# Orbita evolution code

January 13, 2019

## 1 Modifications to the "orbita_evolution" code

This is a brief description about the recent modifications done on the last version of "orbita_evolution_pa.py" code, recently improved by Suvrat. This code studies the evolution of a system composed by a planet in a circular orbit around a solar-like star, using a stellar model with an initial mass of $1M_\odot$, solar metallicity and an initial angular velocity of $2.9 \times 10^{-5}s^{-1}$. In the Suvrat's version of the code, we can give the mass of the planet and the initial orbital distance as input parameters, studying the evolution of the system and the possible outcomes or final fates of the planet from the PMS until the turn off. The included physics is the same as in Rao et al. 2018.
As next step, we want to study the evaporation process of exoplanets, in particular focussing our attention on the impact of the non-thermal contribution of the xuv flux, strictly related to the stellar dynamo and the angular momentum evolution of the star convective envelope. We should expect a stronger xuv luminosity by faster rotating stars, considering the possibility of entering the saturation regime when the Rossby number is lower than $R_0 = 0.13$.
In the following, we describe how the code has been modified:

- **angular velocities**: in order to explore a good range of initial angular velocities for the star, considered as solid body at the very beginning of the evolution, we have modified the code "orbita_evolution_pa.py" including the initial angular velocity of the star as an input parameter, scaled as a fraction of the solar angular velocity $2.9 \times 10^{-6}s^{-1}$. At the line $86 - 87$ of the routine "orbita_evolution_pa.py", we mupltiply the original angular velocity of the stellar model computed by Patrick with the Geneva code for the numerical factor chosen at the beginning in the list variable "fraction" (line 54). The new initial value of the angular velocity (called "omega_new[0]") is given as input to the function f_evo.evo_orbit_calc_new".

- **starting age of the evolution**: since we are dealing with slow-medium and fast rotators, the starting age of the evolution changes from 1 Myr for fast rotators to 5 Myr for slow rotators ($\omega_{\rm ini} = 2 - 3 \times \rm omega_{sun}$), in order to reproduce a more realistic disappearance timescale of the primordial disk.

- **envelope and core angular momenta**: the angular momenta of the core and the envelope are computed directly in the function "evo_orbit_calc_new" in the "function_oe_pa.py" routine, using the value of the new initial angular velocity:

$$\mathrm{L_{env}}[0] = I_{env}[0] \times omega[0]$$
$$\mathrm{L_{core}}[0] = I_{core}[0] \times omega[0].$$

- **stronger magnetic braking**: following the paper of Gallett & Bouvier (2013) we have used a stronger magnetic braking prescription, putting $\mathrm{K_1} = 1.8$, instead of 1.3. In this way we can reproduce better the angular velocity of the Sun at the solar age.

- **Correction in "L_dot_env" - "L_dot_core"**: computing models for fast rotators, we discovered a problem in the functions which compute the time evolution of the angular momenta of the envelope and the core. In particular, we have found that using an initial evolution age of 1 Myr, when the momentum of inertia of the core is lower of 3 order of magnitude respect to the one of the envelope, the difference of the angular velocity between envelope and core becomes negative and the coupling timescale cannot be computed ("nan" value). In this version of the code, when the timescale is "nan", this is artificially put egual to zero. But this kind of solution produces a non-physical decoupling of the core-envelope, due to the fact that we cannot compute the power of a negative number with index 0.076 in t_c, causing too high angular velocities, sometimes higher than the critical velocity.

```
D_L_max = (I_env*L_core - I_core*L_env)/(I_env +
    ↪ I_core)
omega_sun = 2.9*(10**(-6))
delta_omega = L_core/I_core - L_env/I_env
t_c = 30.0*(10**6)*cst.year*(0.2*omega_sun/delta_omega
    ↪ )**0.076
L_dot_core_env_coupling = (1.0/t_c)*D_L_max -
    ↪ (2.0/3.0)*(Rcore**2.0)*(L_env/I_env)*(M_core_dot
    ↪ )
```

```
    if np.isnan(L_dot_core_env_coupling):
        L_dot_core_env_coupling = 0.0
```

In order to solve this problem, we have put the module in the computation of "delta_omega", having a good coupling between core and envelope also for fast rotators and obtaining plots of the core and envelope angular velocities closer to the one in Gallet & Bouvier (2013), as shown in figure 1.

```
D_L_max = (I_env*L_core - I_core*L_env)/(I_env +
   ↪ I_core)
omega_sun = 2.9*(10**(-6))
delta_omega = abs(L_core/I_core - L_env/I_env)
t_c = 30.0*(10**6)*cst.year*(0.2*omega_sun/delta_omega
   ↪ )**0.076
L_dot_core_env_coupling = (1.0/t_c)*D_L_max -
   ↪ (2.0/3.0)*(Rcore**2.0)*(L_env/I_env)*(M_core_dot
   ↪ )

    if np.isnan(L_dot_core_env_coupling):
        L_dot_core_env_coupling = 0.0
```

