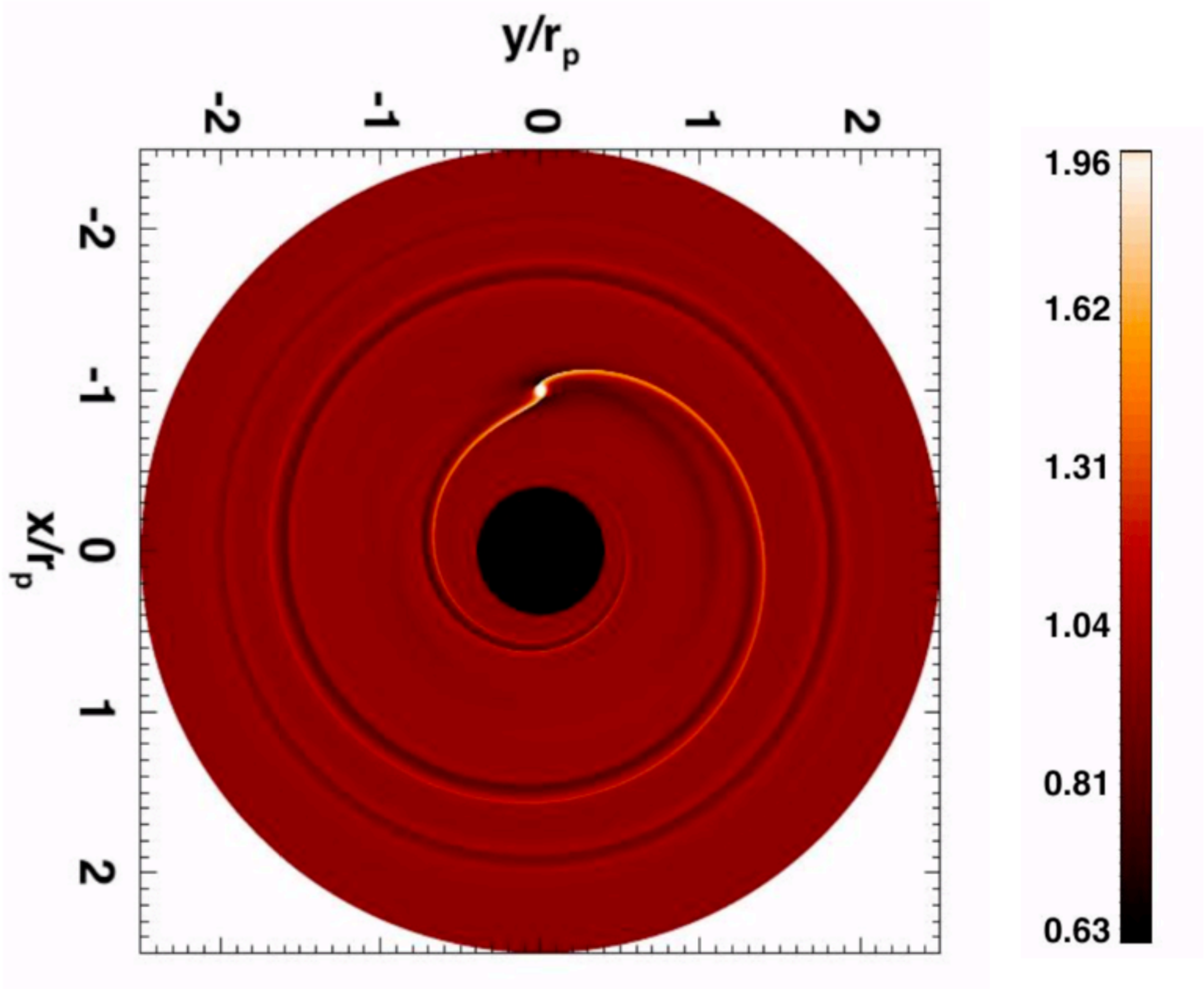
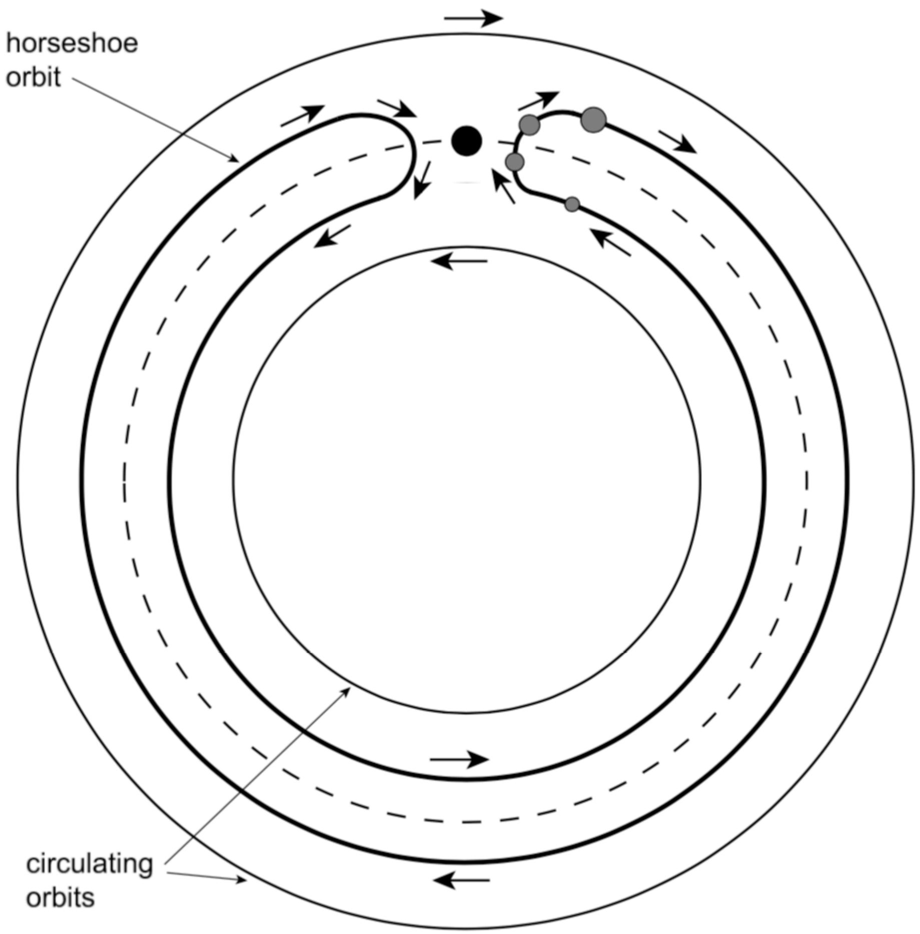
Disk-planet interaction





Resonances

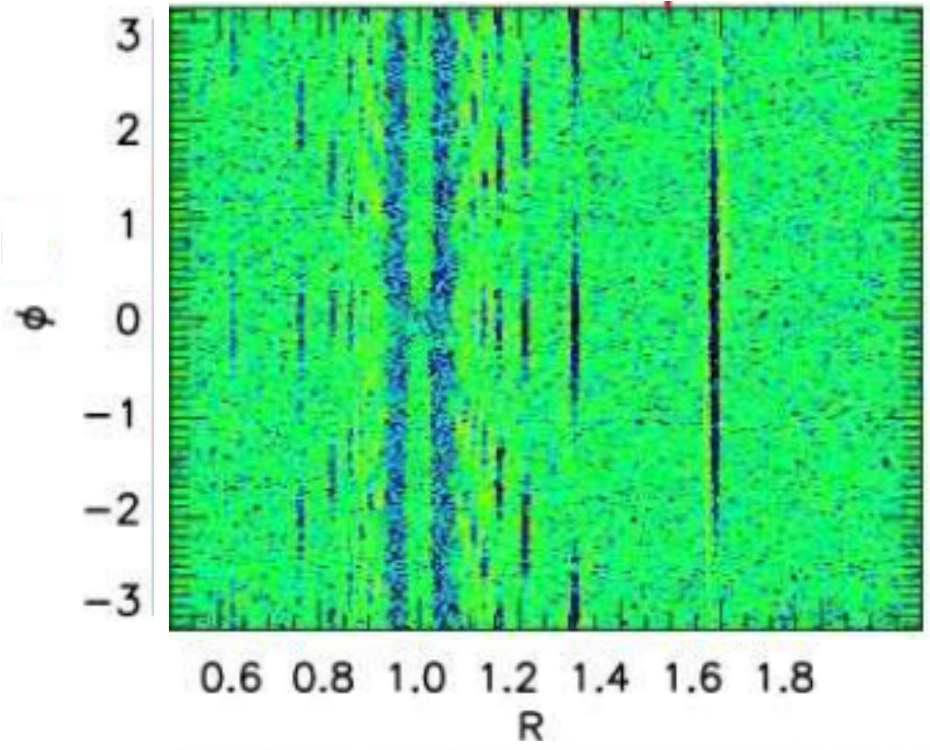
In resonances, the interaction with the planet is amplified.

