New approach to identify a brown dwarf companion in a circumstellar disk by studying SED profile of the system

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Introduction

Planetary systems are formed in protoplanetary disks that surround young stellar and substellar objects. In the first hundred thousand years, such disks could contain hot and massive fragments. After a few million years, planetary and substellar companions may be detected in protoplanetary disks, and later in debris disks. Disk sizes, masses and structures are determined by the initial core characteristics and can be derived from the central object's physical parameters, assuming a given evolutionary stage. I investigate the possibility to identify the different stages of planet formation by studying the spectral energy distribution (SED) of the system.

SEDs modeling approach

I've calculated the total SED from the system (F) as 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 are 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, $B_\lambda(T)$ is the Plank function, R_* and T_* are the stellar radius and effective temperature and R_{pl} and $T_{pl,ef}$ are the companion's radius and effective temperature. These parameters were taken from Baraffe & Chabrier (1998), for each age.

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 the companion and F_{gap} is a flux from the part of the disk that has been cleared by the companion.

The gap inner ($R_{in,gap}$) and outer ($R_{out,gap}$) radii are determined by the distance to the companion r_p and its Hill radius R_H:

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

For protoplanetary and debris disks, I assumed that the companion is moving along a circular orbit and that there is no material inside the gap. To model SEDs from optically thick gas-rich protoplanetary disk I used the approach, presented by Andrew & Williams 2005. For the optically thin debris disk I followed the strategy described in Hughes et al. 2011.

