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 \text{star}), the debris disk (F \text{disk}) and the companion (F \text{comp}):
\[ F = F_{\text{star}} + F_{\text{disk}} + F_{\text{comp}} \]

Fluxes from the star and the companion are calculated using the black-body approximation:
\[ F_\nu = \frac{2 \pi R^2 \sigma T^4}{d^2}, \]
where \( d \) is a distance to the object, \( B_\nu(T) \) is the Planck function, \( R \) and \( T \) are the stellar radii and effective temperature and \( R_{\text{comp}} \) and \( T_{\text{comp}} \) 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
\[ F_{\text{disk}} = F_{\text{disk, total}} - F_{\text{gap}} \]
where \( F_{\text{disk, total}} \) is the flux from the disk as it would be without the gap opened by the companion and \( F_{\text{gap}} \) is a flux from the part of the disk that has been cleared by the companion.

The gap inner \( R_{\text{in, gap}} \) and outer \( R_{\text{out, gap}} \) radii are determined by the distance to the companion \( r_p \) and its Hill radius \( R_H \):
\[ R_{\text{in, gap}} = r_p - R_H \quad \text{and} \quad R_{\text{out, gap}} = r_p + R_H \]

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 used the approach, presented by Hughes & Williams 2005. For the optically thin debris disk I followed the strategy described in Hughes et al. 2011.

Results

The models have been performed for systems with a 0.8 \( M_{\odot} \) 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 \(-0.04 M_{\odot} \) (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 objects (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 \((M_{\text{comp}})\) 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 and 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 \( \mu \)m. 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 100-1000 \( \mu \)m, for protoplanetary disks, and at \( \sim 80 \mu \)m, 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 \( M_J \).

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References:
Zakhozhay O.V. 2015, RFCB (in russian), 31,39