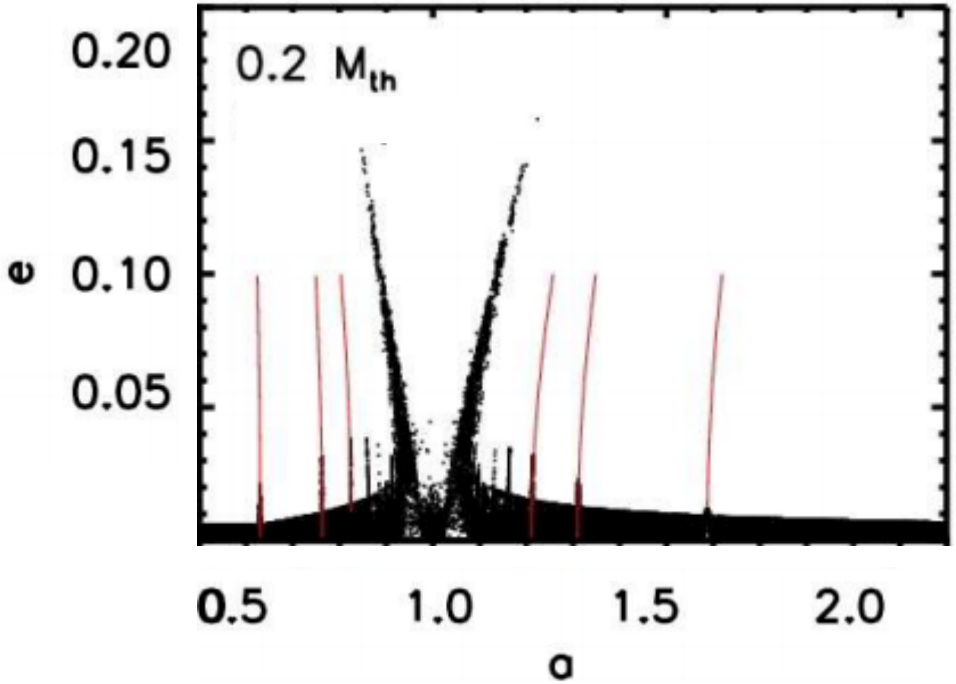
The gas only interacts with the planet at resonances

$$m(\Omega - \Omega_p) = \begin{cases} \kappa & \text{Inner Lindblad Resonance} \quad \Omega = \Omega_p + \kappa/m \\ 0 & \text{Corotation} \quad \Omega = \Omega_p \\ -\kappa & \text{Outer Lindblad Resonance} \quad \Omega = \Omega_p - \kappa/m \end{cases}$$

Location of Lindblad resonances

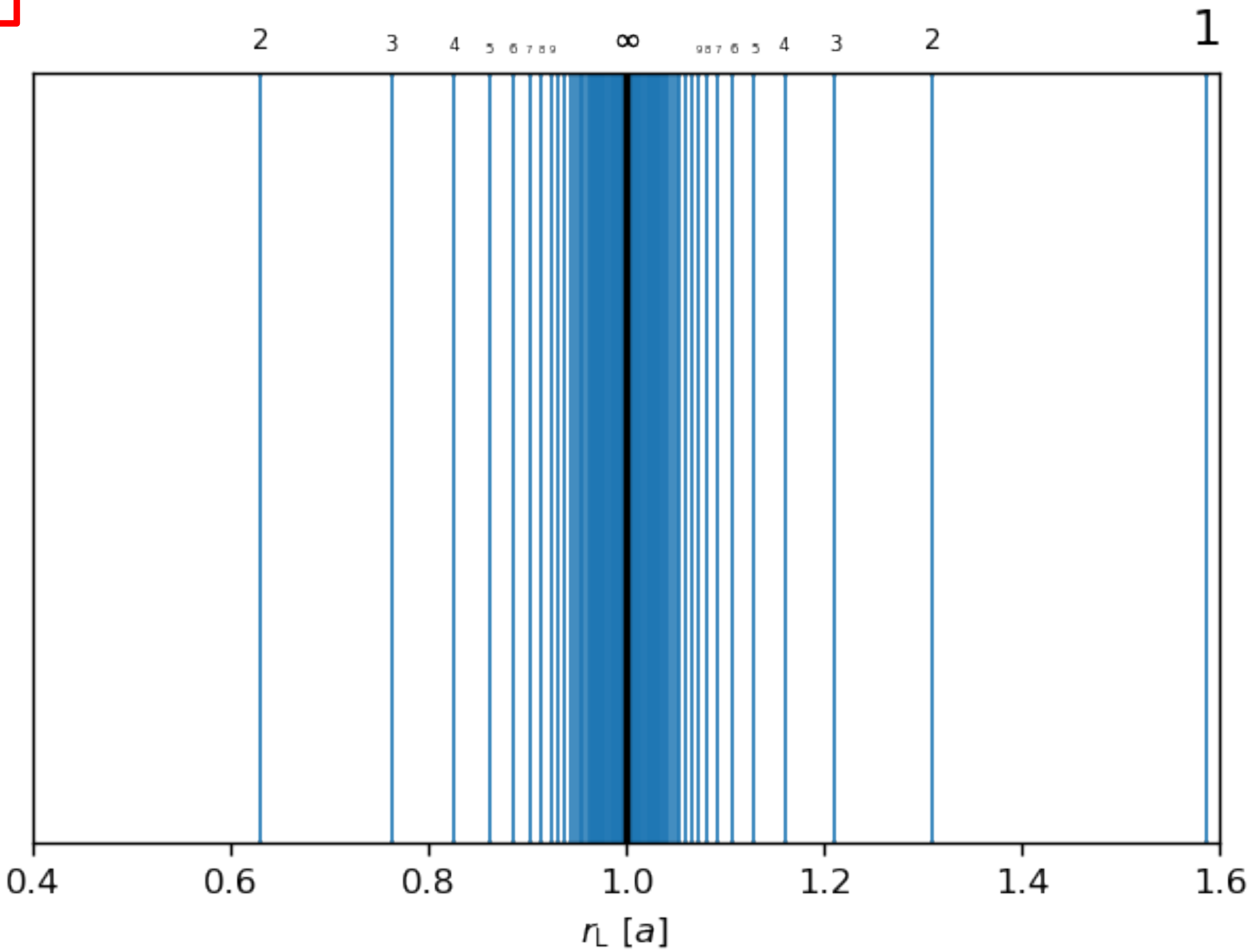
$$r_{L\pm} = r_p \left(1 \pm \frac{1}{m}\right)^{2/3}$$