Results

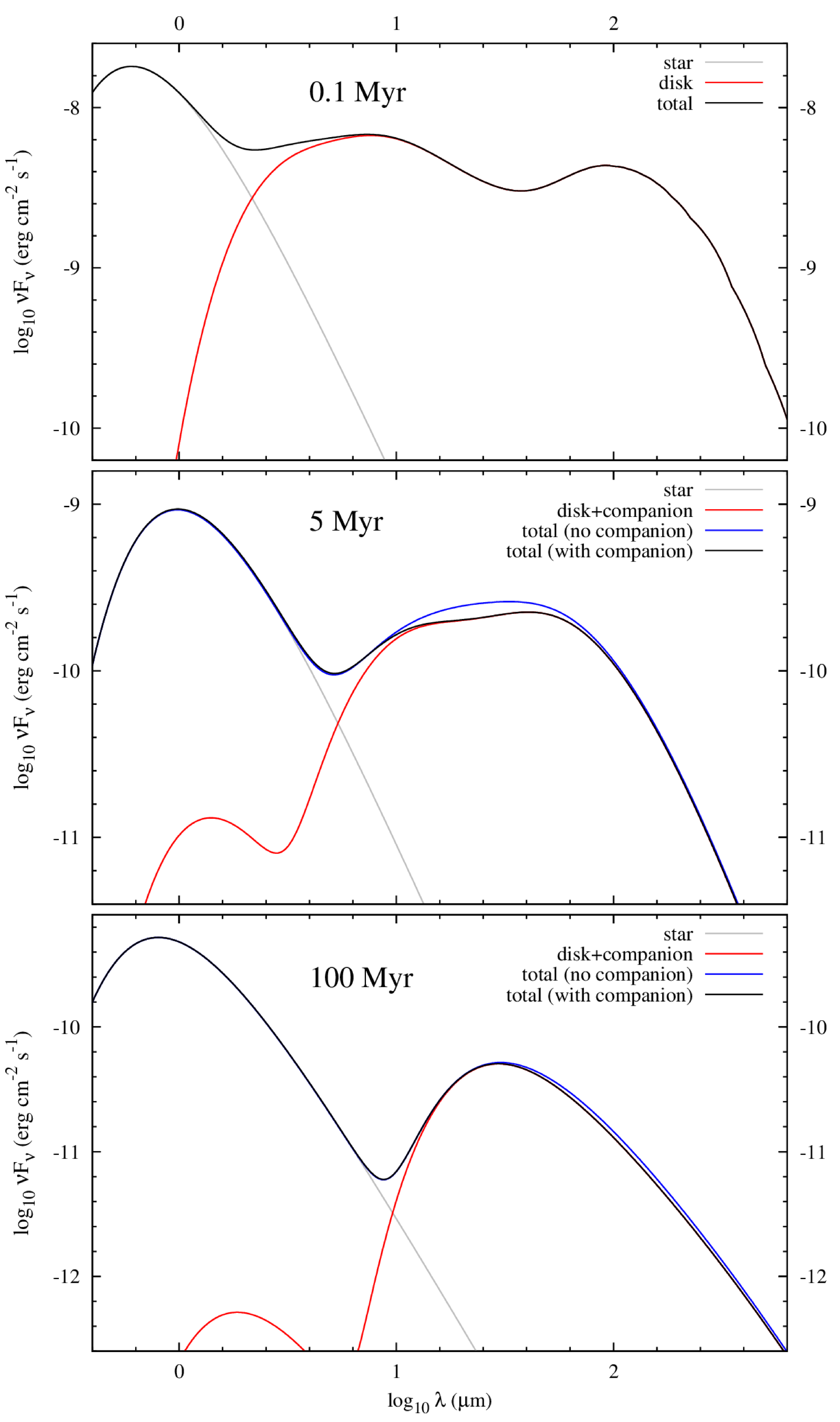

Fig. 1. SEDs of modeled system with protostellar (top panel, Vorobyov et al. 2013), protoplanetary (middle panel) and debris (bottom panel) disks. On all panels are shown the fluxes from the star or protostar (—), from the disk, that include the companion or a fragment (—) and the total flux from the system (—). On the middle and bottom plots is also shown the flux from the system with the same parameters but without a companion (—). d = 100 pc.

