UV-controlled physical and chemical structure of protoplanetary disks

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Introduction

Ultraviolet (UV) radiation is an important factor in the physical and chemical evolution of protoplanetary disks. It heats up a disk atmosphere, affecting both its structure and an emergent spectral energy distribution, and also, which is important, controls the molecular content of the upper disk. A UV part of spectrum comes primarily not from the star itself but from the inner region of an accretion flow (accretion shock, accretion column etc.). As a result, the shape of the UV continuum and UV emission lines varies from a star to a star. Unlike the black body (BB) part of the spectrum, its near UV part may significantly depend on details of a particular source, which is confirmed by existing UV observations of T Tauri stars. In this contribution, we consider possible effects of a UV continuum on the observational appearance of a protoplanetary disk, both in terms of continuum and molecular lines. These effects are related to the disk heating by the central source and to the rates of photoreactions. It is reasonable to expect that UV part of the irradiating spectrum is most influenced by the grain evolution (growth and sedimentation) which marks the very initial stage of planet formation.

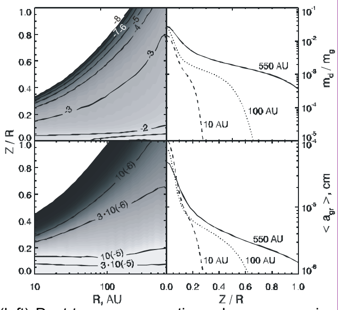
Disk Model

Density distribution is based on a 1+1D disk model with α prescription for viscosity (D'Alessio et al. 1998); $\alpha = 0.01$, accretion rate $5{\cdot}10^{-9}\ M_{\odot}$ year^{-1}, $M_* = 0.65\ M_{\odot}$, $R_* = 1.2\ R_{\odot}$.

Dust temperature distribution is determined with a 1D two-stream radiative transfer (RT) model with full frequency treatment. Dust is the dominant opacity agent in the most part of the disk, so in the source function for the RT equation we only consider thermal emission, absorption and isotropic scattering on dust grains. Solution of the RT equation in *z*-direction is repeated for a number of radial distances *R*, that results in the full temperature distribution $T(R,z)$.

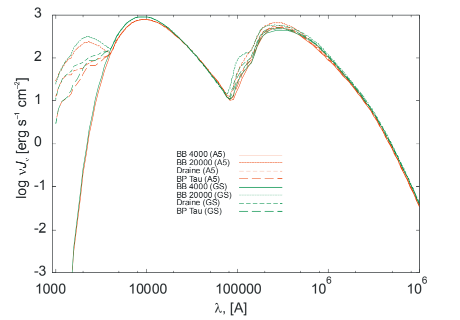
Dust evolution is modeled using a slightly modified version of the code presented in Brauer et al. (2008), a statistical, mass conserving code which implicitly solves the Smoluchowski equation, taking coagulation, fragmentation and cratering into account. To calculate the vertical distribution of grains having different sizes, we assume that this distribution is controlled by the equilibrium between gravitational settling and turbulent stirring. Vertical scale heights are computed separately for each grain size bin. As a result, we have grain size distributions and dust-to-gas mass ratio as a function of coordinates *R* and *z* within the disk.

Dust distribution



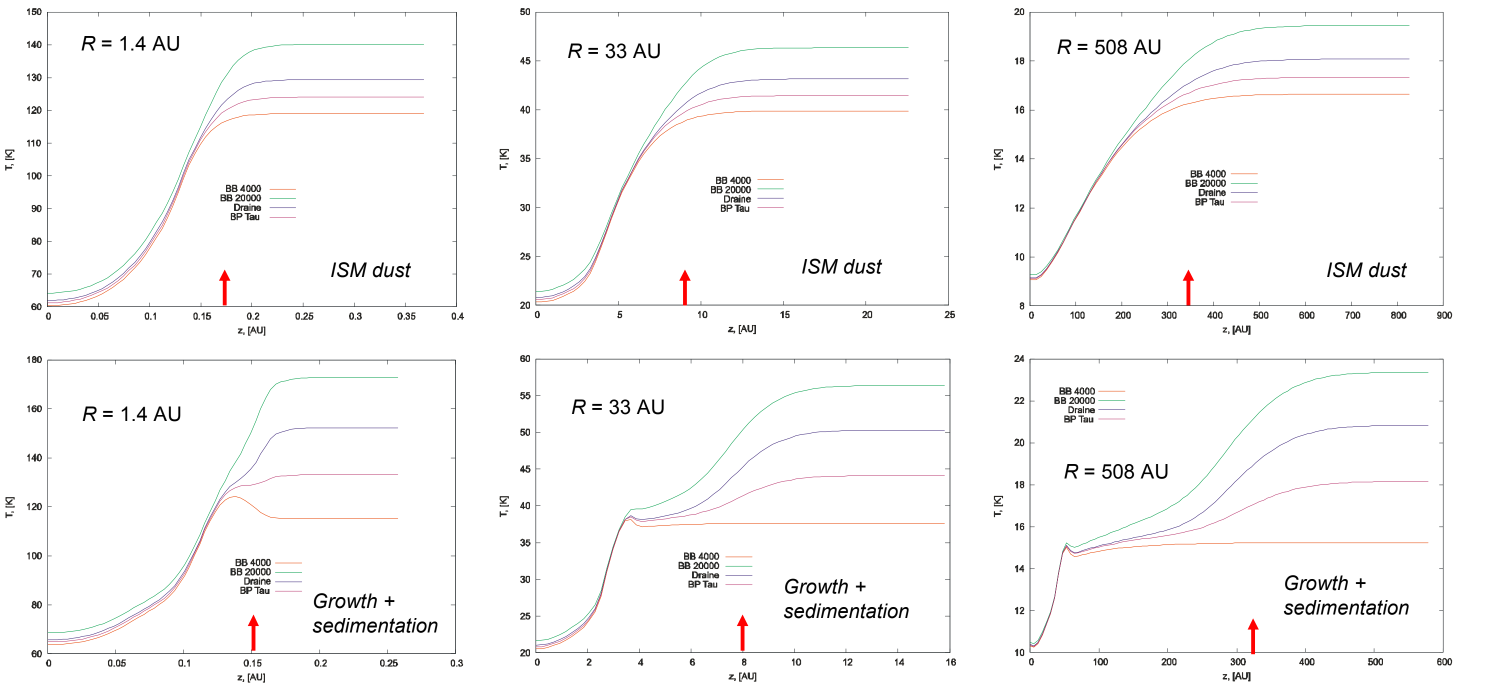
(left) Dust-to-gas mass ratio and average grain size distributions over the disk. The original (unevolved) values are 0.01 and 10^{-5} cm. In the upper disk atmosphere dust-to-gas ratio is reduced by six orders of magnitude because of sedimentation. The average grain size is an order of magnitude smaller than the `canonical' value. This changes significantly volume opacity and affects both dust heating and photoreaction rates. On the other hand, in the disk midplane both dust-to-gas mass ratio and average grain size are greater than interstellar values. (right) Vertical profiles dust-to-gas mass ratio and average grain size for three representative radii.