$$r_{L\pm} = r_p \left(1 \pm \frac{1}{m}\right)^{2/3}$$

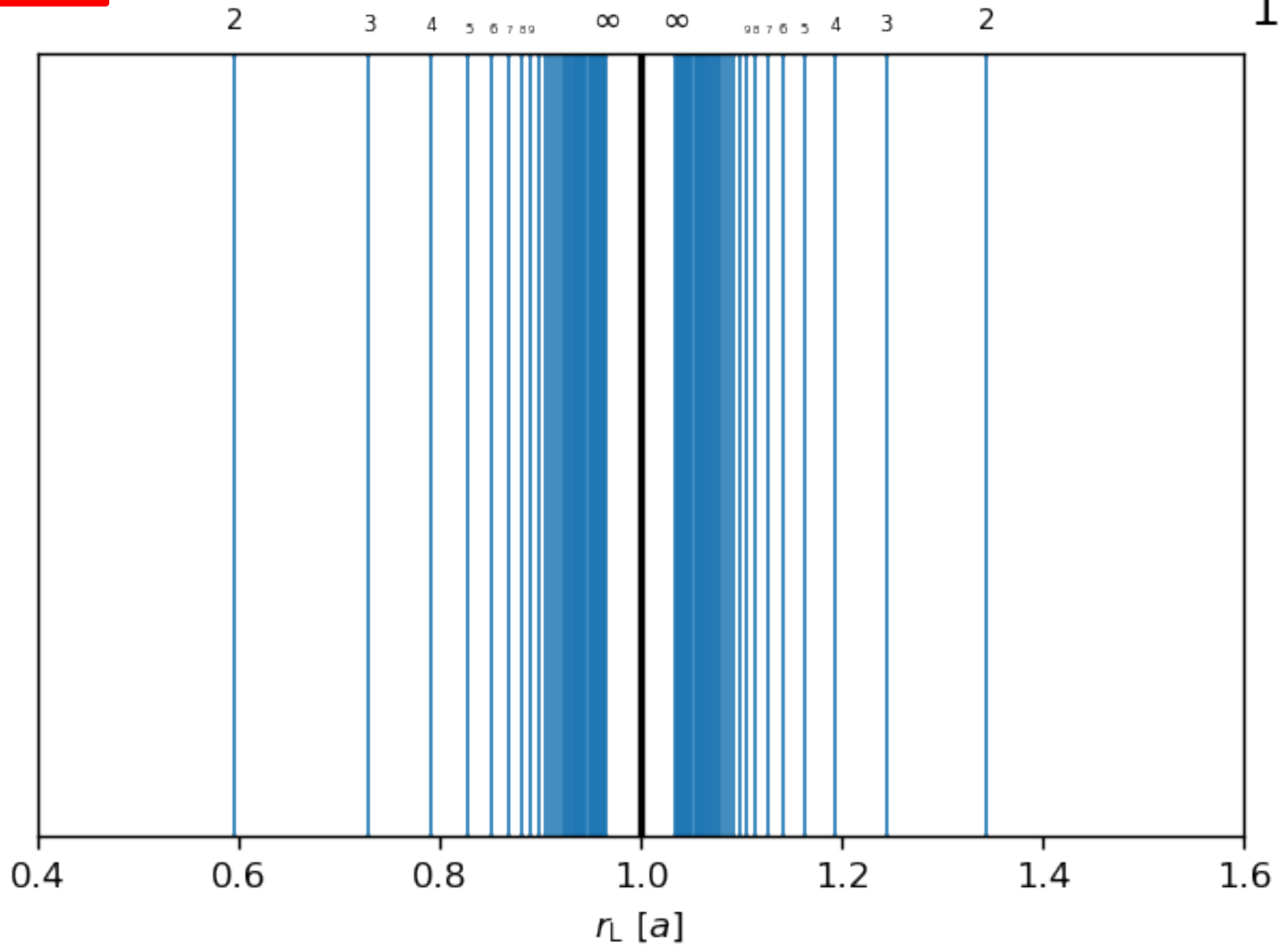
Lindblad Resonances



$$r_{L\pm} = r_p \left(1 \pm \frac{1}{m}\right)^{2/3} \pm \frac{2H}{3}$$

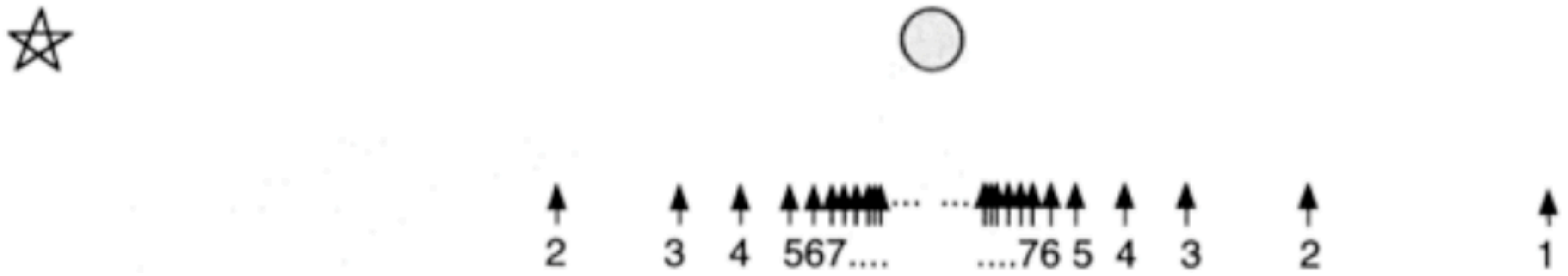
Lindblad Resonances

1



Lindblad Resonances

$$m(\Omega - \Omega_p) = \pm \kappa$$

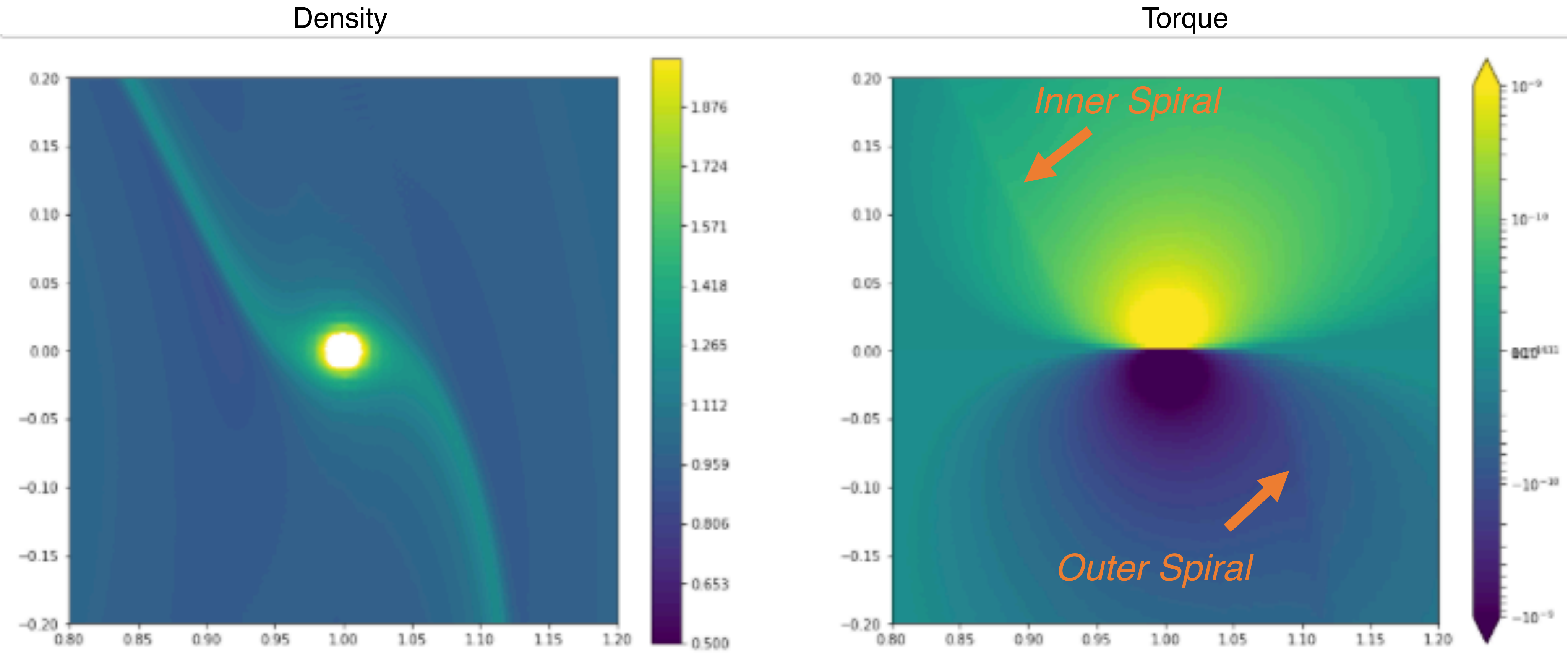


Asymmetry!

Outer Lindblad resonance is **closer to the planet** than inner Lindblad resonance for same m.

$$r_{\pm} = a\left(1 \pm \frac{1}{m}\right)^{2/3}$$

Migration Torques



Outer spiral is **closer** to the planet

Lindblad torque is **negative**

The **migration** it causes is ***inward***

Total Torque

$$m(\Omega - \Omega_p) = \begin{cases} \kappa & \text{Inner Lindblad Resonance} & \Omega = \Omega_p + \kappa/m \\ 0 & \text{Corotation} & \Omega = \Omega_p \\ -\kappa & \text{Outer Lindblad Resonance} & \Omega = \Omega_p - \kappa/m \end{cases}$$

Sum the torques from all resonances

$$\Gamma = \Gamma_{\mathrm{CR}} + \sum_{m=1}^{\infty} (\Gamma_{\mathrm{ILR}}^{m} + \Gamma_{\mathrm{OLR}}^{m})$$

??

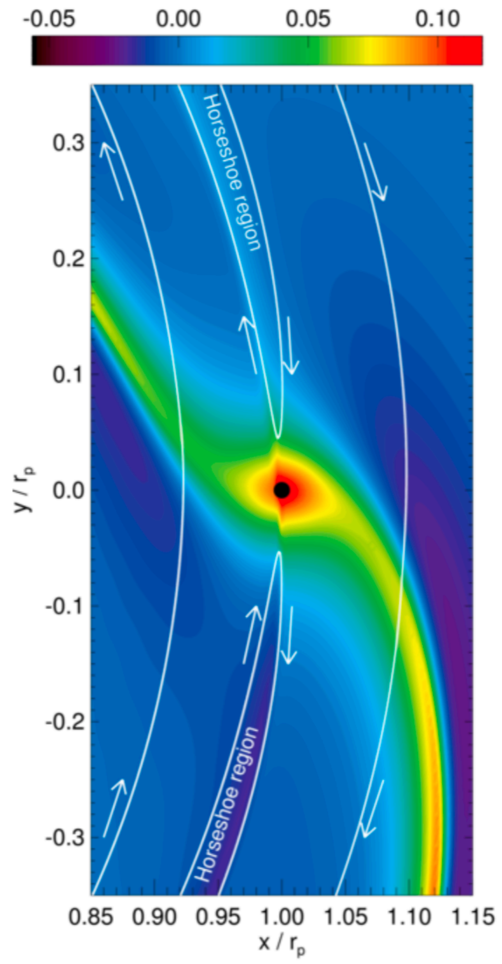
Negative

Corotational Torque
(Horseshoe Drag)

