Radiative Hydrodynamical Simulations of Protoplanetary Disks: Vertical Oscillation Excited by Irradiation

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Abstract:

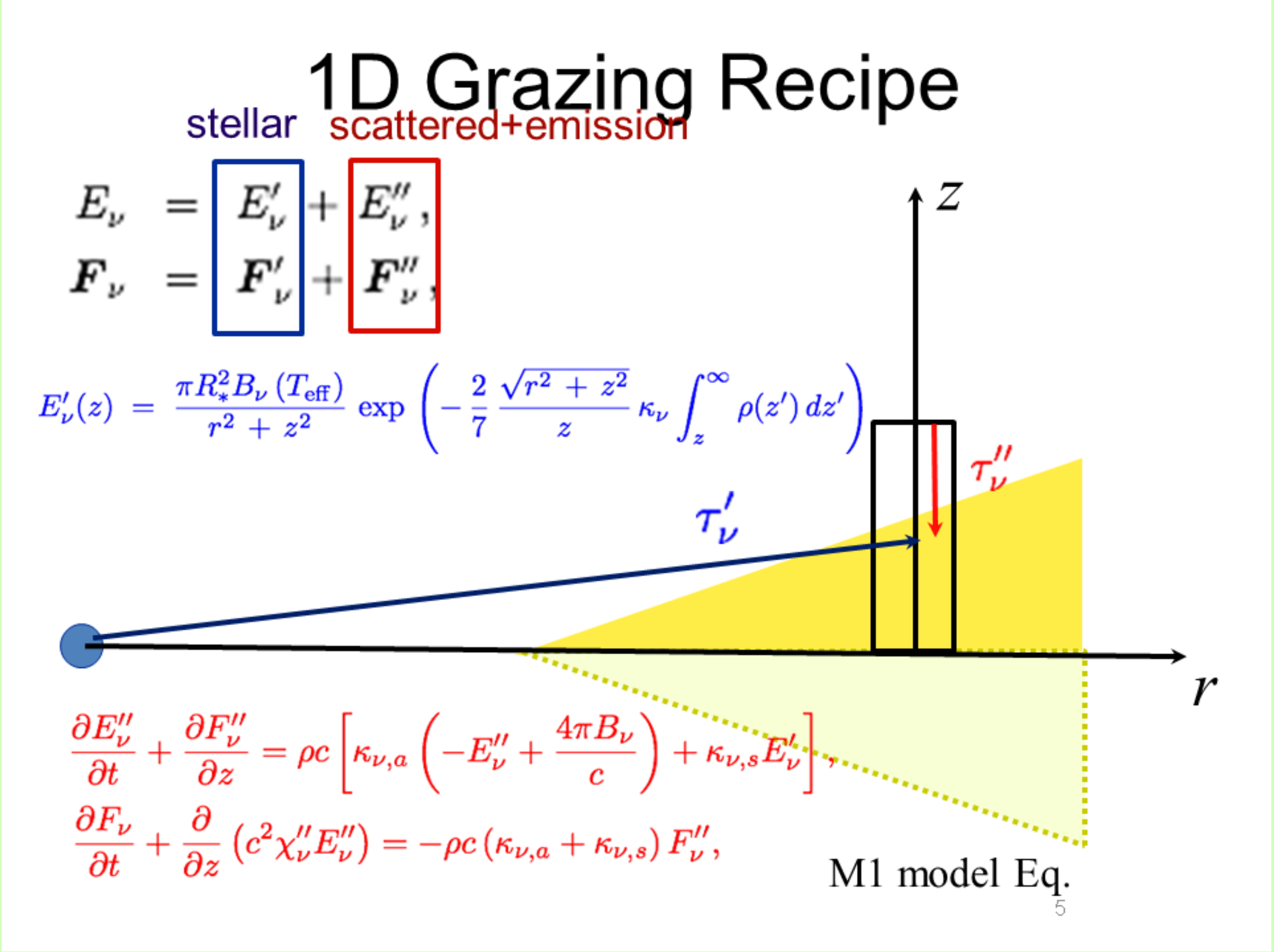
We show 1D multi color radiative hydrodynamical simulations in which vertical oscillation is excited by irradiation. The oscillation has a node between hot surface layers and cold disk main body. When the cold main body is compressed, the hot surface layers expand to receive more radiation from the star. When the main body expands, the hot surface layers are compressed to receive less. Thus the main body has a higher pressure in the expansion than in contraction. As a result, the oscillation is overstable. The oscillation changes brightness at various wavelengths including the molecular line spectra through the Doppler shift. The oscillation may result in the mass loss.