Mean intensity



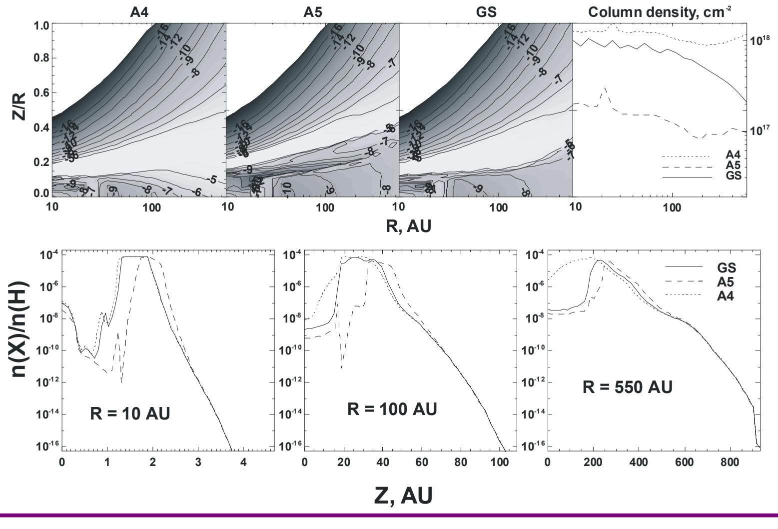
Representative mean intensities at R = 1.4 AU, at the height, corresponding to τ(1000Å) = 1. Green lines are used for a model with dust growth and sedimentation. Spectra for a model with dust properties typical for ISM (no growth, no sedimentation) are shown with red lines. Different line styles denote different ways to characterize an UV excess in the incident radiation. Solid lines correspond to a purely blackbody spectrum with T = 4000K. Short dashes correspond to a diluted blackbody spectrum with T = 20000K. Draine (1978) interstellar field is shown with medium dashes. Long-dashed lines depict the real UV excess for BP Tau taken from Kravtsova and Lamzin (2003). In all cases excess UV continuum is added only for λ < 4000Å. All added UV contributions are normalized to have the same mean intensity at λ = 4000Å.

Temperature distributions



These plots show vertical temperature distributions at R = 1.4 AU (left), 33 AU (middle), and 508 AU (right) for various ways to set up a UV excess. Diagrams in the top row show thermal structure for a disk with unevolved dust, while diagrams in the bottom row show thermal structure for a disk with dust coagulation and sedimentation. Different temperatures of the upper disk for different UV excess models are caused by differences in the UV luminosity of the central source for the adopted excess normalization. Red arrows indicate heights at which τ(1000Å) = 1.

There is a noticeable difference between cases with unevolved and evolved dust in the sense that temperature in a disk with evolved dust is much more sensitive to the shape of the UV continuum. At a level of τ = 1 temperature difference between bracketing incident spectra is 20 K for unevolved dust and 50 K for evolved dust at 1.4 AU. Further from the star the difference decreases, but it still persists at 33 AU, being 5 K for unevolved dust and 15 K for evolved dust. The temperature bump between the midplane and the disk atmosphere appears because the *slope* of frequency dependence of absorption and scattering coefficients changes in vertical direction.



Disk chemistry

UV irradiation of the disk coupled to the dust evolution also has a profound effect on its molecular structure. On diagrams to the left we show distribution of CO molecules as an example. Three models shown are ISM dust (A5), dust with an artificial order of magnitude increase in the grain average size (A4), and evolved dust (GS). Almost over the entire disk (at R < 500 AU) column density of CO molecules is smaller in model A5 (unevolved dust) than in model GS (evolved dust) as the latter model is more transparent to UV radiation and is characterized by more effective photodesorption, which increases gas-phase CO abundance. This fact coupled to temperature differences may lead to observable differences in molecular line profiles.

Conclusions

1. UV radiation is an important factor in the evolution of protoplanetary disks affecting their observational appearance both in terms of continuum observations and molecular line observations.
2. Influence of UV irradiation onto the disk structure gets stronger as dust particles grow bigger at the initial phase of planet formation.
3. The detailed thermal structure of a disk depend on the strength and shape of the UV continuum. Thus, in order to interpret observations of a particular star+disk system its UV spectroscopy is highly desirable.