Gas in corotation

librates around the planet

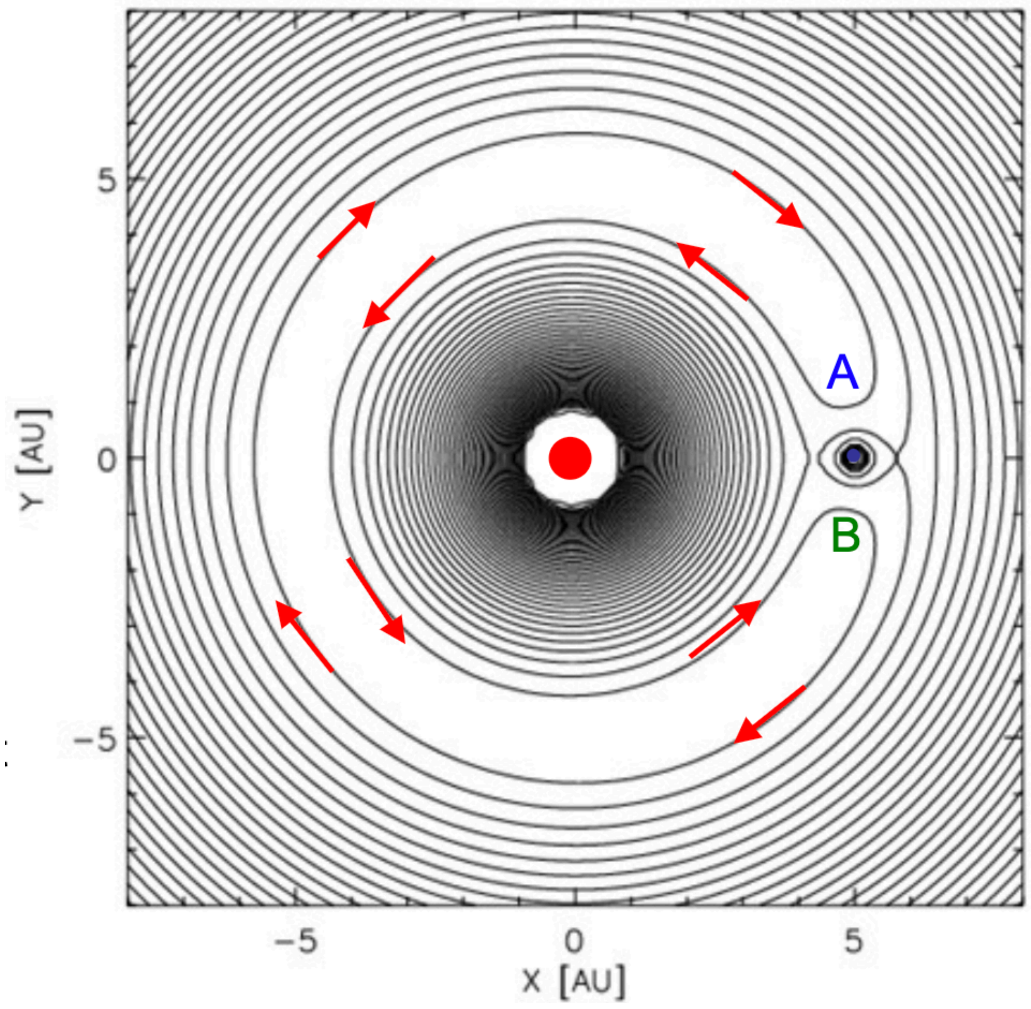
in “horseshoe orbits”



Horseshoe Drag

In the **leading (A) U-turn**, the gas loses angular momentum, so its torque on the planet is **positive**

In the **trailing (B) U-turn**, the gas gains angular momentum, so its torque on the planet is **negative**



The excitation of density waves at the Lindblad and corotation resonances by an external potential.

Show affiliations

Goldreich, P.; Tremaine, S.

The linear response of a differentially rotating two-dimensional gas disk, both with and without self-gravity, to a rigidly rotating external potential is calculated on the assumptions that the speed of sound is much smaller that the orbital velocity and that the external potential varies on the scale of the disk radius. The results show that: (1) the external potential exerts torques on the disk only at the Lindblad and corotation resonances; (2) the torque is positive at the outer Lindblad resonance and negative at the inner Lindblad resonance; (3) the torque at corotation has the sign of the radial vorticity gradient; and (4) the torques are of the same order of magnitude at both types of resonance and independent of the speed of sound in the disk. It is found that the external potential also excites density waves in the vicinity of the Lindblad and corotation resonances, that the long trailing wave is excited at a Lindblad resonance, and that short trailing waves are excited at the corotation resonance. The behavior of particle disks is briefly discussed, and the external torques on particle disks are proven to be identical to those on gas disks

$$T_c = \frac{m\pi^2}{2}\left[\frac{\varphi_1{}^2}{d\Omega/dr}\frac{d}{dr}\left(\frac{\sigma}{B}\right)\right]_{r_c}$$

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Horsehoe Orbit Drag

Show affiliations

Ward, W. R.

No abstract

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Pub Date: March 1991

Bibcode: 1991LPI....22.1463W

Keywords: Planetary Science

HORSESHOE ORBIT DRAG. Wm. R. Ward, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109.

A ring of particles occupying a horseshoe orbit region interacts gravitationally with and, in general, exerts a net cumulative torque on a perturbing body. Quinn and Goodman (1) have provided an estimate of this torque in connection with their discussion of sinking satellite galaxies. Their torque expression is proportional to the local gradient of the disk's surface density, $d\sigma/dr$. However, the disturbing potential in the horseshoe region of a perturber in a circular orbit is dominated by a series of overlapping corotation resonances (2) and torques associated with such resonances are known to be proportional to the gradient, $d(\sigma/B)/dr$; where $B \equiv (2r)^{-1}d(r^2\Omega)/dr$ is the Oort constant measuring disk vorticity (2,3). Here we show that this is indeed the case for the horseshoe ring torque as well, clarifying its connection with corotation resonances. In cases where the density gradient is mild, this additional dependence may reverse the expected sign of the torque. Such situations are common in astrophysical applications.

Consider a perturber, M_p, in a circular orbit, r_p, of mean motion, Ω_p, that is approached from the rear by an interior particle ($m \ll M_p$) in a circular orbit of radius $r_i < r_p$ and mean motion $\Omega_i > \Omega_p$, [assuming the Oort constant $A \equiv (r/2)d\Omega/dr < 0$]. The particle experiences a torque during its approach that increases its angular momentum. This, in turn, promotes the particle to a higher orbit. If the initial differential semi-major axis is small enough, i.e., $|r_p - r_i| \lesssim W \approx |GM_p/2AB|^{1/3}$, the orbit radius will drift above r_p before encounter (1). The relative mean motion $\Omega - \Omega_p$ reverses sign and the particle falls behind the perturber on an outer orbit $r_o > r_p$,

Tanaka (Isothermal) Torque

Sum the torques from all resonances

$$\Gamma = -(1.36 + 0.54\alpha) \left(\frac{M_p}{M_*}\right)^2 \left(\frac{H}{a}\right)^{-2} \Sigma\, a^4\, \Omega_K^2$$

Still negative…

Non-isothermal

If horseshow turn is fast compared to heat transfer, the dynamics is adiabatic

Entropy is conserved!