1. Introduction and Aim

Stellar radiation is a main heating source for protopnanetary disks and has been suspected to cause an instability. This is because the disk may expand more if it receive more stellar radiation by expansion. The instability has been studied but under the assumption of either hydrostatic or thermal equilibrium (see, e.g,. Watanabe & Lin 2008). We study the dynamics of the protoplanetary disk taking account of both hydrodynamics and thermal evolution on the basis of 1D multi color radiative hydrodynamical simulations.

2. Model and Methods of Computation

We use the grazing recipe (Chiang & Goldreich 1997) to follow the vertical motion of gas and dust .



1D Grazing Recipe

stellar scattered+emission

$$E_\nu = \boxed{E'_\nu} + \boxed{E''_\nu},$$
$$\boldsymbol{F}_\nu = \boxed{\boldsymbol{F}'_\nu} + \boxed{\boldsymbol{F}''_\nu},$$

$$E'_\nu(z) = \frac{\pi R_*^2 B_\nu(T_{\rm eff})}{r^2+z^2} \exp\left(-\frac{2}{7}\frac{\sqrt{r^2+z^2}}{z}\kappa_\nu \int_z^\infty \rho(z')\,dz'\right)$$

$$\frac{\partial E''_\nu}{\partial t} + \frac{\partial F''_\nu}{\partial z} = \rho c\left[\kappa_{\nu,a}\left(-E''_\nu + \frac{4\pi B_\nu}{c}\right) + \kappa_{\nu,s}E'_\nu\right],$$
$$\frac{\partial F_\nu}{\partial t} + \frac{\partial}{\partial z}\left(c^2\chi''_\nu E''_\nu\right) = -\rho c\left(\kappa_{\nu,a}+\kappa_{\nu,s}\right)F''_\nu,$$

M1 model Eq.

We assume that the gas and dust have the same temperature for simplicity. The gas to dust ratio is assumed to be 100 and uniform. We ignore radial accretion for simplicity. Then the hydrodynamical equations are expressed as

assumption : $T_{\rm gas} = T_{\rm dust}$

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}(\rho v_z) = 0,$$
$$\frac{\partial v_z}{\partial t} + v_z\frac{\partial v_z}{\partial t} + \frac{1}{\rho}\frac{P}{\partial z} + \frac{GMz}{(r^2+z^2)^{3/2}} = 0,$$
$$T\frac{ds}{dt} = \int_0^\infty \kappa_{\nu,a}\left[cE_\nu - 4\pi B_\nu(T)\right]d\nu\,.$$
$$\alpha\frac{\partial E''_\nu}{\partial t} + \frac{\partial F''_\nu}{\partial z} = \rho c\left[\kappa_{\nu,a}\left(-E''_\nu + \frac{4\pi B_\nu}{c}\right) + \kappa_{\nu,s}E'_\nu\right],$$
$$\alpha\frac{\partial F_\nu}{\partial t} + \frac{\partial}{\partial z}\left(c^2\chi''_\nu E''_\nu\right) = -\rho c\left(\kappa_{\nu,a}+\kappa_{\nu,s}\right)F''_\nu,$$

speed reduction : $\alpha = 10^{-4} \rightarrow c = 30\ {\rm km\ s^{-1}}$

We solve the above partial differential equations **explicitly**.

Our finite difference scheme is designed so that all the physical variables approach to the equilibrium ones in the limit of $\Delta t = \infty$.

Fixed boundaries at z = 0 and 70 AU for hydro and outgoing boundary for E'' and $\boldsymbol{F}$'' at z = 70 AU.

