New strategy to search for planetary or substellar companions in debris disk

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Overview

A planet or brown dwarf (hereinafter companion) that is forming in a protoplanetary disk opens a gap along its orbit. While it is impossible to directly detect the companion by investigating the spectral energy distribution (SED), it might be possible to identify the gap in the debris disk emission. We investigate the possibility to detect a companion in a debris disk and to determine the companion's physical parameters that could be derived with this method. We present the results of numerical calculations for system with 0.8 M_{sun} central object and companion with mass of 0.03 M_{sun} at 0.1 Gyr. We vary the debris disk particle radii from 10 μm to 10 cm and assume disk masses of 10^{-5} stellar masses. Width of the gap opened by the companion is determined as a diameter of the planet's Hill sphere. The distance from the companion to the central star is varied within all possible positions along the disk radius.

SEDs calculation algorithm

The total flux from the system (F) is the sum of fluxes from the central star (F_*), the debris disk (F_d) and the companion (F_{pl}):

$$F = F_d + F_{pl} + F_* \,.$$

Fluxes from the star and the companion is calculated using the black-body approximation:

$$F_* = \frac{\pi R_*^2}{d^2} B_\nu(T_*)\,, \qquad F_{pl} = \frac{\pi R_{pl}^2}{d^2} B_\nu(T_{pl,ef})\,,$$

where d is a distance to the object, $B_\nu(T)$ is the Plank function, R_* and T_* are the stellar radius and effective temperature, R_{pl} and $T_{pl,ef}$ are the companion's radius and effective temperature. $T_{pl,ef}$ for day ($T_{pl,ef,d}$) and night ($T_{pl,ef,n}$) sides of the companion are calculated using formulas:

$$T^4_{pl,ef,d} = T^4_{pl} + \frac{L_{in,gap}}{4\pi r_p^2 \sigma}\,, \qquad T^4_{pl,ef,n} = T^4_{pl} + T^4_{d(r_p)}\,,$$

where T_{pl} is the companion's effective temperature without heating from the star, $L_{in,gap}$ is the disk luminosity at the inner edge of the gap ($R_{in,gap}$), r_p is the distance from the star to the companion, $T_{d(r_p)}$ — the temperature at which the disk material would be heated by the star at r_p. The stellar and companion's physical parameters (R_*, T_*, R_{pl}, T_{pl}) are taken from Baraffe et al. (1998) for a given age and mass.

The SED from the disk is

$$F_d = F_{disk} - F_{gap}\,,$$

where F_{disk} is the flux from the disk as it would be without the gap opened by companion, F_{gap} is a flux from the part of the disk that has been cleared by the companion.

The dynamics of dust grains in optically thin systems are dominated by radiative and collisional processes when the effects of gas drag are negligible (gas to dust ratio <0.1). Following the procedure described in Hughes et al. (2011) for a single characteristic grain size a, the flux density from the optically thin disk is

$$F_{\nu,disk} = \frac{\pi a^2 Q_\nu}{d^2}\int_{R_{in}}^{R_{out}} B_\nu(T_r) n_r 2\pi r dr, \qquad (*)$$

where Q_ν is a wavelength dependent dust grain emission efficiency, R_{in} and R_{out} - inner and outer disk radii. The number density of grains is $n_r = \Sigma_r/m_g$, where m_g is the mass per dust grains and surface density is

$$\Sigma_r = \frac{M_d r^p (2+p)}{2\pi(R_{out}^{2+p} - R_{in}^{2+p})}\,,$$

where M_d is a disk mass and power law p could be within -1.5 (of the current solar system) and 0 - constant surface density (Carpenter et al. 2009).

The single dust temperature is calculated with the requirement that the dust grains are in radiative equilibrium with the star and are spatially extended (Hughes et al. 2011):

$$T_r = \left[\frac{L_*}{\sigma r^2}\frac{\pi^3}{240}\frac{1}{(\beta+3)!\zeta(\beta+4)Q_0}\left(\frac{\lambda_0 k}{hc}\right)^{-\beta}\right]^{\frac{1}{4+\beta}},$$

where ζ is the Riemann zeta function, and Q_0 is the dust grain emission efficiency at the critical wavelength $\lambda_0 = 2\,\pi a$.

