Planet migration in accretion disk in a binary system

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Abstract

We study a binary system containing a red giant and a MS star which hosts a planetary system. The red giant looses mass by stellar wind without Roche lobe overflow while an accretion disk forms around the MS companion. We use the alpha-disk model for two different accretion regimes. The first is a standard accretion α-disk. In the second one matter is accreted on the entire disk surface. The aim is to calculate time of planet type-I migration toward the star, resulting in a planet-star merger. Metzger, Giannios, Spiegel (2012) showed that such processes can lead to a transient with luminosity $\sim 10^{36}\,[erg\,s^{-1}]$. These authors discussed only single stars. We calculate time of planet migration in binary system depending on stelalr masses of, binary separation, planet mass, initial semimajor axis of the planet and compare this time with the lifetime of a red giant.

Main Objectives

1. Calculation of parameters of two accretion thin α-disks with different regimes of accretion.
2. Calculation of time of planet migration using the obtained disk parameters.
3. Comparison of the migration time with the lifetime of a red giant.

Model description

M_1 – mass of a red giant, M_2 – mass of a MS star, a_b – binary separation, G – gravitational constant,
T_2, R_2 – effective temperature and radius of the MS star,
ν – viscosity, c_s – sound speed in the disk, H – disk scale height,
α – viscosity parameter (we assume $\alpha = 0.01$), Ω – Keplerian angular velocity,
Σ – surface density, H – scale height of the disk, p – gas pressure,
γ – adiabatic index, ρ – disk density, σ – Boltzmann constant,
μ – mean molecular weight, κ – opacity, m_H – hydrogen atom mass,
R_0 – initial semimajor axis of the planet, R_{in} – inner radius of the disk.

Standard thin disk

$$\nu = \alpha c_s H,\ \ H = \frac{c_s}{\Omega},\ \ \tau = \frac{1}{2}\tilde{\kappa}\Sigma,\ \ p = \frac{\gamma k_B \rho T_c}{\mu m_H},\ \ c_s^2 = \frac{p}{\rho}.$$

Energy balance equation: $\frac{9}{4}\nu\Sigma\Omega^2 = \frac{8\sigma T_c^4}{3\tau}$.

Solution of Navier-Stokes equation for a thin disk:

$$\nu\Sigma = \frac{\dot{M}_{tot}}{3\pi}\left(1 - \left(\frac{R_{in}}{R}\right)^{1/2}\right),$$

here $\dot{M}_{tot}$ is wind captured by the MS companion.
Expressions for the disk parameters:

$$\Sigma = 8.04 \cdot \alpha^{-4/5}\left(\frac{\mu}{\gamma}\right)^{4/5} m^{1/5}\dot{m}^{3/5} f^{3/5} r^{-3/5}\ \left[\frac{g}{cm^2}\right]$$

$$H = 2.28 \cdot 10^{11}\ \alpha^{-1/10}\left(\frac{\gamma}{\mu}\right)^{2/5} m^{-7/20}\dot{m}^{1/5} f^{1/5} r^{21/20}\ [cm],$$ here

$r = \frac{R}{AU}$, $m = \frac{M_2}{M_\odot}$, $\dot{m} = \frac{\dot{M}}{\dot{M}_{RG}}$, $M_\odot = 1.98 \cdot 10^{33}\,[g]$,
$\dot{M}_{RG} = 6.28 \cdot 10^{18}\,\left[\frac{g}{s}\right]$.

Thin disk with matter fall and changing opacity

Material falls on the entire surface of an accretion disk and mass transfer rate through it is:

$$\dot{M}(R) = \begin{cases} \frac{R_a + R_{in} - R}{R_a}\dot{M}_{tot}, & R < R_a \\ \frac{R_{in}}{R_a}\dot{M}_{tot}, & R \geq R_a. \end{cases}$$

Here R_a is the Bondi radius, $\dot{M}_{tot}$ – accretion mass rate.