Spectral range and resolution are.

$$0.1\ \mu{\rm m} \le \lambda \le 1\ {\rm mm}$$
$$\Delta \log\lambda = \Delta\log\nu = 0.1$$

Opacity: Draine (2003) Interstellar

3. Results

Equilibrium Model

M_* = 2.2 M_o, R_* = 3.8 Ro, $T_{\rm eff}$ = 6250 K, r = 100AU

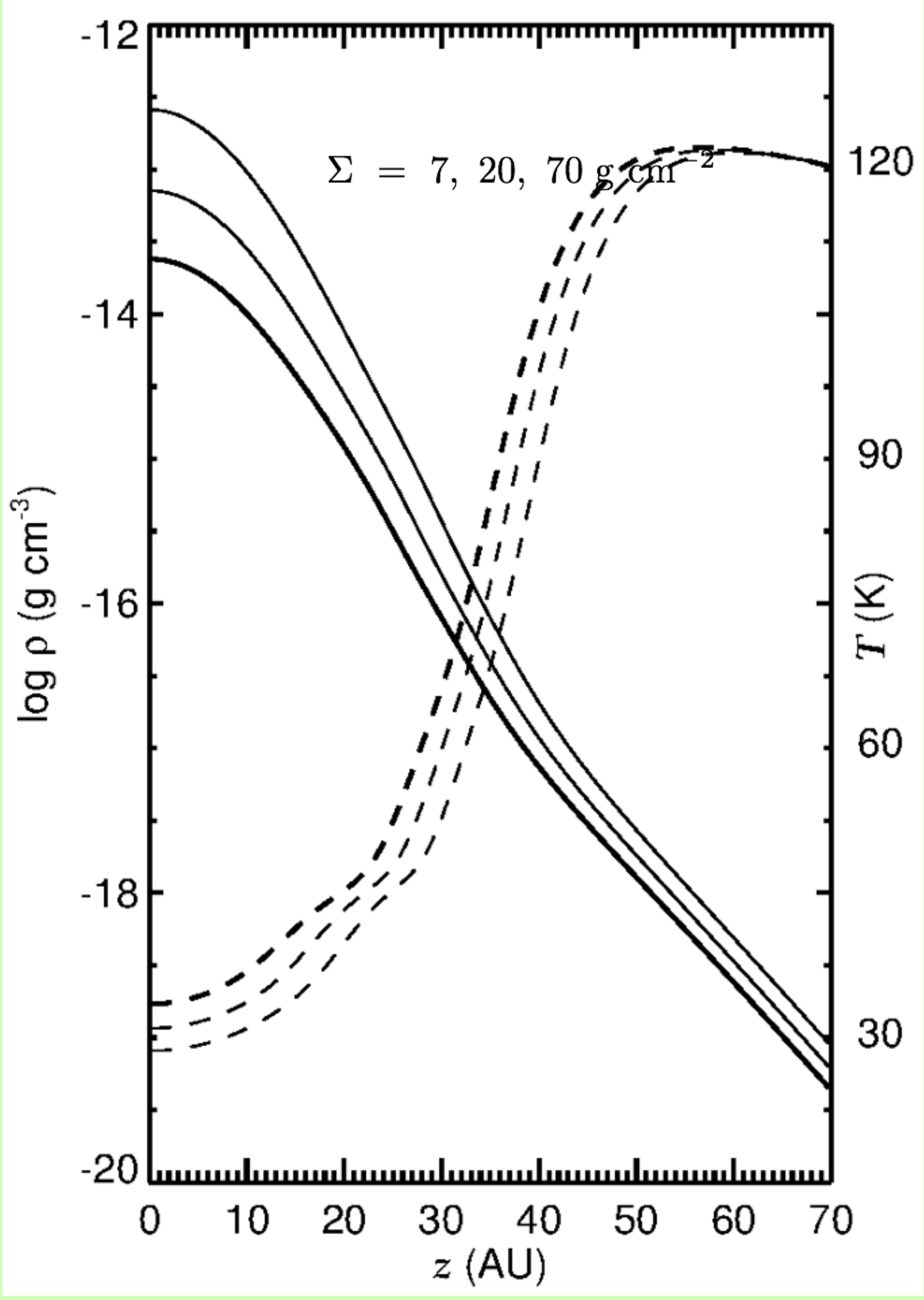


Fig. 1. The solid and temperature in the equilibrium, respectively.