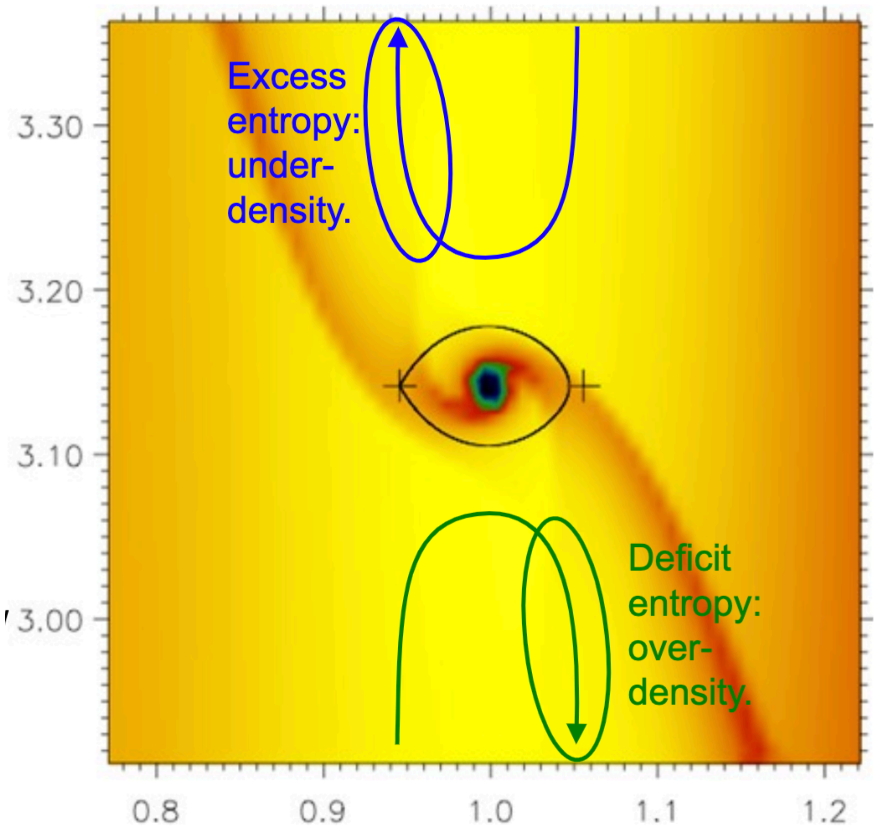
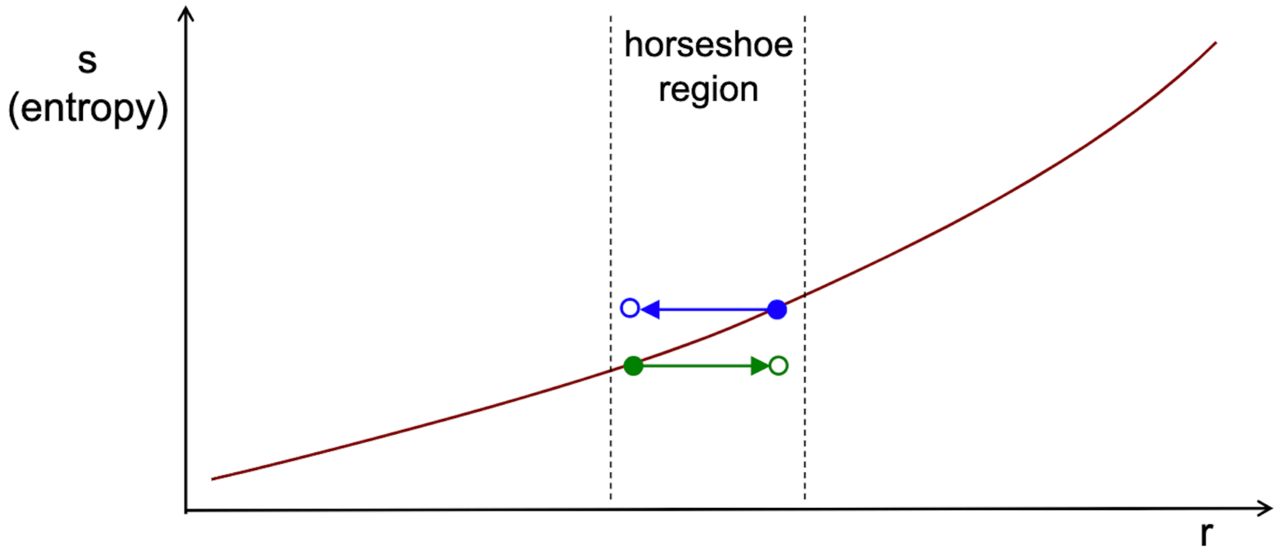
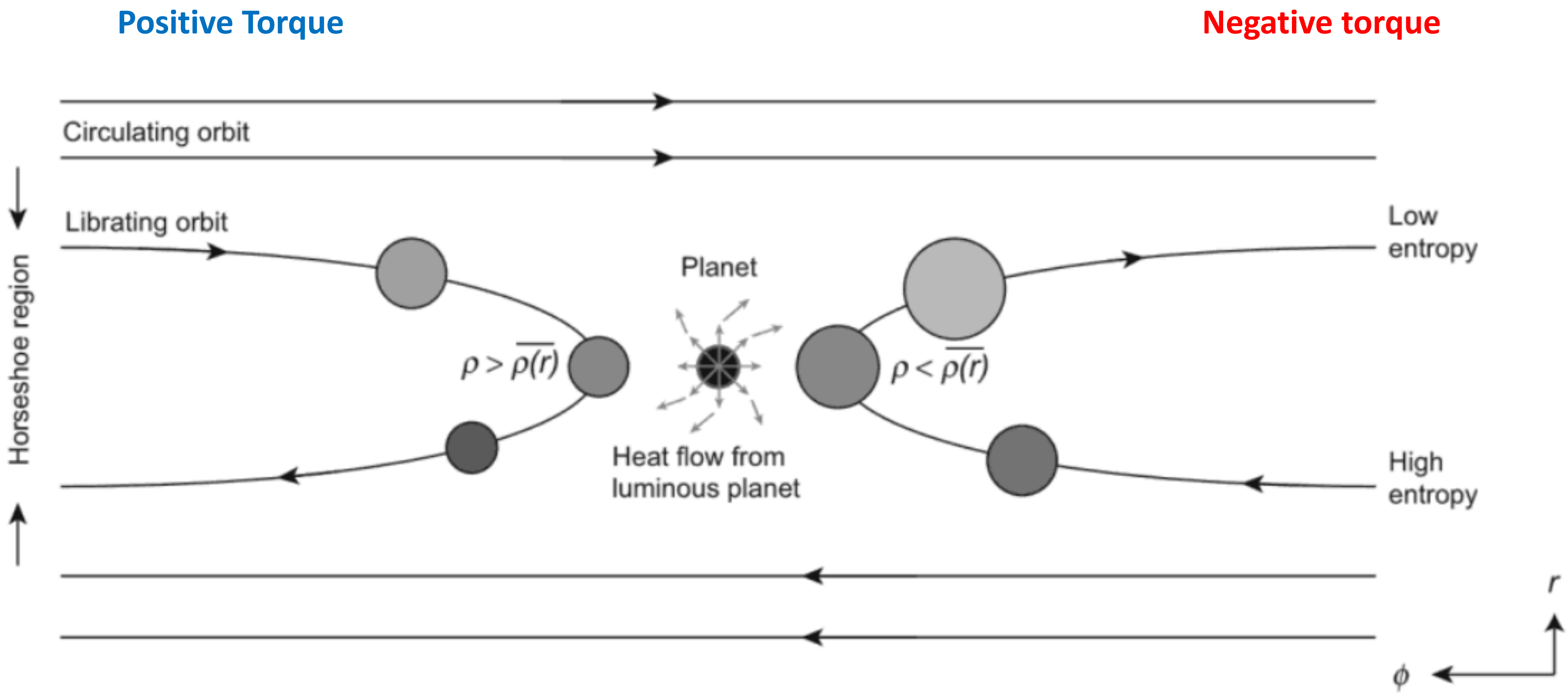


Image: D'Angelo, Henning & Kley (2002)





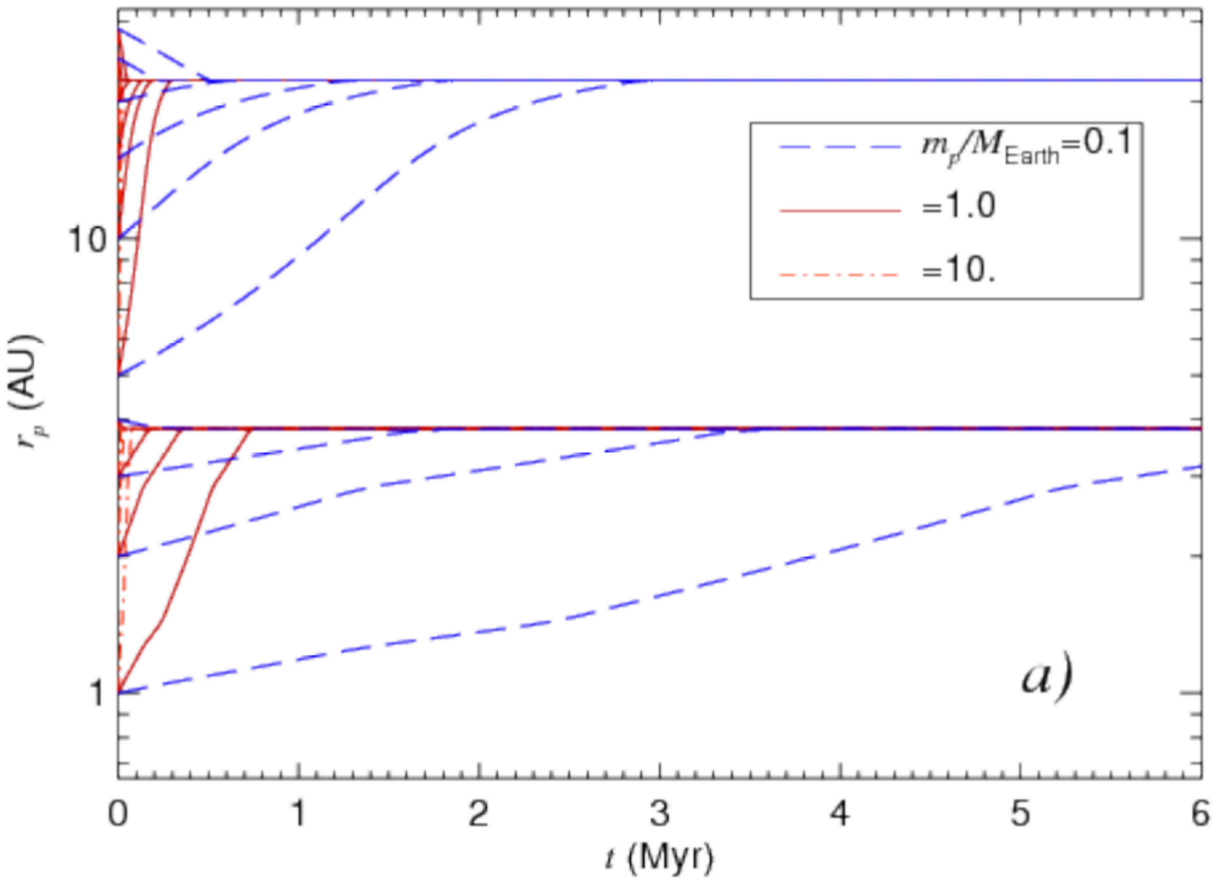
Positive Torque
Negative torque
Circulating orbit
Librating orbit
Horseshoe region
Planet
$\rho > \overline{\rho(r)}$
$\rho < \overline{\rho(r)}$
Heat flow from
luminous planet
Low
entropy
High
entropy
r
ϕ