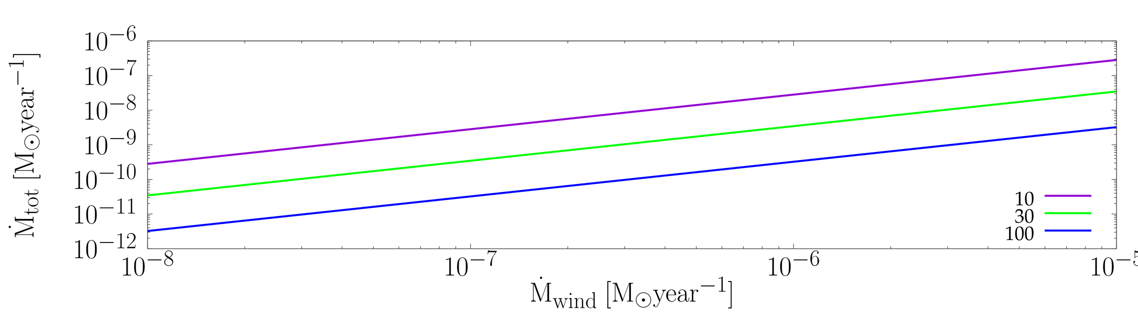

Figure 1: Relation between accretion mass rate $\dot{M}_{tot}$ and mass loss rate of a red giant star $\dot{M}_{wind}$. Colored lines refer to binary separations in [AU].

Angular momentum conservation yields:

$$\nu\Sigma = \frac{\dot{M}}{3\pi}\left(1 - \left(\frac{R_{in}}{R}\right)^{1/2}\right) + \frac{1}{3\pi R^2\Omega}\int_{R_{in}}^{R} 2\pi\Omega R^3\,\dot{\Sigma}_{ext}\,dR.$$

While solving equation of the standard accretion disk we use:

$$\dot{\Sigma}_{ext} = \begin{cases} \frac{\dot{M}_{tot}}{2\pi R R_a}, & R < R_a \\ 0, & R \geq R_a \end{cases},\ \ R_a = \frac{2GM_2}{v_r^2 + c_{s\,wind}^2},\ \ v_r^2 = v_w^2 + v_o^2,$$

$$v_o^2 = \frac{GM_1^2}{(M_1+M_2)a_b},\ \ c_{s\,wind} = 2\cdot 10^6\,[km/s],\ \ v_w = 1\cdot 10^6\,[km/s].$$

Opacity: $\tilde{\kappa} = \kappa_0\left(\frac{T_c}{T_{evap}}\right)^{-14}$, $\kappa_0 = 2\,[cm^2 g^{-1}]$,
$T_{evap} = 1380\,[K]$ – dust evaporation temperature.

Energy balance equation:
$T_c^4 = T_V^4 + T_W^4 + T_I^4$, here T_c – midplane temperature of the disk,
$T_V^4 = \frac{27\kappa\nu\Sigma^2\Omega^2}{64\sigma}$ – viscous temperature,

$$\sigma T_W^4 = \begin{cases} \frac{GM_2\dot{M}_{tot}}{2\pi R^2 R_a}, & R < R_a \\ 0, & R \geq R_a \end{cases}$$ – energy of falling matter.

Irradiation temperature of the host star:

$$T_I^4 = \frac{2}{3\pi}\left(\frac{R_2}{R}\right)^3 T_2^4 + \frac{1}{7\Omega(R)R}\left(\frac{R_2}{R}\right)^2 T_c^{1/2}\left(\frac{\gamma k_B}{\mu m_H}\right)^{1/2} T_2^4.$$

Solving energy balance equation numerically we obtain T_c and other disk parameters as Σ, H.

Planet migration

We consider that a planet experiences type I migration.
The following formula is used for calculation of the torque, exerted by disk on the planet (Tanaka et al. 2012):

$$\frac{dJ}{dt} = -(1.36 + 0.54\tilde{\alpha})\left(\frac{M_p}{M_2}\right)^2\left(\frac{H}{R}\right)^{-2}\Sigma\Omega^2 R^4.$$

Here parameter $\tilde{\alpha}$ is defined via $\Sigma \sim R^{-\tilde{\alpha}}$.