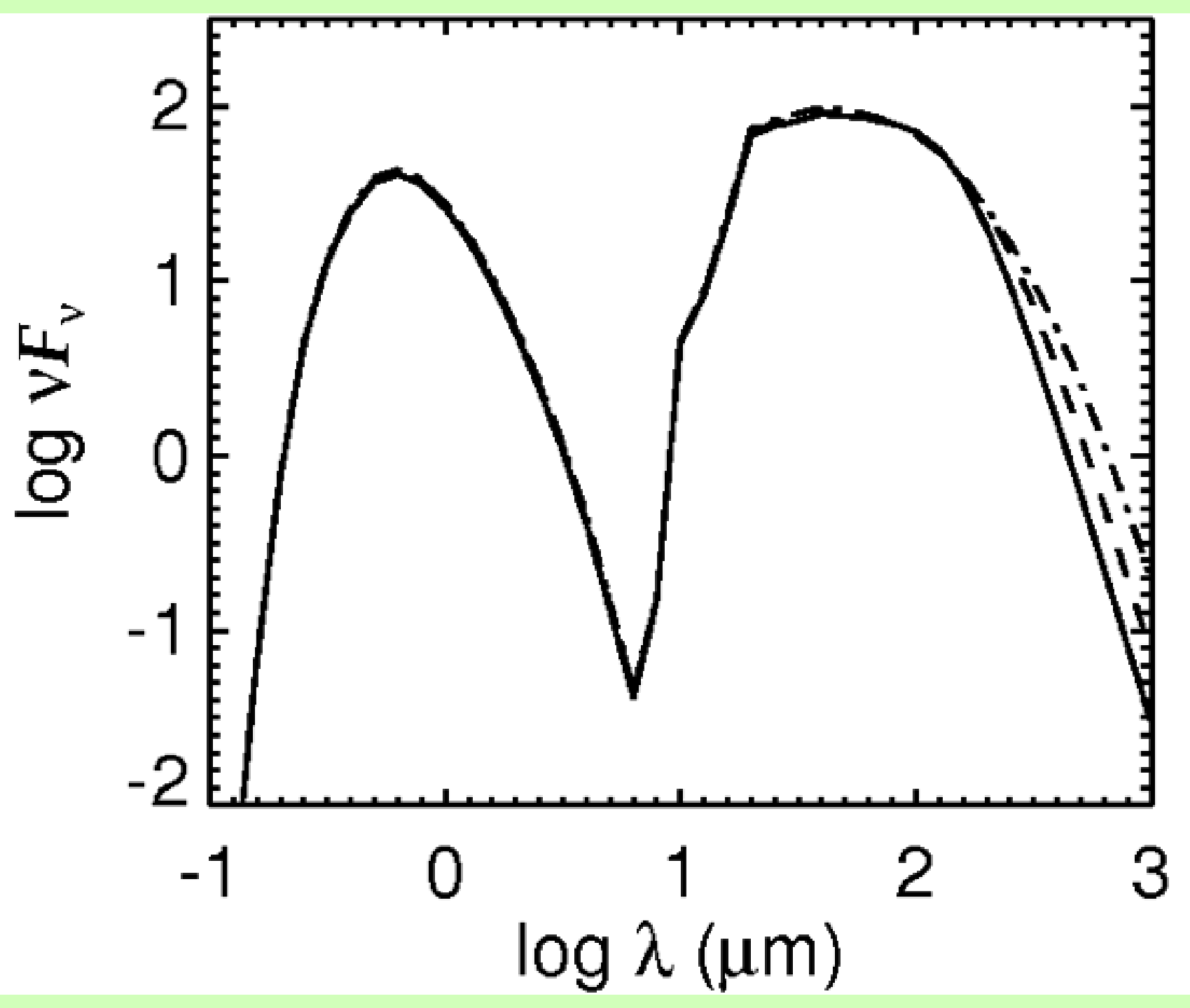


Fig. 2. SED model for the equilibrium, shown in Fig. 1. The solid is for Σ = 7 g cm^{-2}. The dashed and dash-dotted are for Σ = 20 and 70 g cm^{-2}, respectively

The equilibrium models are overstable. Fig. 3 shows the evolution in the density and temperature in the model starting from the equilibrium of Σ = 7 g cm^{-2}.