The flux from the part of the disk that has been cleared by the companion (F_{gap}) is calculated using the same approach as F_{disk}, except in formula (*). The integration is within $R_{in,gap}$ and $R_{out,gap}$ — gap inner and outer radii, that are determined by r_p and the Hill radius R_H:

$$R_{in,gap} = r_p - R_H\,, \qquad R_{out,gap} = r_p + R_H\,.$$

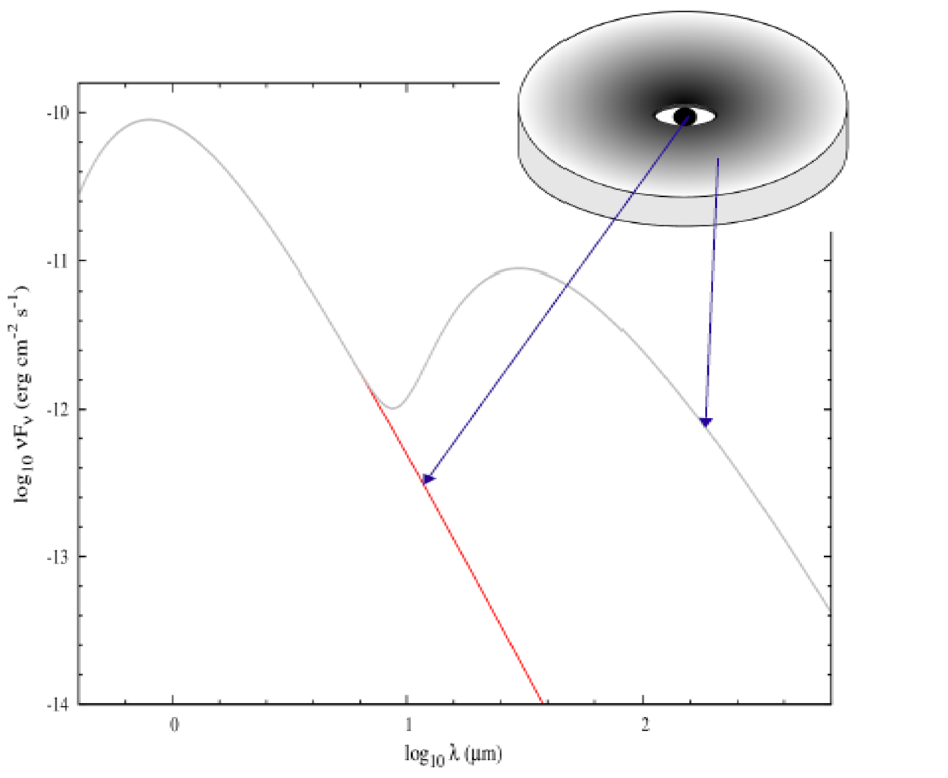

Fig. 1. SED of modeled system with debris disk (—). Flux from the star (—) with age = 100 Myr, M_* = 0.8 M_{sun}, L_* = 0.39 L_{sun}. The disk extends from 0.1 AU to 150 AU, a = 1 mm, M_d = $10^{-5} M_*$, d = 250 pc.