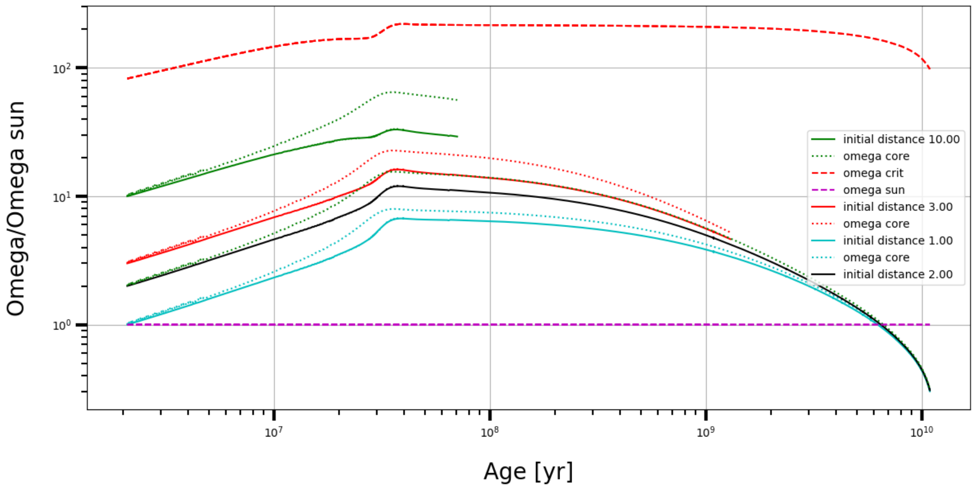


Figure 1: Core and envelope angular velocities for fast, medium and slow rotators, using an initial distance of 0.03 a.u. for the planet, not including the star-planet interaction in the computation of the angulr momentum. Starting age equal to 2 Myr.

- **Correction to "L_core and L_env"**: in the evolution of the star reproduced by this code, we want to consider the angular momentum which is subtracted by the radiative core to the convective envelope, since the radiative core for $1M_\odot$ star appears in the PMS phase and increases in mass during the evolution. For this reason, we have included this effect in the function "evo_orbit_calc_new" (in "function_oe_pa.py"), after the integration by the Runge-Kutta method (lines 1302-1312).

```
if Rcore[i+1] != 0.0:

    new_L_env_corr = new_L_env - new_L_env*((Rcore[i+1]-
        ↪ Rcore[i])/Rcore[i+1])

    new_L_core_corr = new_L_core + new_L_env*((Rcore[i
        ↪ +1]-Rcore[i])/Rcore[i+1]

    new_L_env = new_L_env_corr
    new_L_core = new_L_core_corr
```

- **Control on critical velocity**: we have added two lines, controlling if the angular velocity of the envelope is larger than the critical velocity (lines 1318-1323 in "evo_orbit_calc_new" - "funciton_oe_pa.py").

```
omega_star_new = new_L_env/mo_ine_ang_env[i+1]
v_star_new = omega_star_new*Rstar[i+1]
v_critic = (2.0*cst.G*mstar[i+1]/(3.0*Rstar[i+1]))**0.5
```

```
if v_star_new >= v_critic:
   print('Velocity larger than the critical value')
   sys.exit()
```

- **Change of the Roche limit**: we have changed the prescription for the Roche limit, using the one in Ginzburg et al. 2017.

```
def roche_lim(m_star, m_pl, val_r_pl): #SRR2018
    """ Function that calculates the Roche limit
    """
    r_pl = val_r_pl
    roche_lim = 2.0*r_pl*((m_star/m_pl)**(1.0/3.0)) #The
       ↪ numerical coefficient is 2.44 for incompressible
       ↪  planets and 2.0 for compressible planets
       ↪ Ginzburg et al. 2017  #CAM2018

    return roche_lim
```

- **output file**: the format of the output file is described in the following table. All the quantities are expressed in cgs units.

| Column | Variable name | Variable meaning |
|---|---|---|
| 0 | Age | System age |
| 1 | Rstar | Radius of the star |
| 2 | Mstar | Mass of the Star |
| 3 | val_a_new | New value of the orbital distance |
| 4 | Veloci | Orbital linear velocity |
| 5 | Lstar | Stellar luminosity |
| 6 | ang_mom_tot | Total angular momentum of the star |
| 7 | ang_mom_fg | Angular momentum lost by frict. And grav. forces |
| 8 | term_K | |
| 9 | term_T | |
| 10 | Mloss | Star mass-loss rate |
| 11 | Menv | Mass of FITM |
| 12 | reg_rad_1 | Radius at the envelope bottom |
| 13 | LgTeff | Log of effective temperature |
| 14 | fri_f | Frictional-drag force |
| 15 | gra_f | Grav. Drag force |
| 16 | m_pl_tot1 | Net planetary mass variation rate |
| 17 | m_pl_tot2 | Net planetary mass variation rate(accretion+evaporation) |
| 18 | Omega | Original angular velocity of the star model |
| 19 | ori_cor_radius | Original corotation radius (isolated star) |
| 20 | ang_mom_new | Planet angular momentum |
| 21 | omega_new | Star angular velocity |
| 22 | Vold | star-original surface velocity |
| 23 | Vnew | New star-surface velocity |
| 24 | cor_radius_new | Corotation radius |
| 25 | ang_sper | Variation of planet angular momentum |
| 26 | logg_star | Log of the star surface gravity |
| 27 | Q_p1 | Q-value corresponding to the dynamical term |
| 28 | t_dyna1 | Dynamical tidal term |
| 29 | t_eq1 | Equilibrium tidal term |
| 30 | val_mpl_new | New value of the planet mass |
| 31 | mpl_rate | Variation rate for the planet mass |
| 32 | val_rpl_new | New value of the planet radius |
| 33 | r_pl_rate | Variation rate for the planet radius |
| 34 | v_crit | Critical velocity |
| 35 | v_core_new | New core velocity |
| 36 | t_mloss1 | |
| 37 | t_drag1 | |
| 38 | Fxuv | XUV flux |
| 39 | Lxuv | XUV luminosity |
| 40 | Lx | X luminosity |
| 41 | Leuv | EUV Luminosity |
| 42 | Rossby | Rossby number |
| 43 | omega_core_new | New core angular velocity |