Orbital Migration of Low-mass Planets in Evolutionary Radiative Models: Avoiding Catastrophic Infall

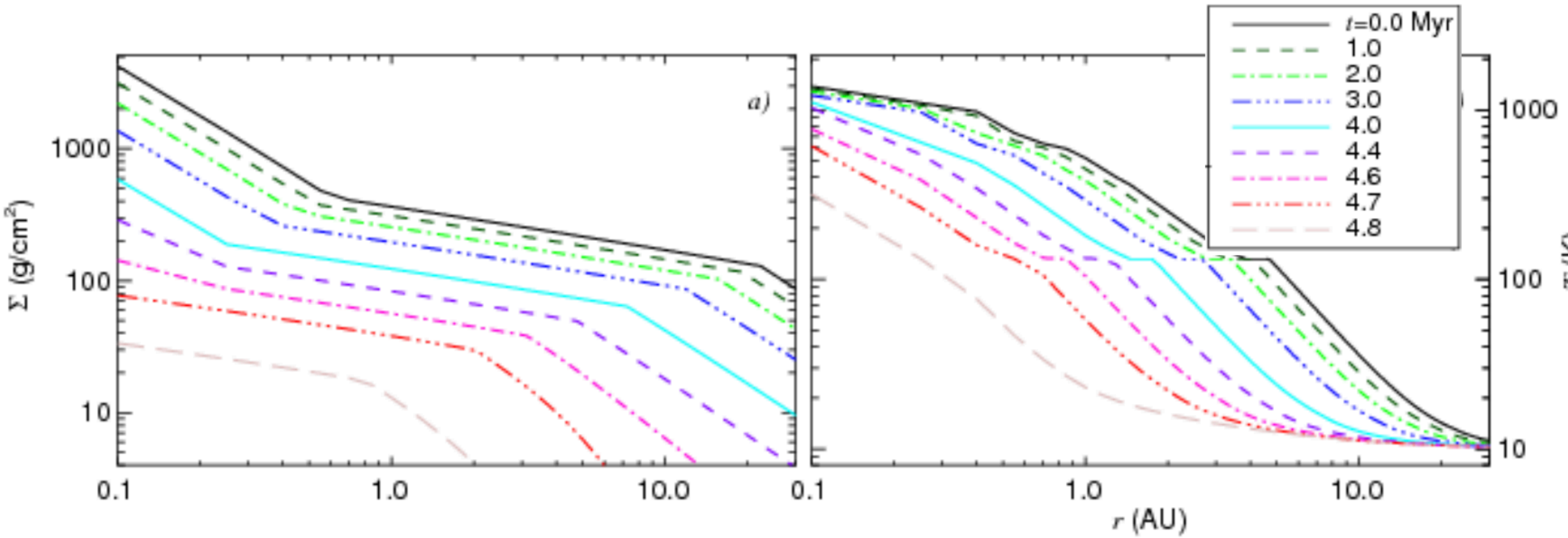
Show affiliations

Lyra, Wladimir; Paardekooper, Sijme-Jan; Mac Low, Mordecai-Mark

Outward migration of low-mass planets has recently been shown to be a possibility in non-barotropic disks. We examine the consequences of this result in evolutionary models of protoplanetary disks. Planet migration occurs toward equilibrium radii with zero torque. These radii themselves migrate inwards because of viscous accretion and photoevaporation. We show that as the surface density and temperature fall the planet orbital migration and disk depletion timescales eventually become comparable, with the precise timing depending on the mass of the planet. When this occurs, the planet decouples from the equilibrium radius. At this time, however, the gas surface density is already too low to drive substantial further migration. A higher mass planet, of 10 $M_{\oplus}$, can open a gap during the late evolution of the disk, and stops migrating. Low-mass planets, with 1 or 0.1 $M_{\oplus}$, released beyond 1 AU in our models avoid migrating into the star. Our results provide support for the reduced migration rates adopted in recent planet population synthesis models.



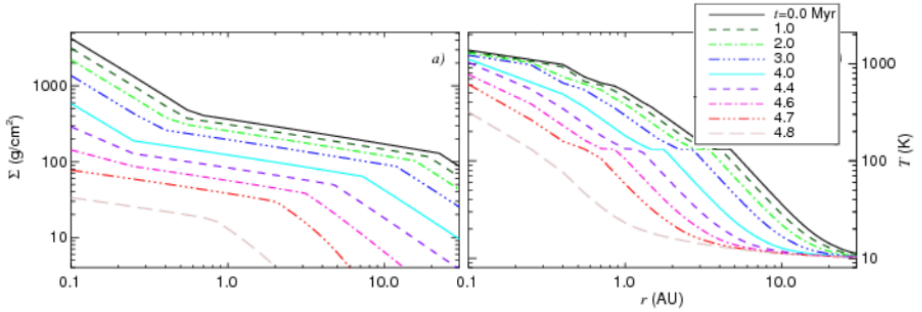
Source: Lyra, Paardekooper, & Mac Low (2010)



a)
Σ (g/cm²)
1000
100
10
0.1
1.0
10.0
r (AU)
T (K)
t=0.0 Myr
1.0
2.0
3.0
4.0
4.4
4.6
4.7
4.8

Migration in Evolutionary Models

Disks evolve in time, due to
photoevaporative winds and viscous evolution



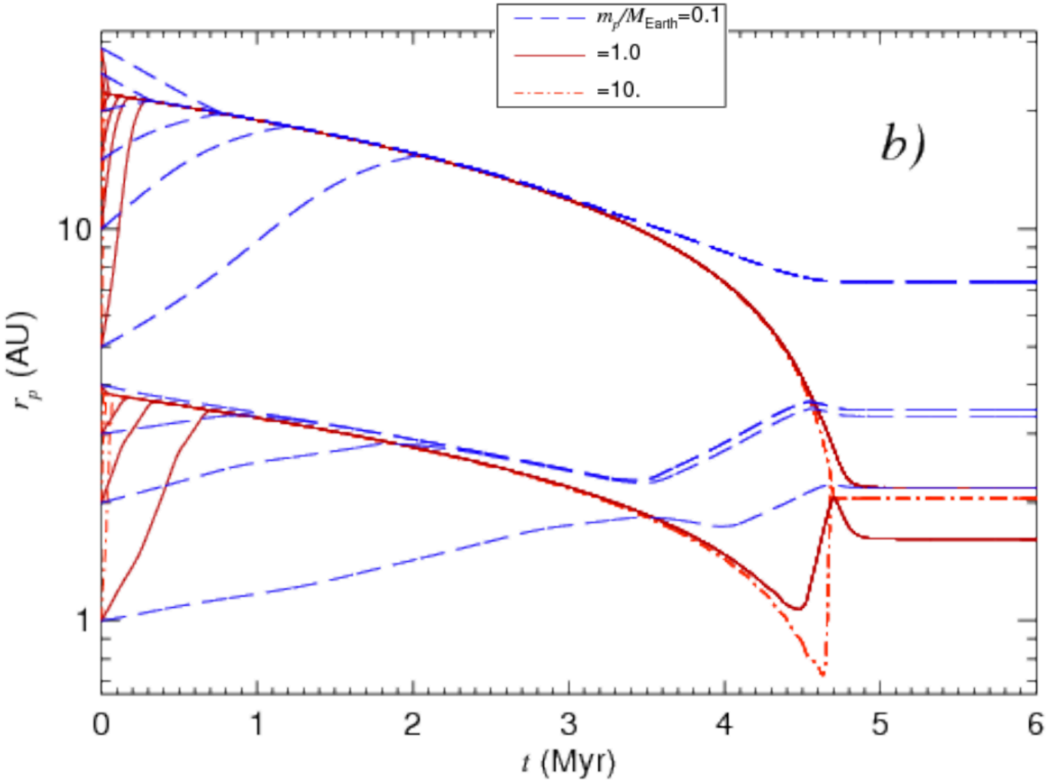
Single planets in a planetary trap evolve in lockstep with the gas at the accretion timescale.

At some point, the disk becomes **too thin** to drive accretion. The planet **decouples** and is **released** in a safe orbit.

Rule of thumb: ***Migration is***

outwards ***in***
steep temperature gradients,

inwards ***in***
isothermal regions.