We obtain the time of migration by integration of the following expression:

$$T_{migr} = \int_{R_{in}}^{R} \frac{1}{2(1.36+0.54\tilde{\alpha})} \cdot G^{-1/2} M_p^{-1} M_2^{3/2} \Sigma^{-1} H^2 R^{-7/2} dR.$$

Results

Accretion disk structure

We present profiles of both types of accretion disks. Solid lines correspond to our results, dashed are results obtained by *Perets & Kenyon* 2013. Color refers to mass loss rates of the red giant in $[M_\odot\,year^{-1}]$. These results are presented for a binary system with companion masses $M_1 = 1\,[M_\odot]$, $M_2 = 3\,[M_\odot]$ and binary separation $a_b = 10\,[AU]$.

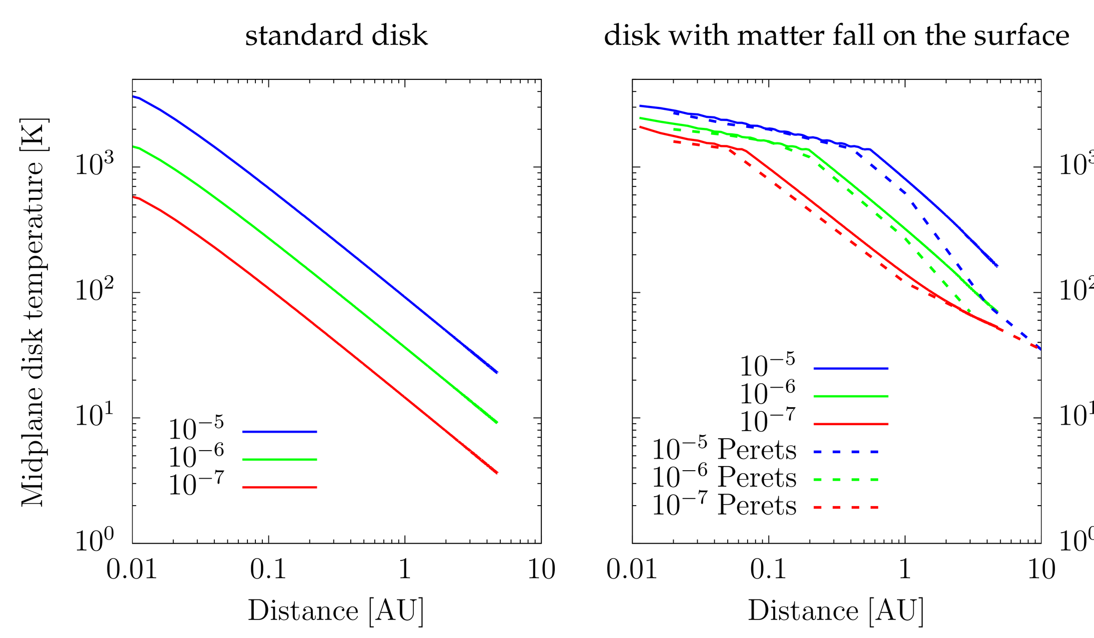

Figure 2: Midplane disk temperature profile. Solid lines correspond to our results, dashed are results obtained by *Perets & Kenyon* 2013. Color refers to mass loss rates of the red giant in $[M_\odot\,year^{-1}]$.