## 2 Output of the code

Implementing the modifications described in the previous section, we have run the code in order to check and compare the results with the ones presented in the report by Georges (file "SUVRAT1.pdf"). We attempted to used the same initial input concerning the initial orbital distances and the mass of the planet, but not for the angular velocity, since it was not clear to me which value has been used by Georges. In the following, we show some pictures about the evolution of a system composed of a planet with initial mass $\mathrm{M_{pl}} = 1\mathrm{M_{Ju}}$, initial orbital distances $\mathrm{a} = [0.02, 0.032, 0.034, 0.04]$ and a starting age of the evolution $\mathrm{t_{in}} = 2\mathrm{Myr}$. We have used initial values for the angular velocities equal to $\omega_{\mathrm{in}} = 2.9 \times 10^{-5}\mathrm{s}^{-1}$ and $\omega_{\mathrm{in}} = 2.9 \times 10^{-6}\mathrm{s}^{-1} = \omega_{\odot}$. The stellar model is the one computed by Patrick, starting from the PMS phase and ending at the TURN OFF, with an initial mass of $1\mathrm{M}_{\odot}$.
Since our goal is to study the evaporation process of exoplanets related to the XUV flux of the star, we present the evolution of the angular velocity ($\omega$), the X luminosity ($\mathrm{L_X}$), the Rossby number (R), the mass and orbital distances of the system.

### 2.1 $\omega = 10 \times \omega_{\odot}$

Starting with the case $\omega_{\mathrm{in}} = 10 \times \omega_{\odot}$, we can see in Fig.2 that the slope of the envelope angular velocity is below the value of the critical velocity (red dashed line). This trend has been confirmed also for larger values of the angular velocity, while in the previous version of the code we have found that the velocity crossed the critical velocity. In the same figure, the slope of the velocities for the four different cases are completely superimposed, showing that the initial orbital distance has not a strong impact on the stellar rotation, at least in this case. The angular velocities reach the value of the Sun velocity approximately at solar age.

In Fig.3 we present the evolution of the Rossby number, showing also the saturation value $\mathrm{R_0} = 0.13$. We are interested in knowing when the Rossby number is above (or below) the saturation regime, since depending on this we use two different prescription for the computation of the X flux. As it is shown in the Fig. 4, as soon as the Rossby number crosses the saturation level, the X luminosity changes slope as well.

In Fig.5, the evolution of the orbits for the $1\mathrm{M_{Ju}}$ planet is shown. The red-dashed line is the minimum orbital distance at which dynamical tides are active, the magenta line is the Roche limit, the green regions represent the stellar envelope (dark green) and the core (light green). The initial orbital distances at 0.02 and 0.032 are respectively indicated by the green and cyan

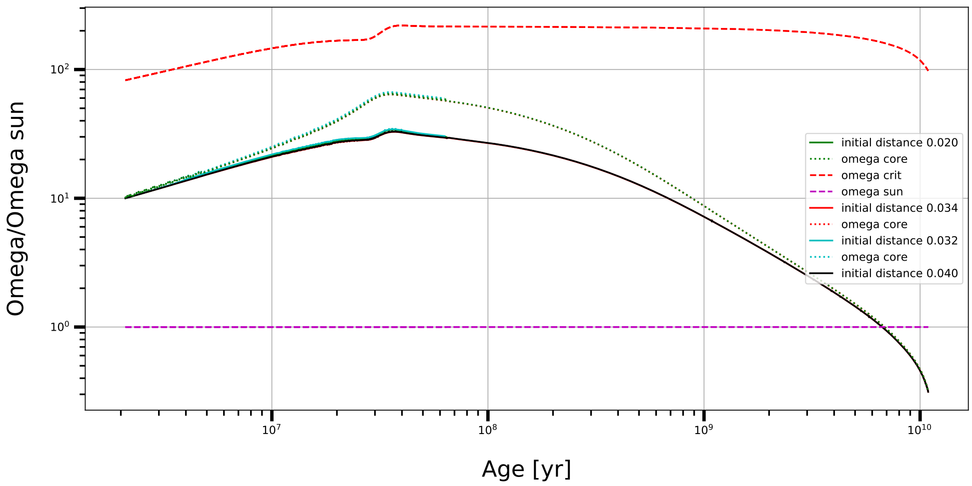


Figure 2: Angular velocity as a function of time. The dotted line is the angular velocity of the core.

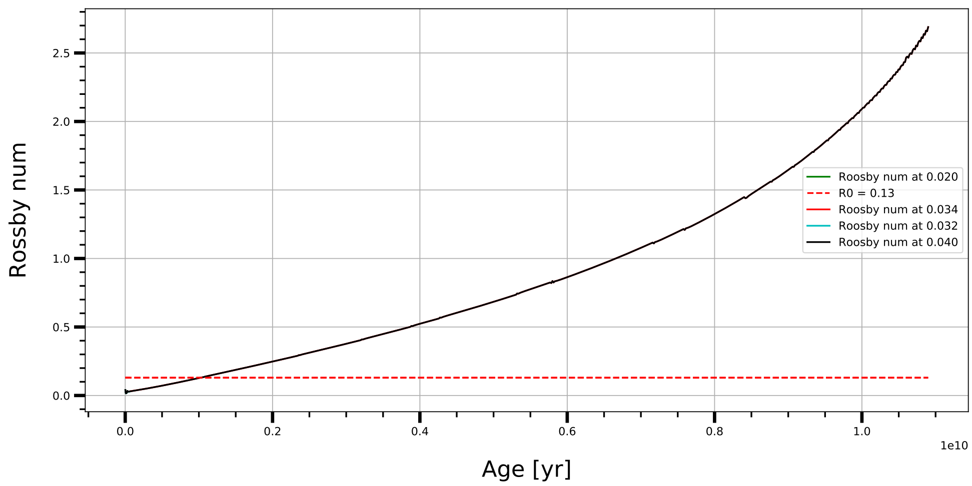


Figure 3: Rossby number as a function of time.