Source: Lyra, Paardekooper, & Mac Low (2010)

Single planets in a planetary trap evolve in lockstep with the gas at the accretion timescale.

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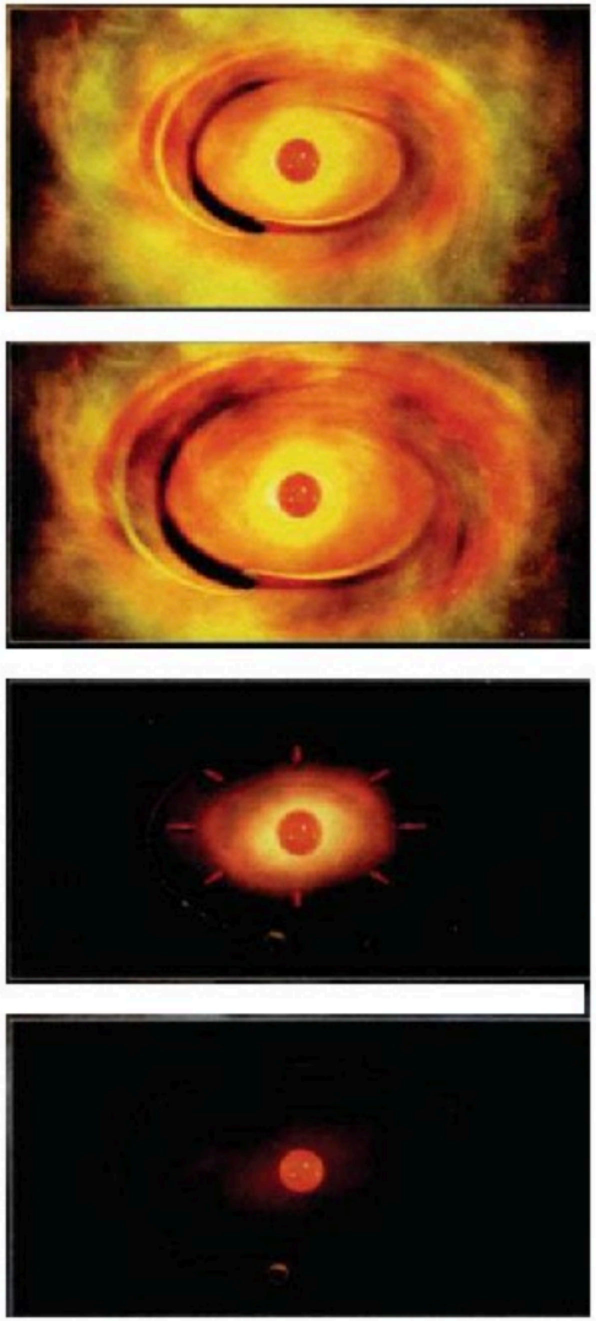
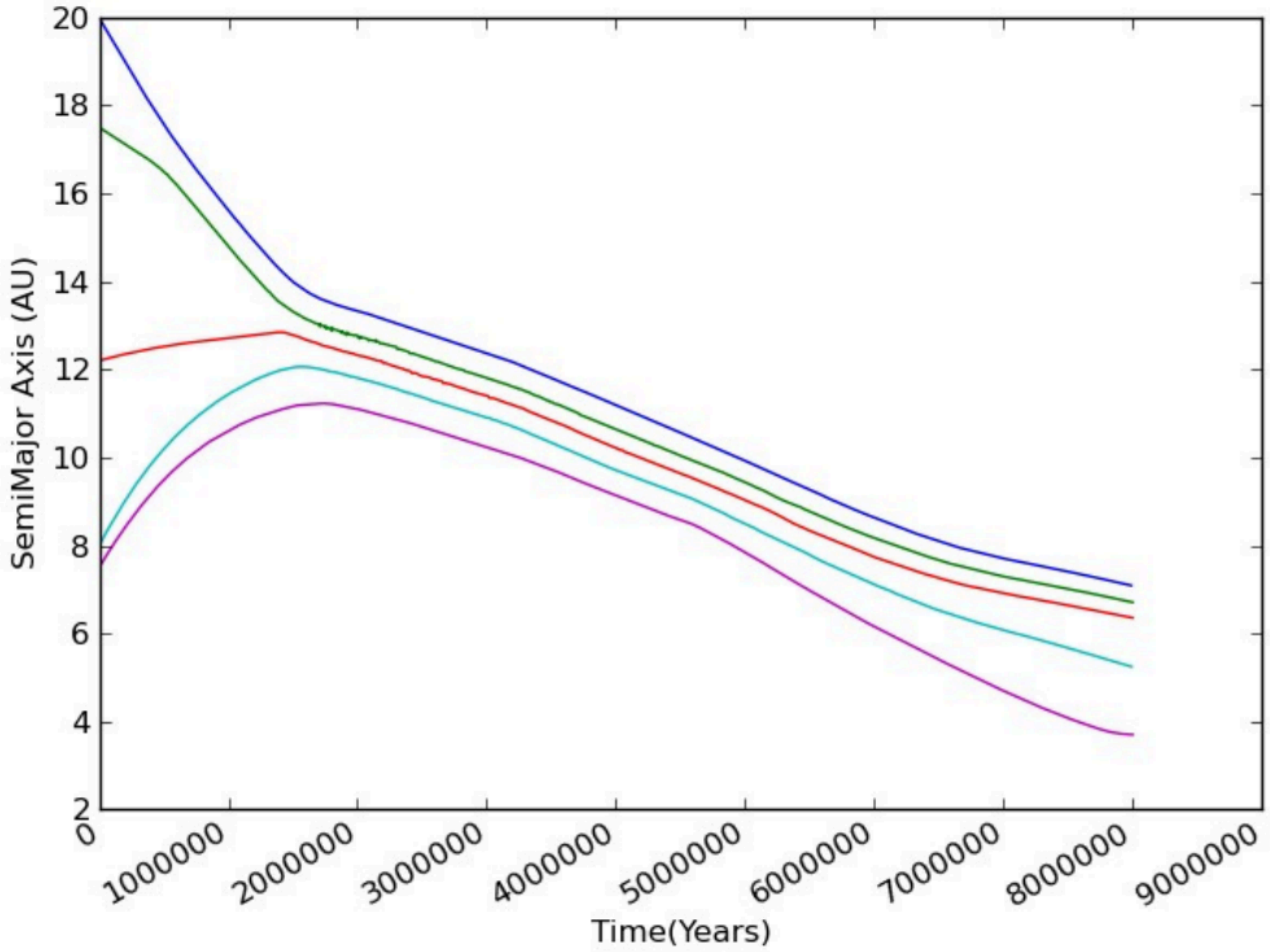
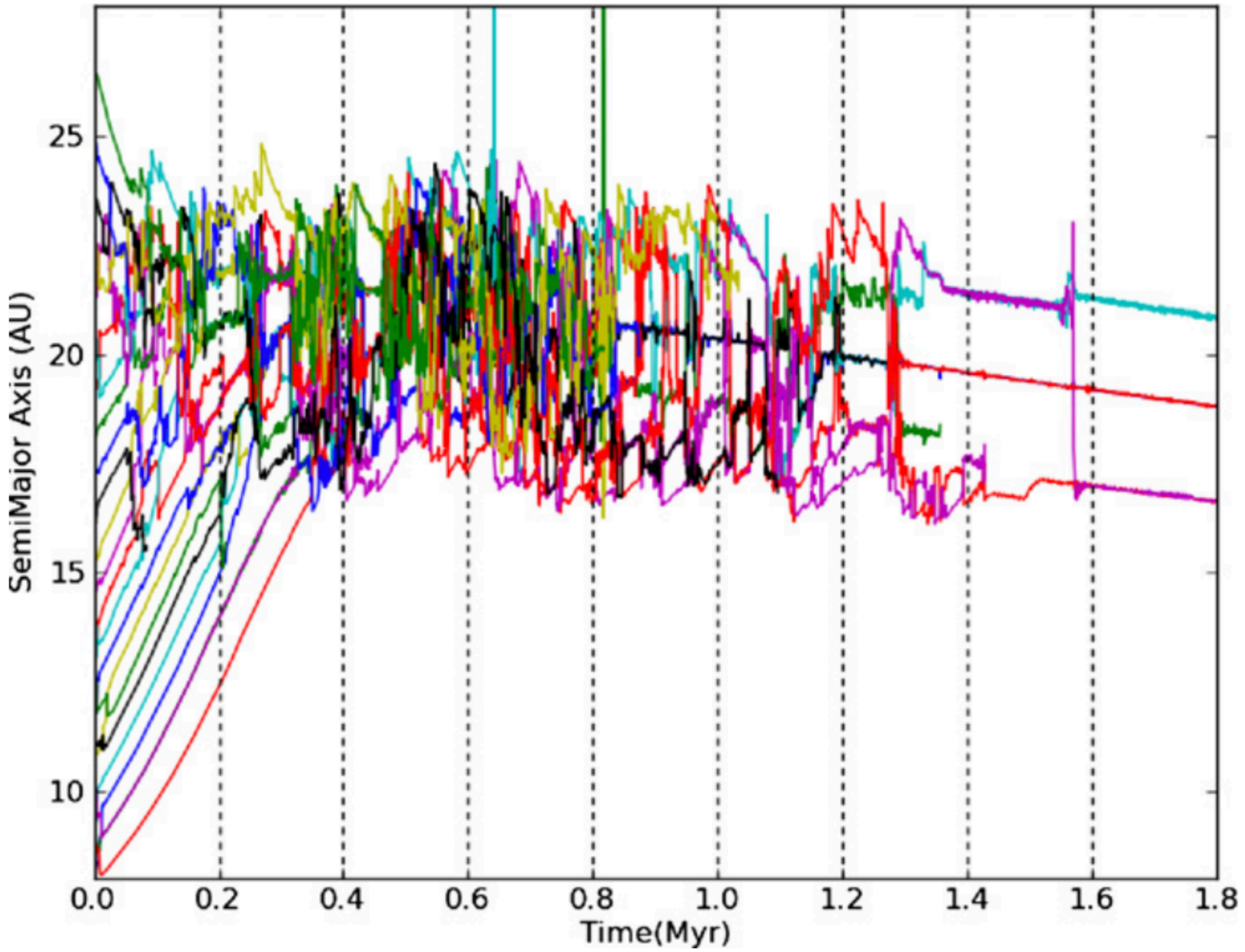
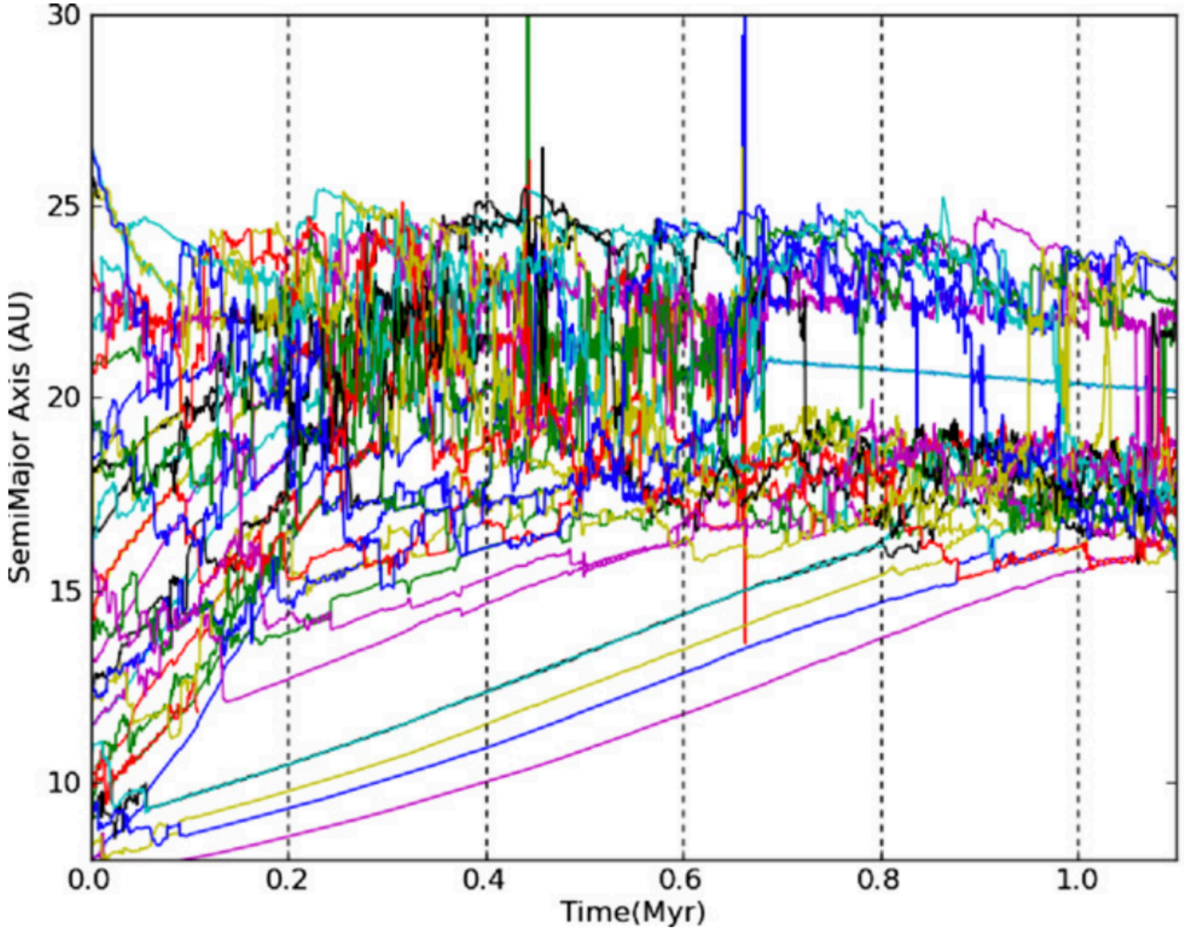