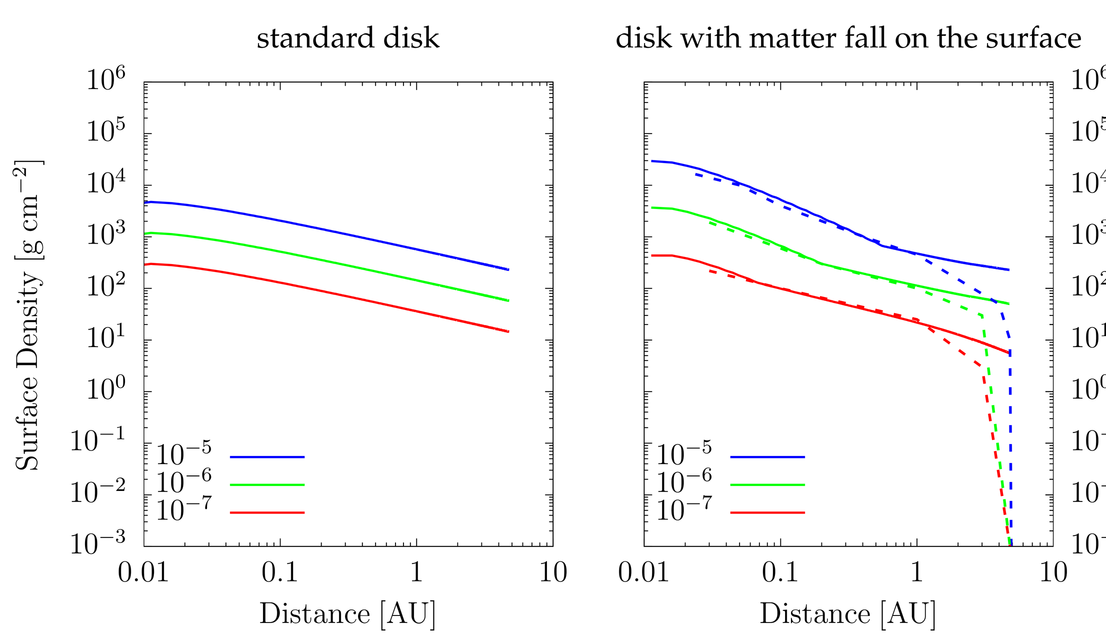

Figure 3: Surface density profile. Solid lines correspond to our results, dashed are results obtained by *Perets & Kenyon* 2013. Color refers to mass loss rates of the red giant in $[M_\odot\,year^{-1}]$.

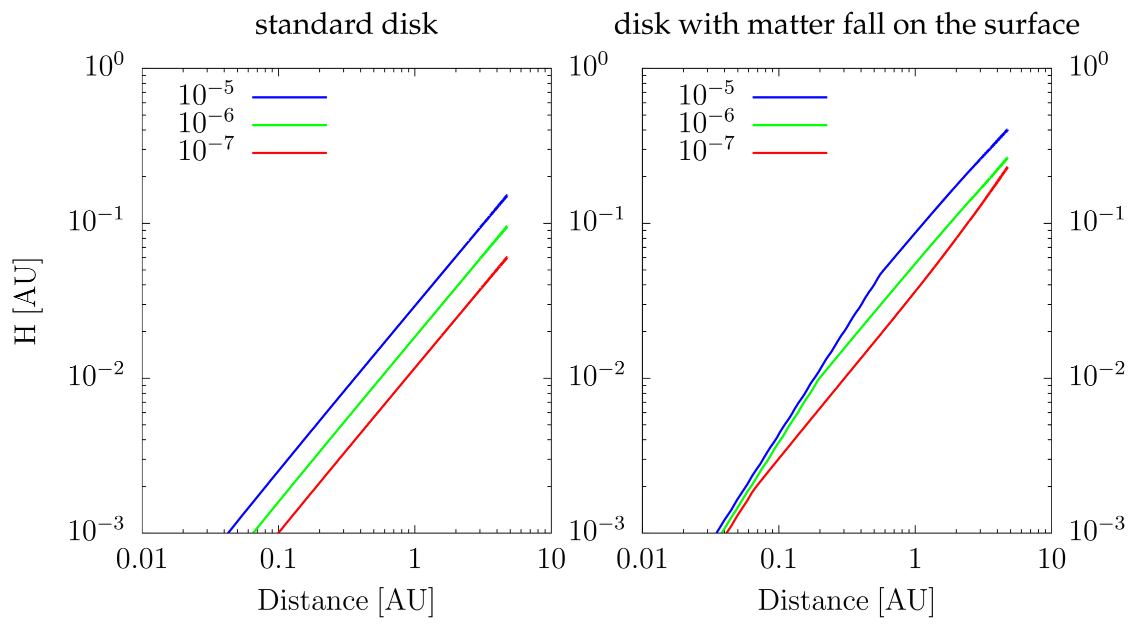

Figure 4: Scale height profile. Color refers to mass loss rates of the red giant in $[M_\odot\,year^{-1}]$.