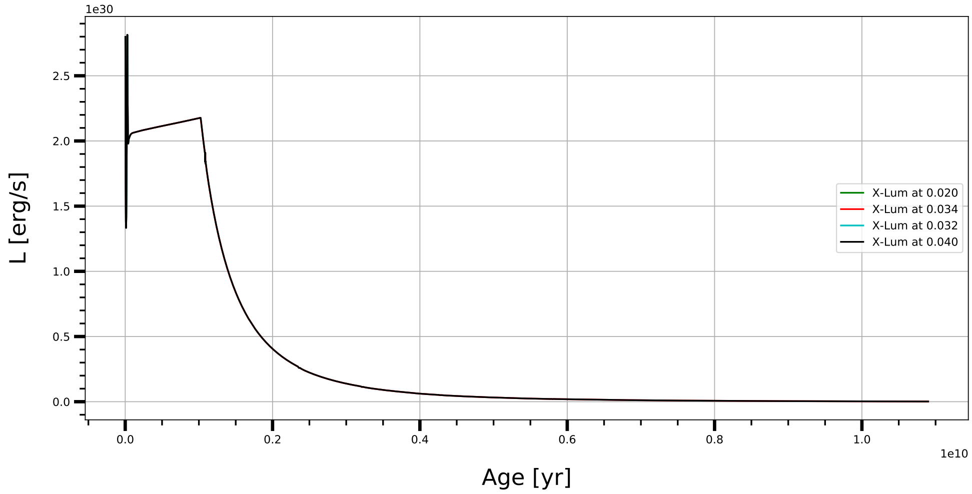


Figure 4: X luminosity as a function of time.

line. In both cases, the orbital distance is below the corotation radius: in the case of 0.02 a.u., the orbital distance starts to shrink only when it reaches the minimum distance for the activation of dynamical tides, then it follows approximately the shape of $a_{min}$, crossing the Roche limit at around $2 \times 10^7$ yr. According to the paper of Dosopoulou et al. 2018, when a planet orbiting a solar-like star with low eccentricity crosses the Roche limit, the most probable outcome is the formation of a disk (made of interacting particles): if we ignore the presence of the Roche limit, we can see from Fig.6 that the orbit continues to shrink, until the planet evaporates at around $6 \times 10^7$ yr (Fig.6). We have a similar fate for the planet starting at 0.032 a.u..
Planets starting with an orbital distance larger than 0.032 a.u. have an orbit which expands, eventually after crossing the corotation radius. In these cases the planet mass remains unchanged.

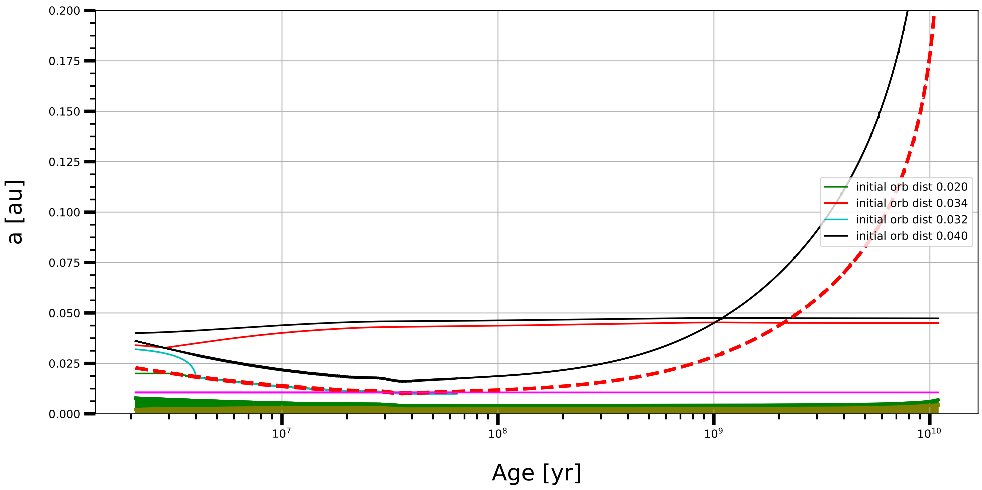


Figure 5: Evolution of the planets orbits.

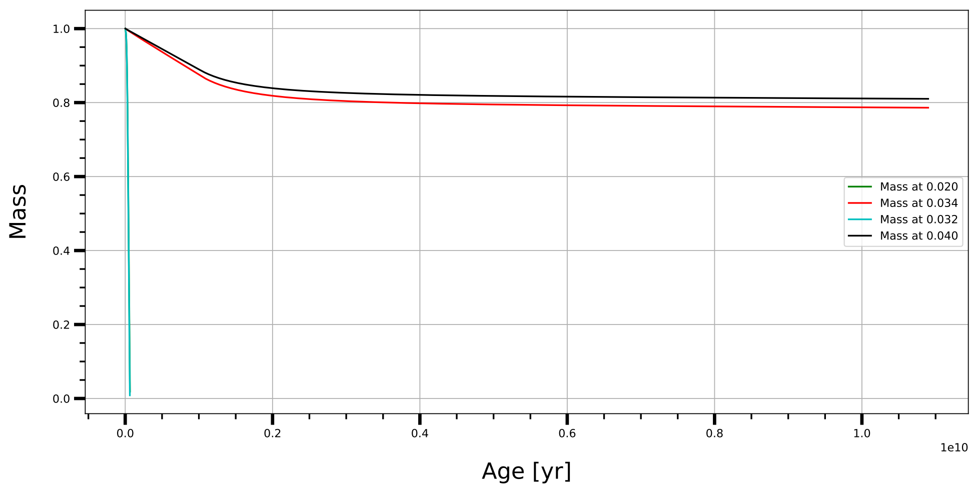


Figure 6: Evolution of the planet mass as a function of time.