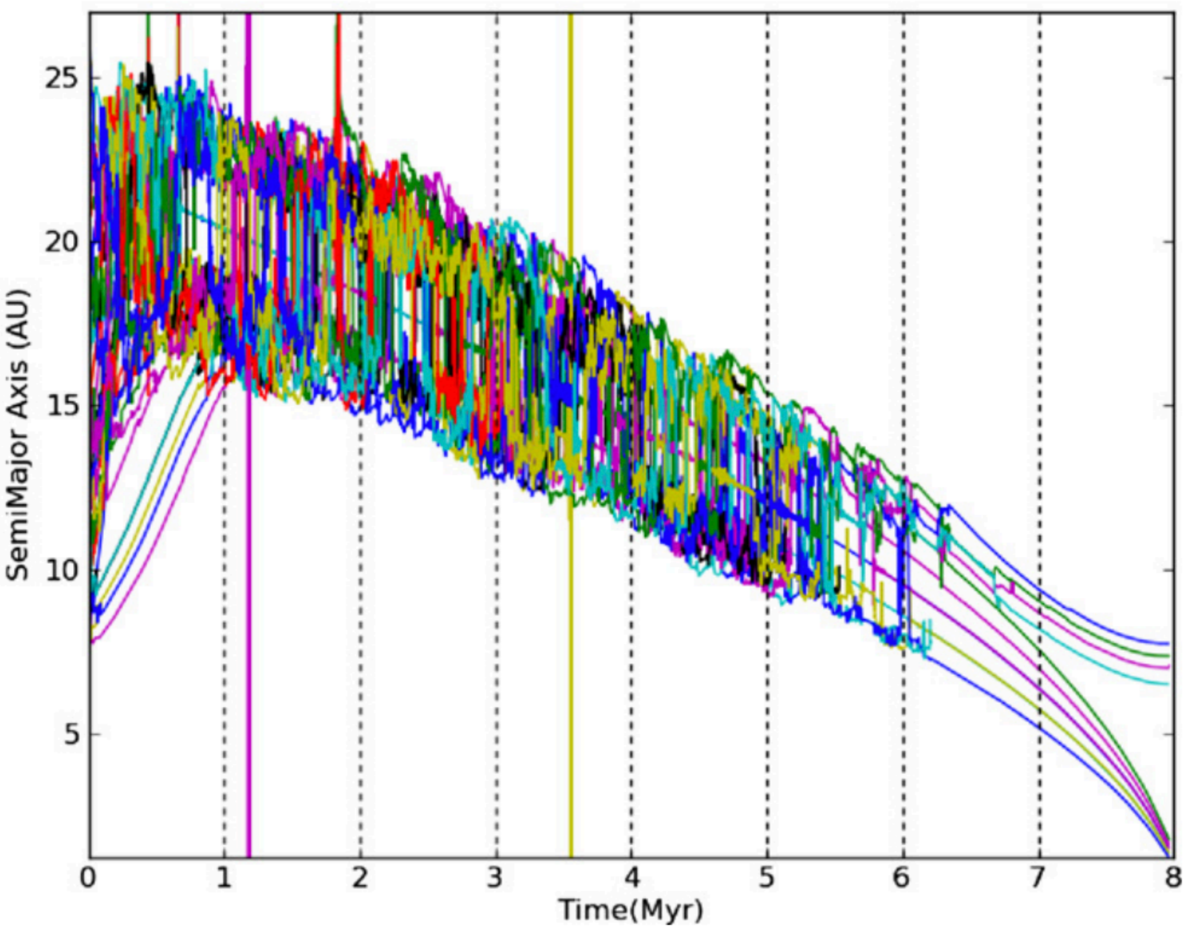
SemiMajor Axis (AU)
20
18
16
14
12
10
8
6
4
2
0
1000000
2000000
3000000
4000000
5000000
6000000
7000000
8000000
9000000
Time(Years)



SemiMajor Axis (AU)
25
20
15
10
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Time(Myr)



SemiMajor Axis (AU)
Time(Myr)
30
25
20
15
10
0.0
0.2
0.4
0.6
0.8
1.0



SemiMajor Axis (AU)
Time(Myr)
25
20
15
10
5
0
1
2
3
4
5
6
7
8