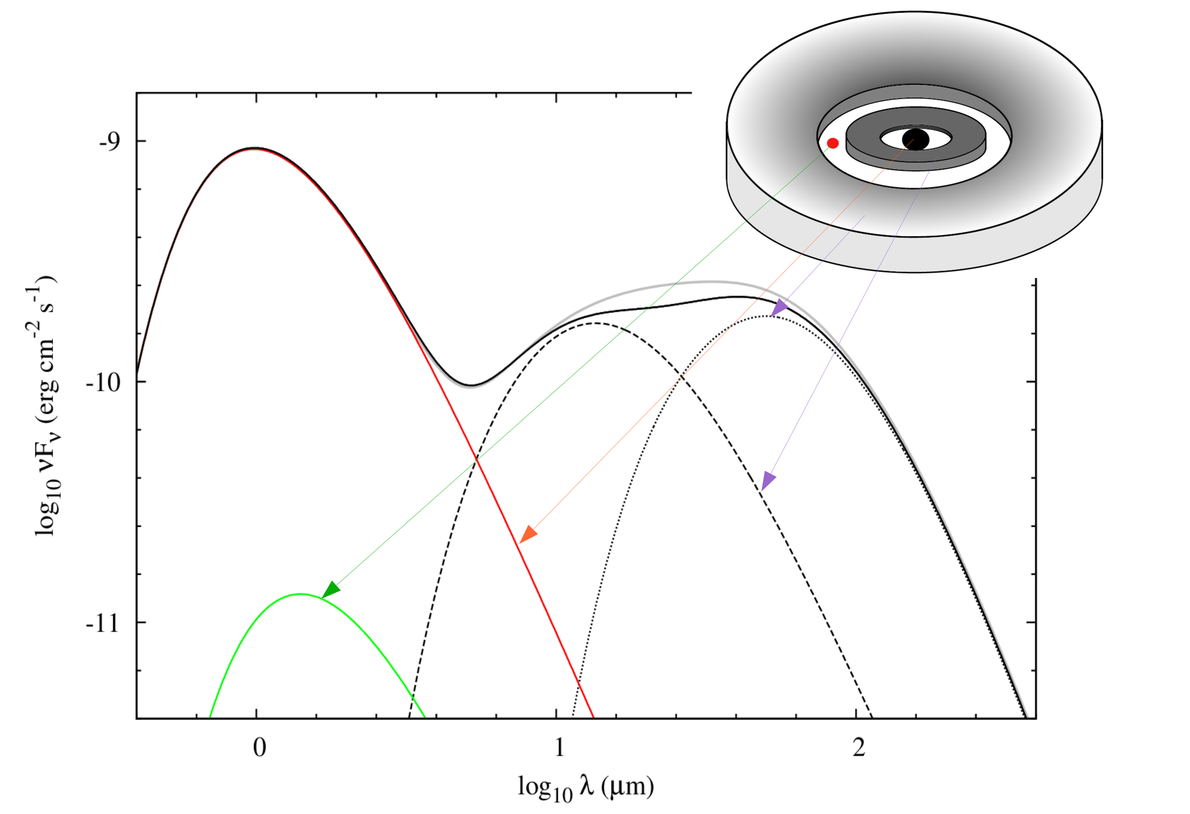

Fig. 2. SED of modeled system with debris disk and companion (—) that consists of inner (--) and outer (····) parts. The disk extends from 0.1 AU to 150 AU, d = 100 pc. Flux from companion (—) with M_{pl} = 30 M_J, r_p = 1 AU, R_H = 0.23 AU and star (—) with M_* = 0.8 M_{sun}. Flux from the system with the same parameters but without a companion (—).

Table Difference of the fluxes from the systems with protoplanetary disks (5 Myr) and with or without embedded companions (M_{pl} = 30 M_J, r_p = 1 AU, M_* = 0.8 M_{sun})

λ (µm)	ΔF (Jy)	$F_{\text{no companion}}$ (Jy)	$F_{\text{with companion}}$ (Jy)
10	**0.02**	0.57	0.55
20	**0.29**	1.63	1.35
34 (ΔFmax)*	**0.43**	2.93	2.50
80	**0.23**	4.28	4.06
100	**0.17**	3.84	3.67
160	**0.08**	2.34	2.26

*34 µm is the wavelength with the maximum difference between the fluxes.

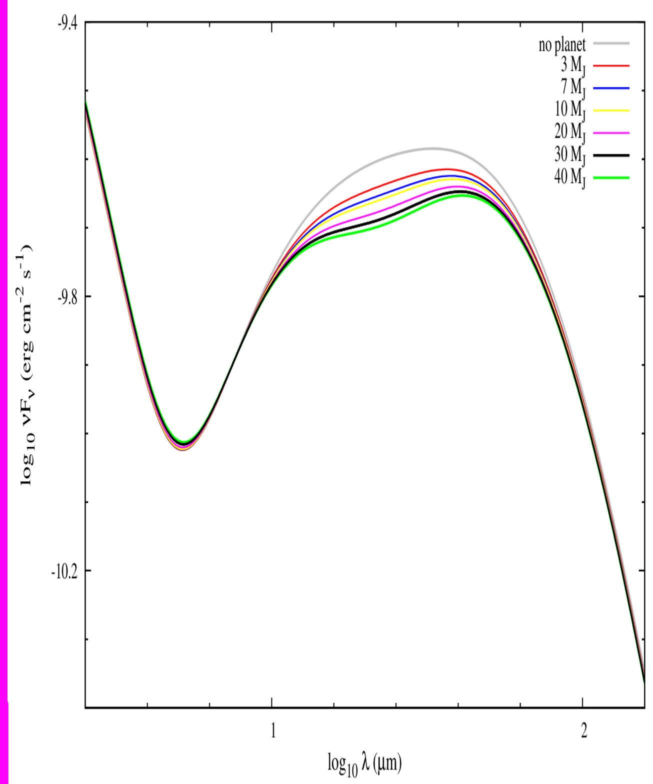

Fig. 3. SEDs of the modeled system with protoplanetary disk with embedded brown dwarf at r_p = 1 AU with different masses.