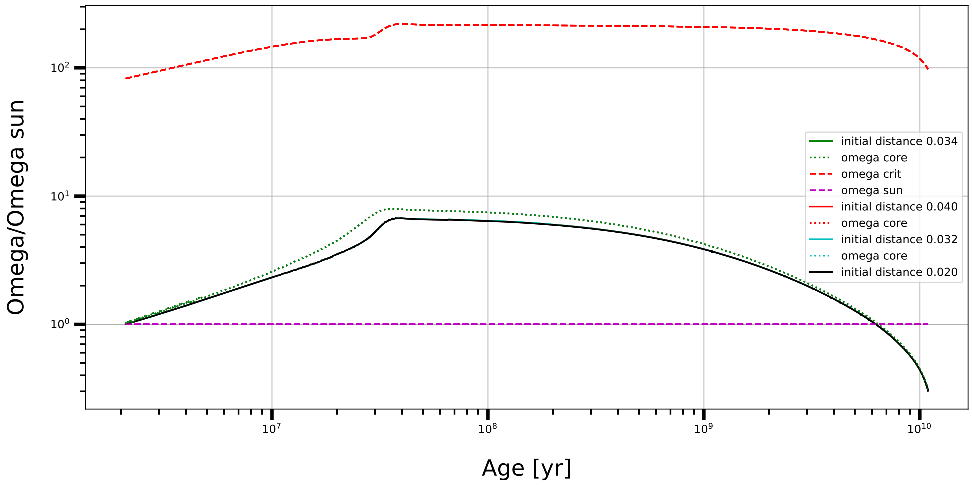


Figure 7: Angular velocity as a function of time. The dotted line is the angular velocity of the core.

## 2.2 $\omega = \omega_\odot$

Using an initial angular velocity equal to the one of the Sun, we can appreciate some differences in the physical properties of this system respect to the one studied in the previous subsection. Firstly, in Fig.8, we note that the Rossby number is always above the saturation value, than we expect a decaying law for the x luminosity, as shown in Fig. (add figure for the X luminosity). The orbital distances evolution is very peculiar (Fig.9), since in this case it seems that planets are not impacted by the effects of tides. Planets do not evaporate and the mass changes more slowly during the evolution (Fig.10).

As shown in fig.15

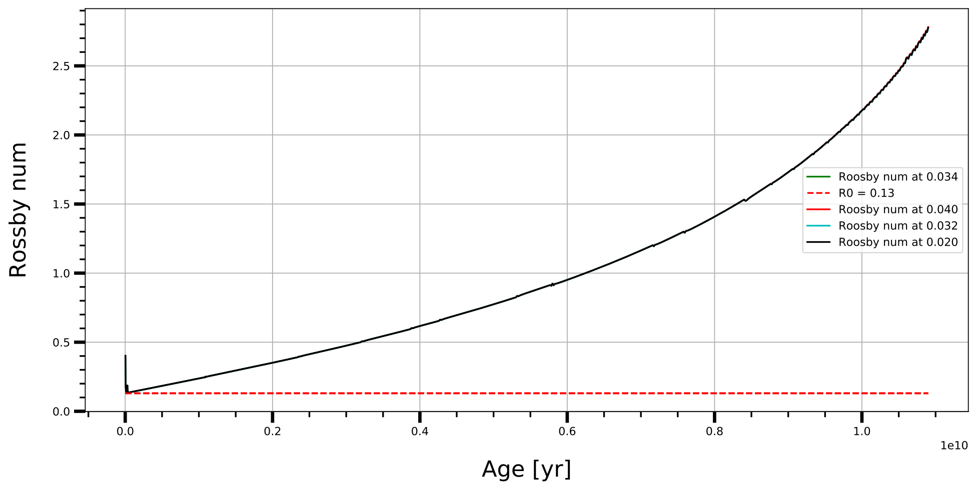


Figure 8: Rossby number as a function of time.

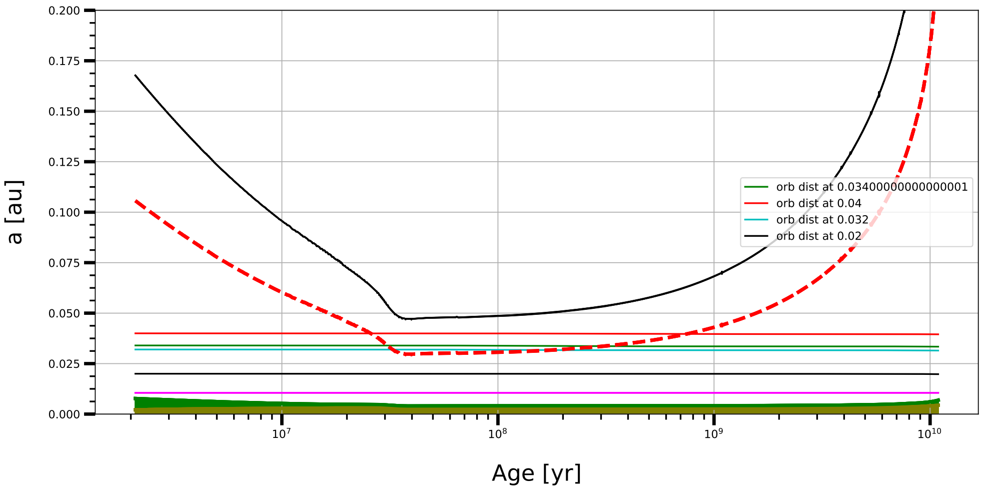


Figure 9: Evolution of the planets orbits.