Time of planet migration

Here we present results on the migration time of a planet embedded in an accretion disk. These results are presented for binary system with companion masses $M_1 = 1\,[M_\odot]$, $M_2 = 3\,[M_\odot]$. The initial planet distance to the host star is $R_0 = 1\,[AU]$.

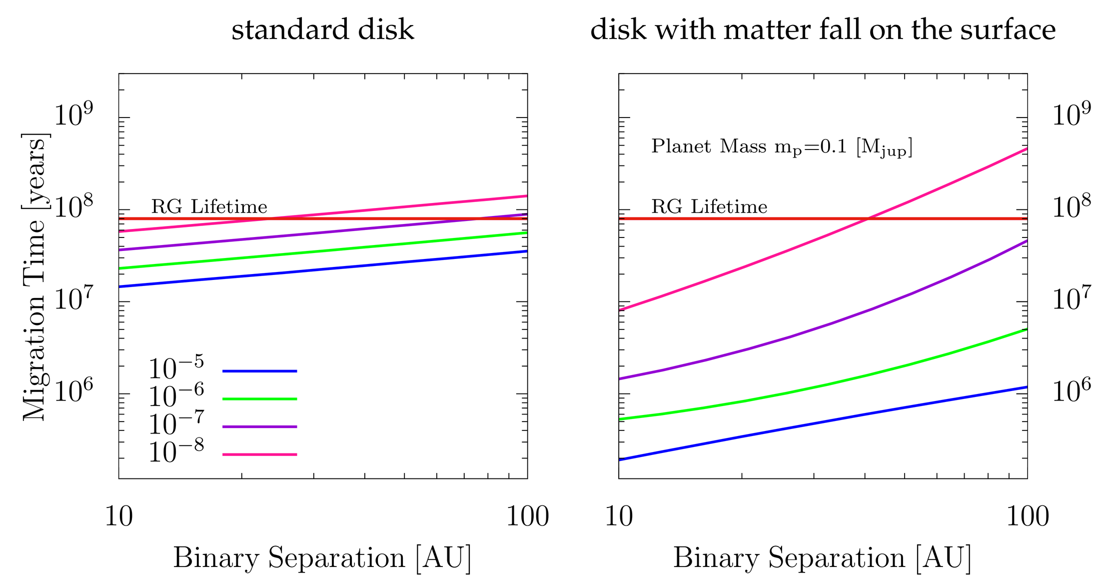

Figure 5: Migration time dependence on the binary separation. Colored lines refer to different red giant mass loss rates in $[M_\odot\,year^{-1}]$.