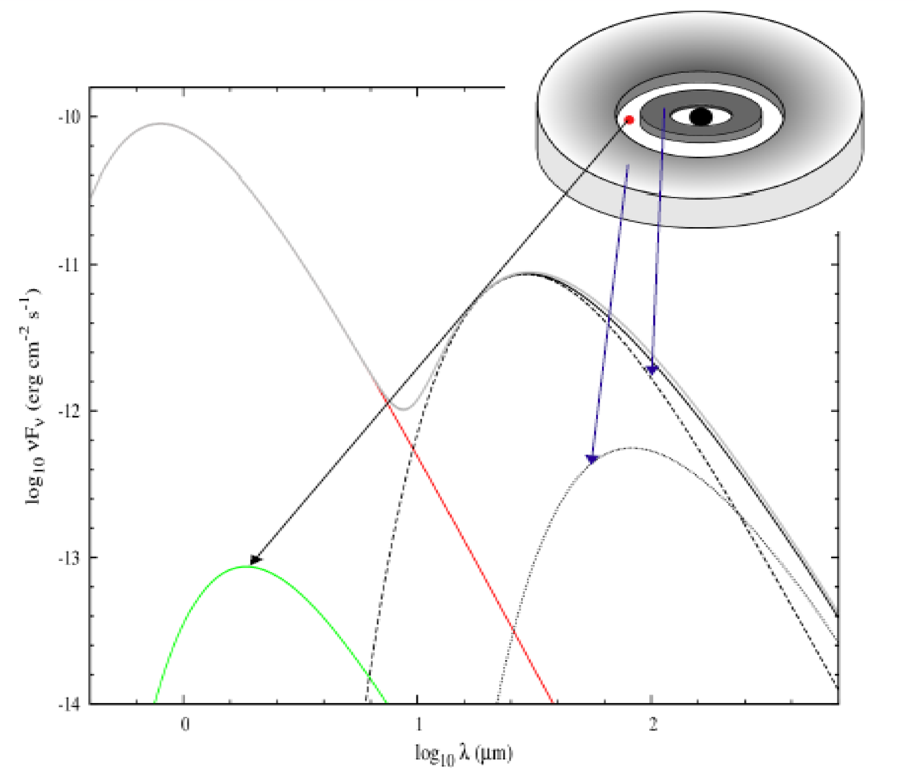

Fig. 2. SED of modeled system with debris disk and companion (—) that contains of inner (--) and outer (····) parts (see text for more details). Flux from companion (—) with M_{pl} = 30 M_J, r_p = 1 AU, R_H = 0.23 AU. Stellar and disk parameters are the same as for Fig. 1.