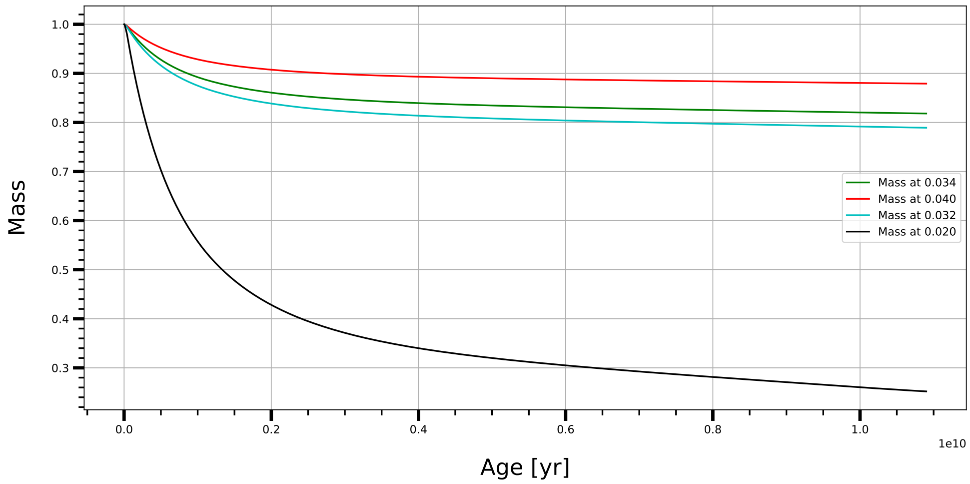


Figure 10: Evolution of the planet mass as a function of time.

In the following sections we study the impact of the dynamical tides on the orbital evolution of close-in planets and the eventual resulting changes on the angular velocities. We are considering the initial orbital distances a $= [0.015, 0.018]$ a.u., an initial angular velocity $\omega = \omega_\odot$ for the slow case and $\omega = 10 \times \omega_\odot$ for the fast case.

## 2.3 Close-in planets: slow case

The evolution of the planets orbit in the slow case seems not to be influenced by tides as expected, as shown in Fig.15. Planets are very close to their Roche limit but they never cross that limit, since the orbit is not shrinking. The Rossby number is always above the saturation limit (Fig.12) and the X luminosity decays very fast (Fig.13).

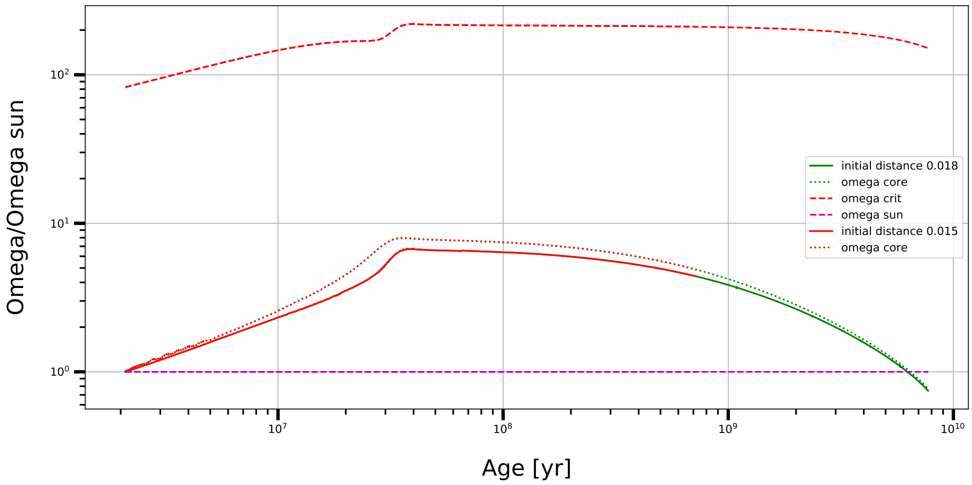


Figure 11: Angular velocity for close-in planets.


Figure 12: Evolution of the Rossby number for close-in planets.