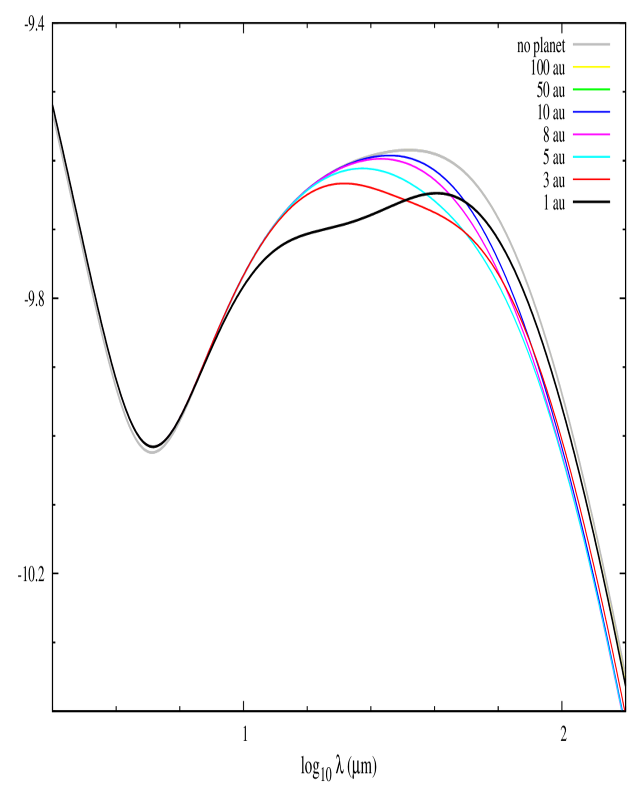

Fig. 4. SEDs of the modeled system with protoplanetary disk with embedded brown dwarf with M_{pl} = 30 M_J at different distances.

Results

The models have been performed for systems with a 0.8 M_{sun} central object and a 30 M_J substellar companion at 5 Myr (protoplanetary disk) and 100 Myr (debris disk). 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) and also to correspond to one of the models for a protostellar fragmenting disk from Vorobyov et al. (2013). **Figure 1** shows SEDs for systems with protostellar (top panel), protoplanetary (middle panel) and debris (bottom panel) disks. The results for protostellar disks around young stellar object (for the system with similar parameters at 0.1 Myr) were previously presented by Vorobyov et al (2013) and here are shown for comparison.

Figure 2 shows SEDs of a system with a protoplanetary disk without a companion (gray line) and with a gap opened by a companion (black line). This figure illustrates the contribution of the companion (green line), disk inner (dashed line) and outer (dotted line) components and also a sketch of the disk to illustrate the geometry. The differences of the fluxes from this system without and with an embedded companion as a function of wavelength are listed in the **table**.

Figures 3 and 4 show how the total system (star+disk+companion) SED depends on the mass of the companion (M_{pl}) and its distance to the star (r_p). Flux from the same system but without the embedded companion and a gap is shown by the gray line on both figures. Visual examination of these figures indicates that the difference between the SEDs of the systems with protoplanetary disk and with or without a companion is evident even if the companion mass is as small as 3 M_J but only when it is located within the disk inner 10 AU.

Conclusions

The results of my modeling indicate that during the earliest stages of companion formation (age 0.1 Myr), they initiate an additional peak at 5-10 µm. During latest stages it initiates a depression in the SED profile due to the gap that it clears along its orbital motion. This depression would be at 10-100 µm, for protoplanetary disks, and at ~ 80 µm, for debris disks. It would be very difficult to identify an embedded companion in a typical debris disk with SED profile analysis. The difference between SEDs of the systems with protoplanetary disk and with or without companion is more evident even if the companion mass is as small as 3 M_J.

References:

Andrews S. M. & Willams J. P. 2005, ApJ, 631, 1134
Baraffe I., Chabrier G., Allard F., et al. Astron. 1998, A&A, 337, 403
Hughes A. M., Wilner D. J., Andrews S. M. et al. 2011, ApJ, 740, 38
Ma B. & Ge J. 2014, MNRAS, 439, 2781
Vorobyov E.I., Zakhozhay O.V., & Dunham M.M. 2013, MNRAS, 433, 3256
Zakhozhay O.V. 2015, KPCB (in Russian), 31,39

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