

timescale $\lesssim$ 0.1 Myr

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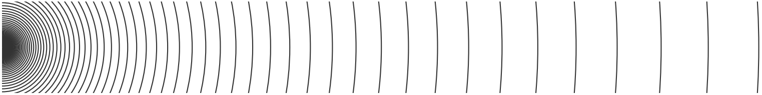

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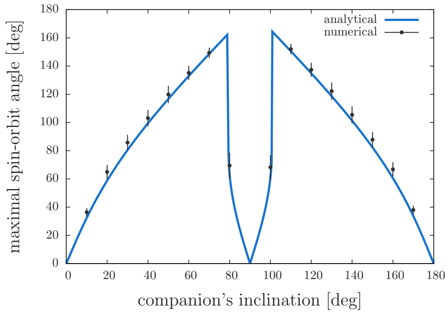

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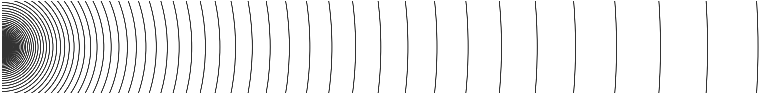

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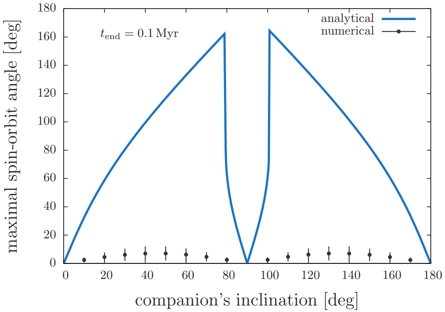
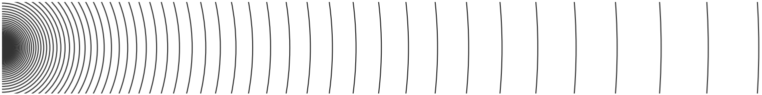


Secular periods

$P_1 \approx 6$ My , $P_2 \approx 900$ My , $P_3 \approx 10$ My , $P_4 \approx 3$ Gy .

Model 2: stars + disk + inner planet



star parameters

mass m_0 $[M_\odot]$	1
radius R_0 $[R_\odot]$	2
rotation period P_0 [d]	10
Love number k_2	0.028
moment of inertia I_0	0.09

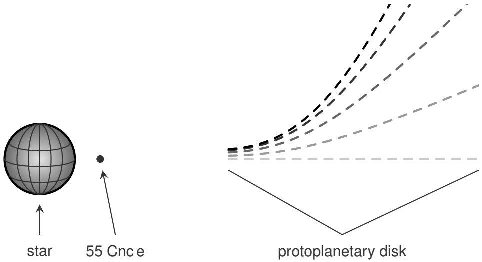
disk parameters

mass $[M_{\rm Jup}]$	10
inner radius $a_{\rm in}$ [au]	0.05
outer radius $a_{\rm out}$ [au]	50
number of rings N	100
surface density Σ	$\propto 1/r$

companion parameters

mass m_p $[M_\odot]$	0.27
semimajor axis a_p [au]	1250
eccentricity e_p	0.93

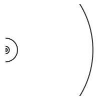
+ planet 55 Cnc e



Secular periods

$P_1 \approx 0.03$ My , $P_2 \approx 5$ My , $P_3 \approx 2$ My , $P_4 \approx 187$ My .

Model 3: stars + 5 planets



star parameters

mass m_0 [$M_\odot$]	0.905
radius R_0 [$R_\odot$]	0.943
rotation period P_0 [d]	42.7
Love number k_2	0.028
moment of inertia I_0	0.09

planet parameters

mass [M_{Jup}]		sma [au]	
m_e	0.027	a_e	0.016
m_b	0.83	a_b	0.11
m_c	0.17	a_c	0.24
m_f	0.16	a_f	0.78
m_d	3.82	a_c	5.74

companion parameters

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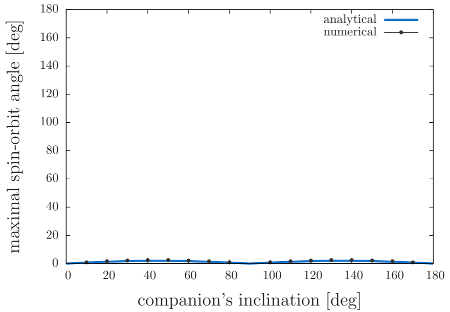


Secular periods

$P_1 \approx 1$ My , $P_2 \approx 800$ My , $P_3 \approx 35$ My , $P_4 \approx 11$ Gy .

Model 4: stars + 8 planets

star parameters

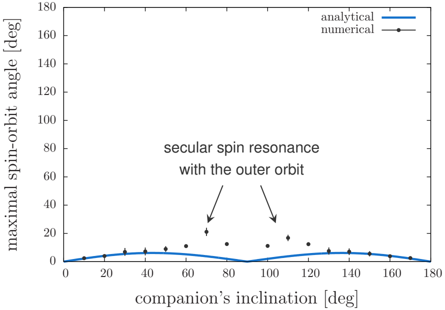
mass m_0 [$M_\odot$]	0.905
radius R_0 [$R_\odot$]	0.943
rotation period P_0 [d]	42.7
Love number k_2	0.028
moment of inertia I_0	0.09

planet parameters

mass [M_{Jup}]		sma [au]	
...	...	...	...
m_S	0.30	a_S	9.5
m_U	0.05	a_U	19.0
m_N	0.05	a_N	30.0

companion parameters

mass m_p [$M_\odot$]	0.27
semimajor axis a_p [au]	1250
eccentricity e_p	0.93



Secular periods

$P_1 \approx 1$ My , $P_2 \approx 900$ My , $P_3 \approx 11$ My , $P_4 \approx 3$ Gy .

Conclusion

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- external torque
- stellar physics
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Perspectives

- multi transits + obliquity $\Rightarrow$ constraints on stellar physics