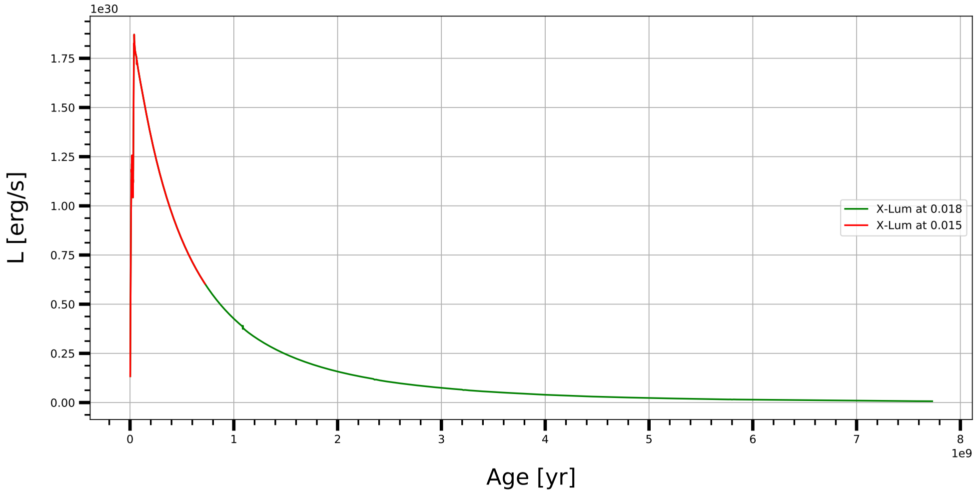


Figure 13: X luminosity for close-in planets vs. time.

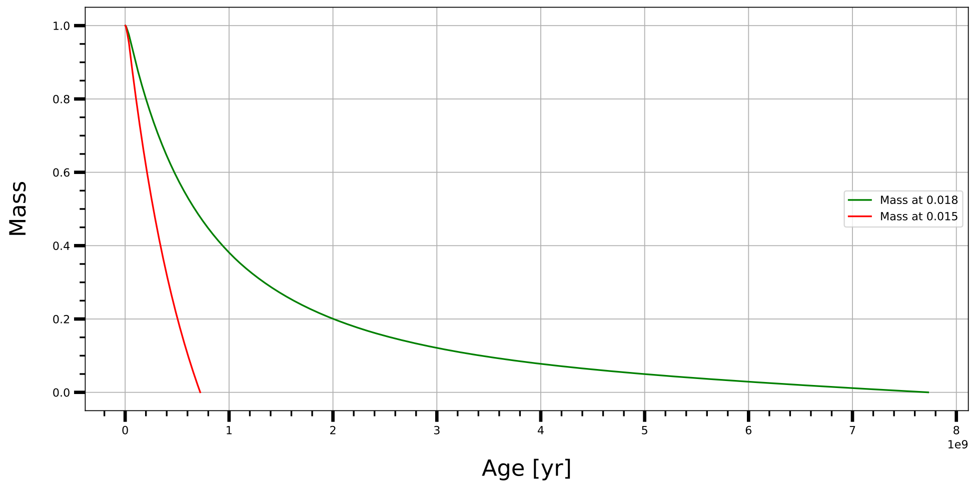


Figure 14: Mass evolution for close-in planets.

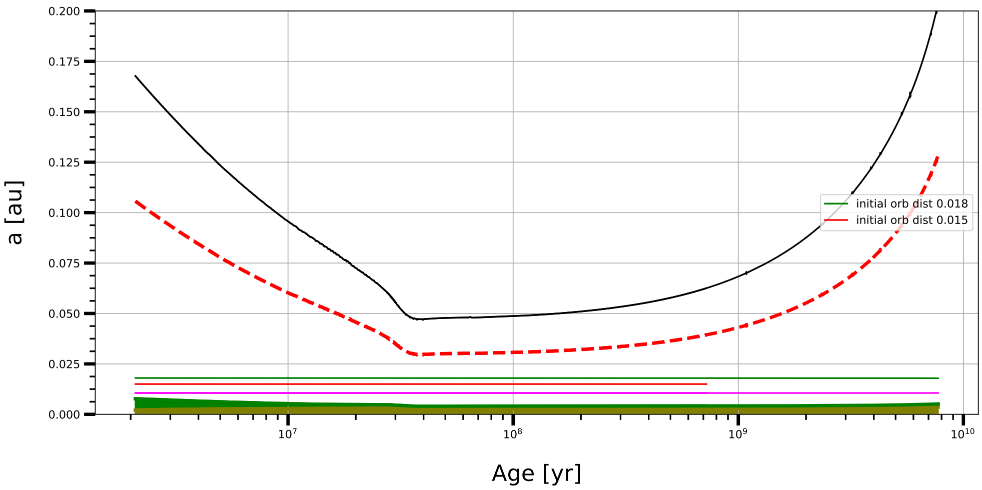


Figure 15: Orbital evolution for close-in planets.

## 2.4 Close-in planets: fast case

In that case, the orbital distances of the planets are able to cross the minimum distance ($a_{min}$) for the activation of the dynamical tides and as soon as it happens then the orbits shrink (Fig.20). The Rossby number is always below the saturation value (as long as the planets evaporate) and, as we expected, the X luminosity is larger respect to the slower case.

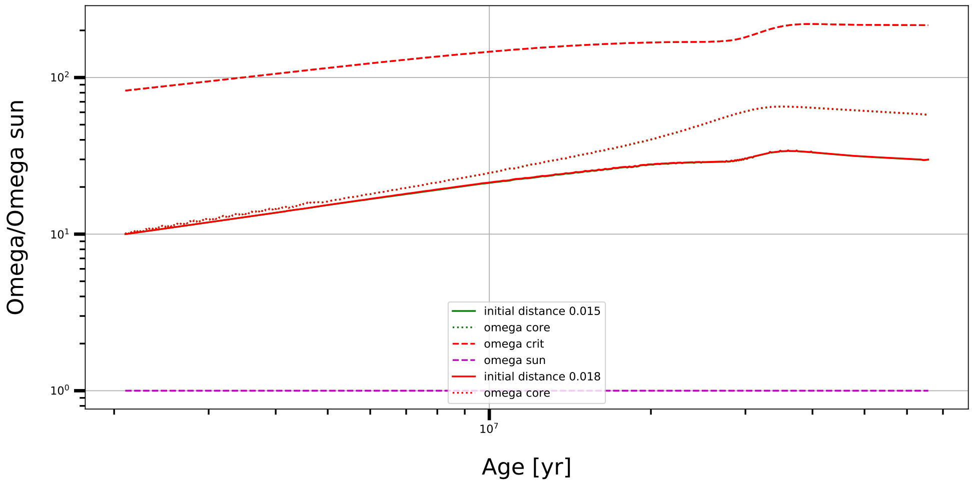


Figure 16: Angular velocity for close-in planets.