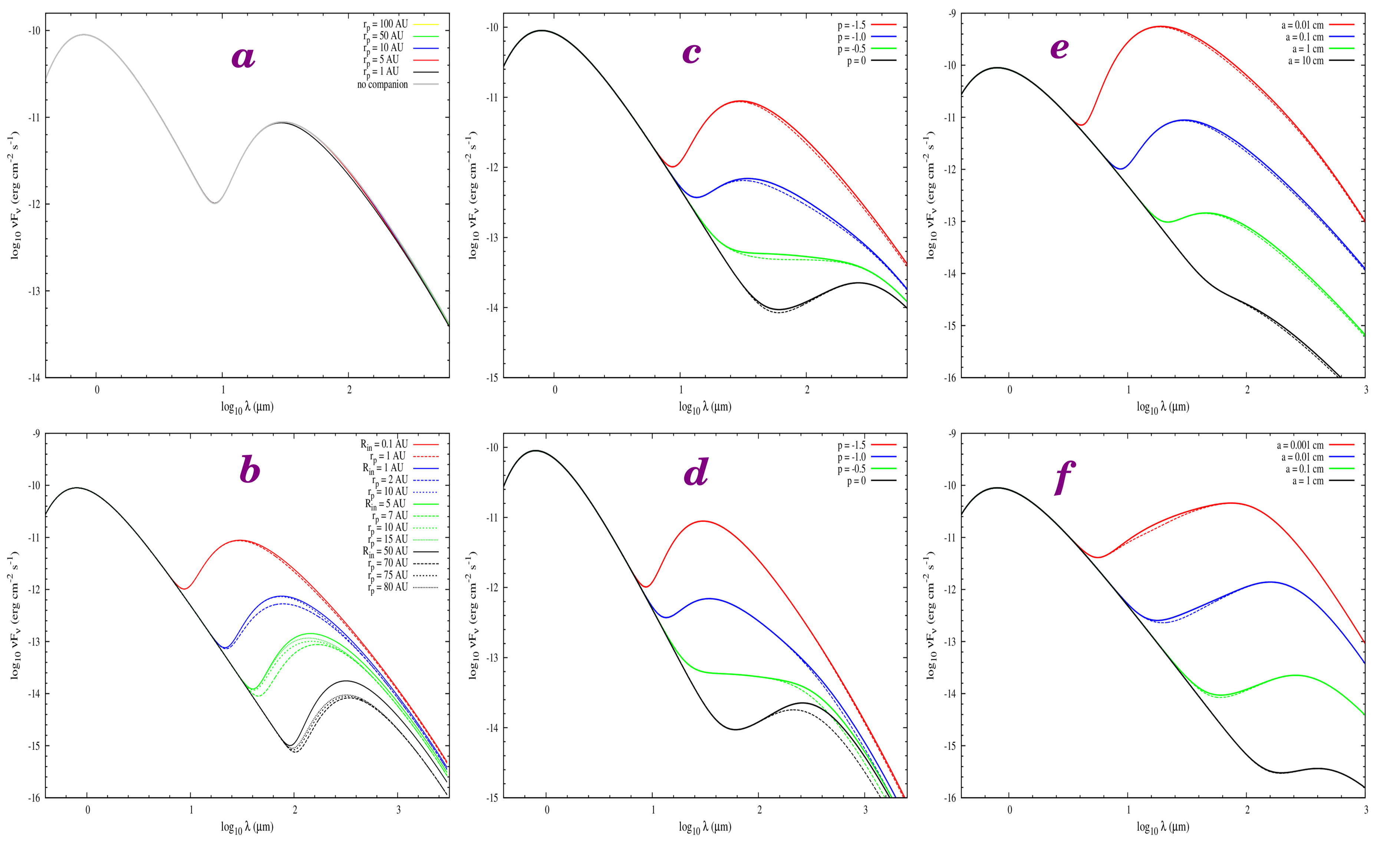

Fig. 3. SEDs of the systems with debris disks that have gaps opened by companions. Each panel illustrates how the SED with and without the companion change for the systems with different parameters: ***a*** - r_p, ***b*** - R_{in} and r_p, ***c*** - p (r_p = 1 AU), ***d*** - p (r_p = 100 AU), ***e*** - a (p = -1.5), ***f*** - a (p = 0). All another parameters (that are not mentioned for each specific case) are the same as presented in Fig.2. In panels ***b*** - ***f*** solid colored lines indicate the SEDs from the systems without the companions (and hence without the gaps) with parameters listed in the legends. Dashed and dotted lines are SEDs of systems with companions at 1 AU (for panels ***c***, ***e***, ***f***), 100 AU (for panel ***d***) and as indicated at legend for panel ***b***.

Results

The models have been performed for systems with 0.8 M_{sun} central object and 0.03 M_{sun} substellar companion at 0.1 Gyr. The companion's mass was chosen to be close to the maximum possible mass of the object that might be formed in a protoplanetary disk ~ 0.04 M_{sun} (Ma & Ge 2013). Figures 1 and 2 show SEDs of a system with a debris disk without a companion (gray line) and with a gap opened by a companion (black line in figure 2). Both figures include also sketches of the disks to illustrate their geometries. Visual examination of figure 2 indicates that even the presence of a quite massive companion would be hard to suspect by analyzing only SED profiles. To find systems with parameters that would highlight the presence of the gap in the disk and, consequently, the companion SEDs were modeled for disks with p = -1.5 – 0, a = 10 μm – 10 cm, R_{in} = 0.1 – 50 AU and r_p = 1 – 80 AU. Figure 3 presents the results for the models with the largest differences between the cases with and without the companion.

One can see that changes in most of the parameters do not change significantly the possibility to suspect a companion in the disk using this method. The exception is the disk inner radius Figure 3*b* illustrates that an increase of R_{in} significantly decrease the total disk emission but at the same time, the difference between the SEDs of the systems with and without the companion is very noticeable, compared to other possible parameter variations. It is also seen that the closer is companion to R_{in}, the clearer the difference is between SEDs profiles.

References:

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