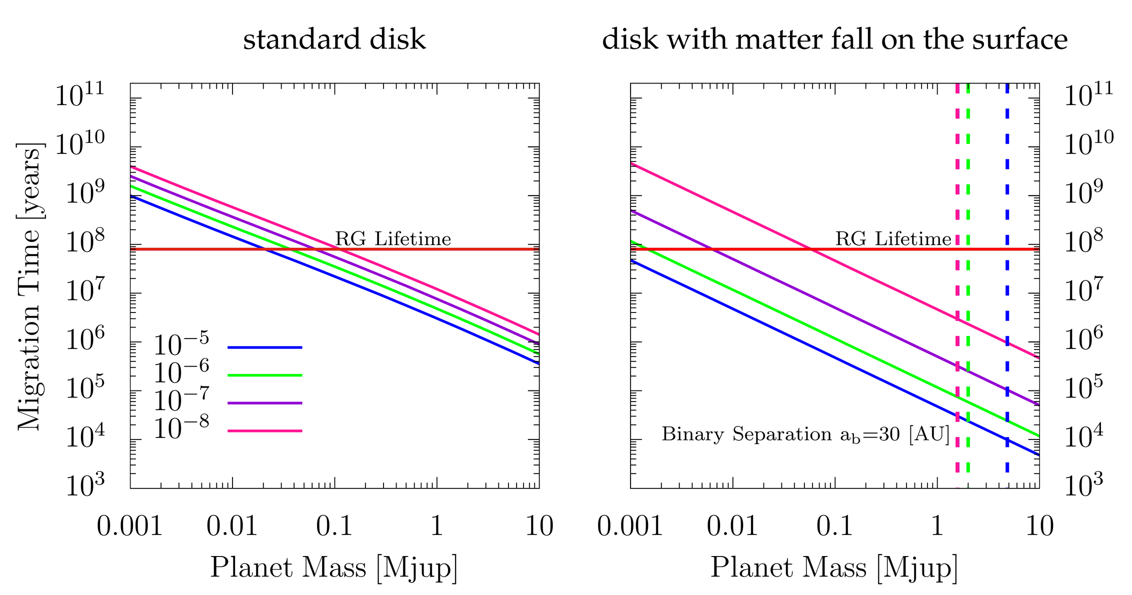

Figure 6: Migration time dependence on the planet mass (solid lines). Dashed lines represent maximum planet mass for type I migration, violet dashed line correspond to maximum planet mass for both violet and pink solid lines. Colored lines refer to different red giant mass loss rates in $[M_\odot\,year^{-1}]$.

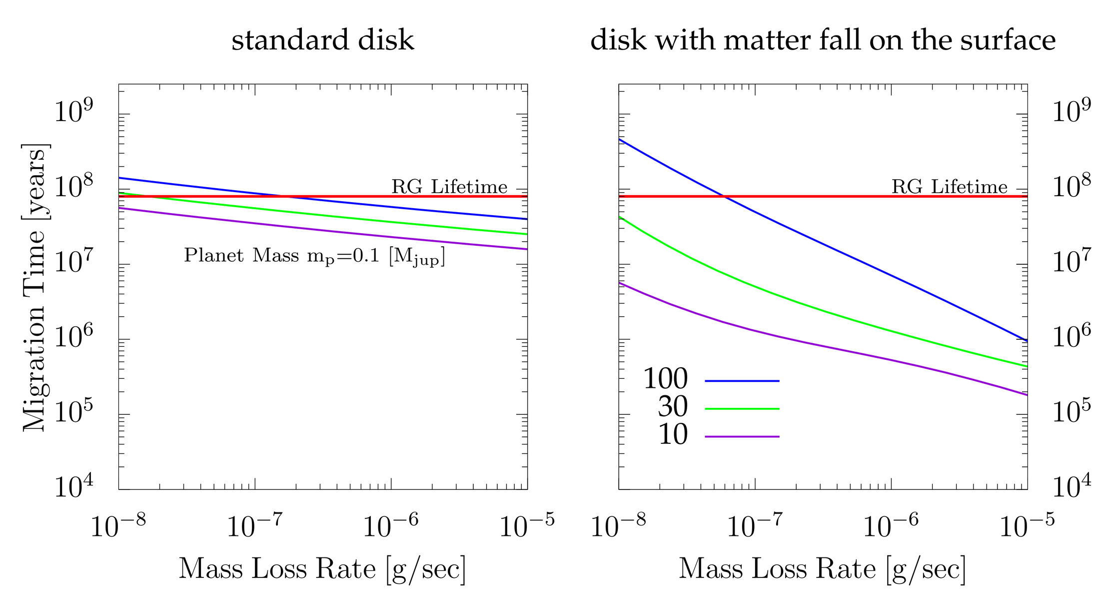

Figure 7: Migration time dependence on mass loss rate. Colored lines refer to different binary separations in $[AU]$.

Conclusions

Our calculations demonstrate that in thin α-disks planets can migrate towards the host star within the lifetime of a red giant for realistic ranges of the main parameters. Thus, it is important to consider binary systems to estimate the total rate of planet-star mergers.

References

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4. Tanaka, H., & Takeuchi, T., & Ward, W. R. 2002, ApJ, 565, 1257.