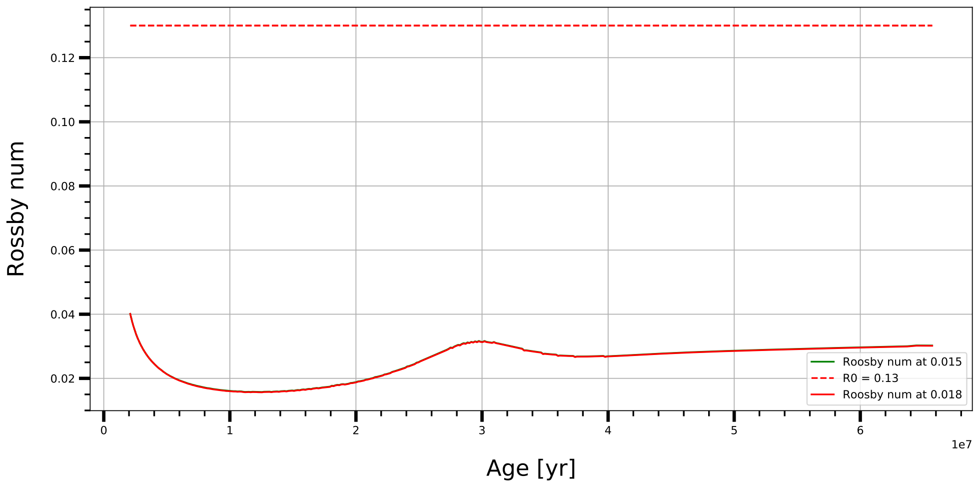


Figure 17: Evolution of the Rossby number for close-in planets.


Figure 18: X luminosity for close-in planets vs. time.

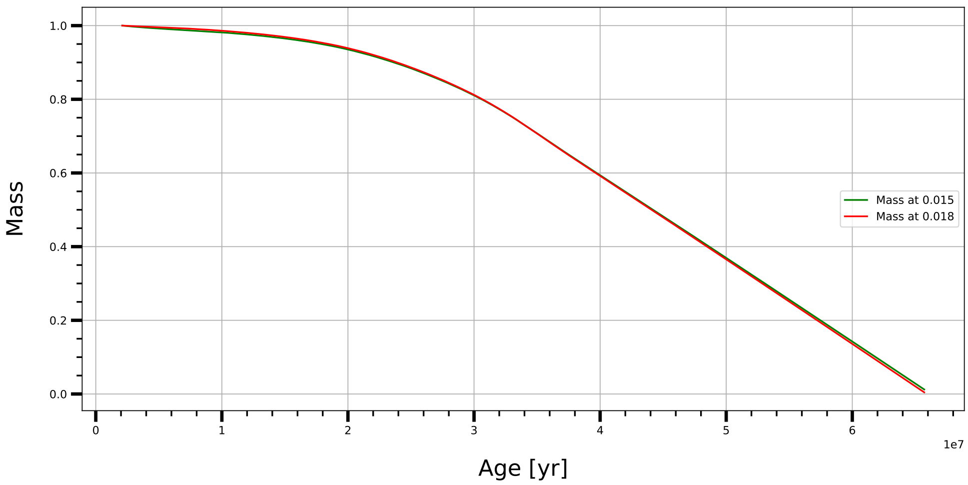


Figure 19: Mass evolution for close-in planets.

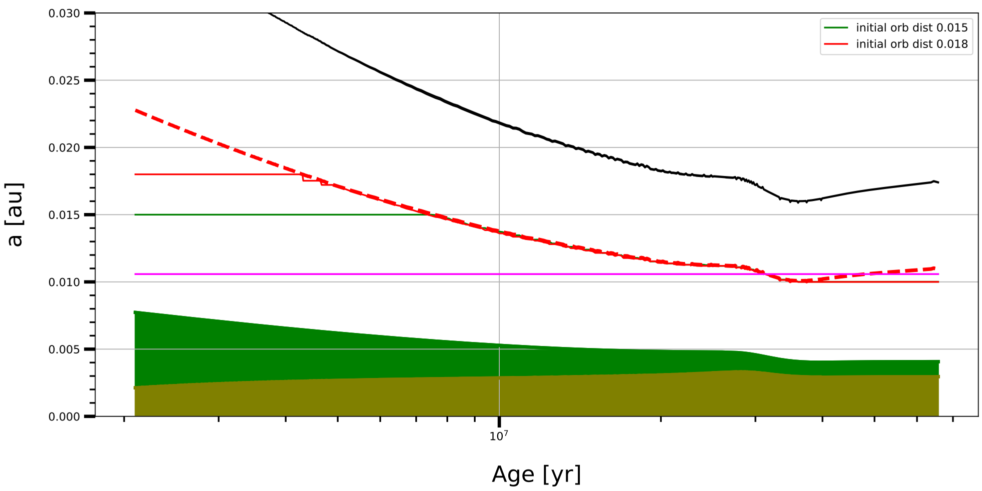


Figure 20: Orbital evolution for close-in planets.