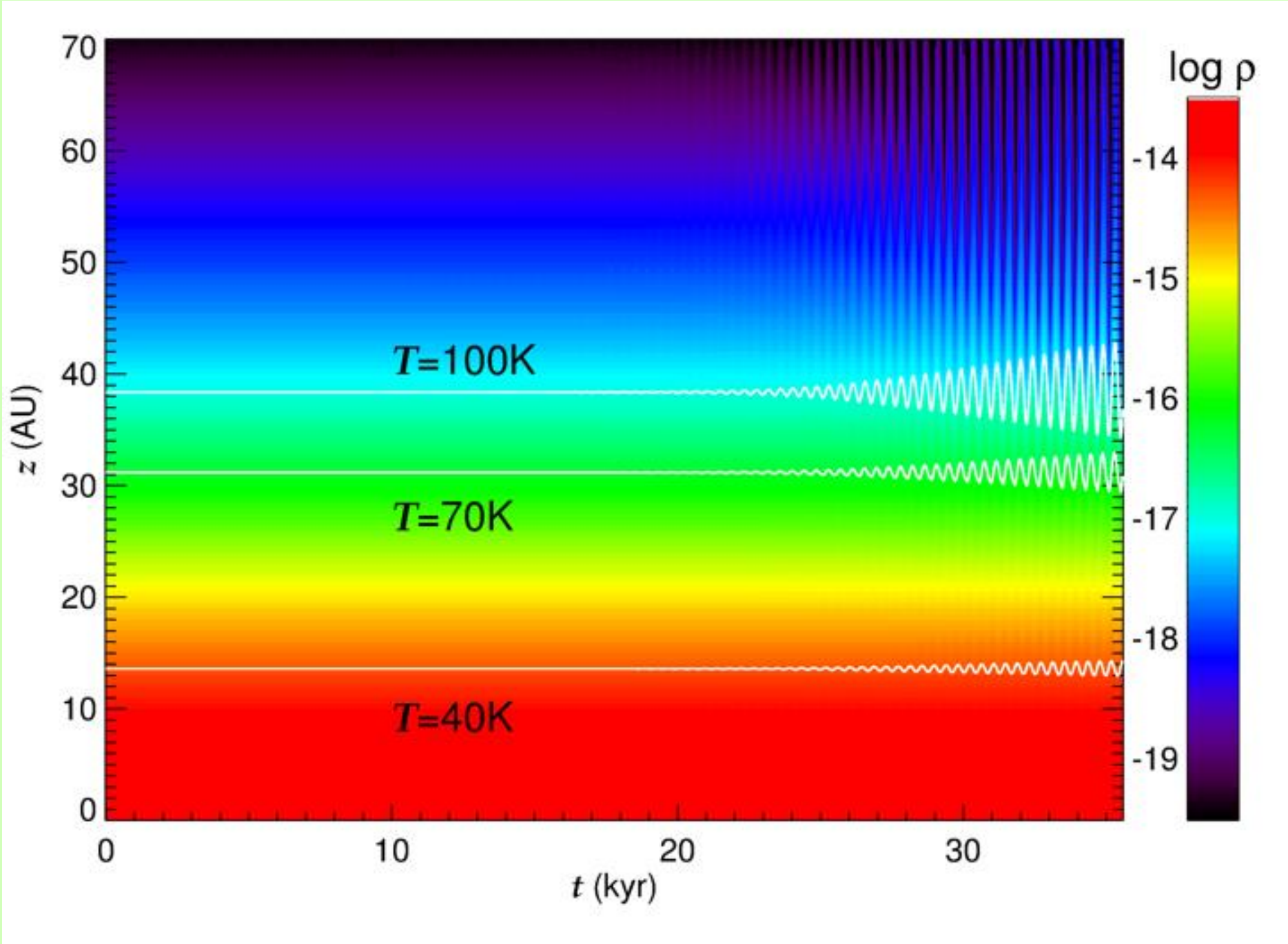


Fig. 3. Color denotes the density as a function of t and z. The white lines are the contours of T = 40, 70 and 100 K.

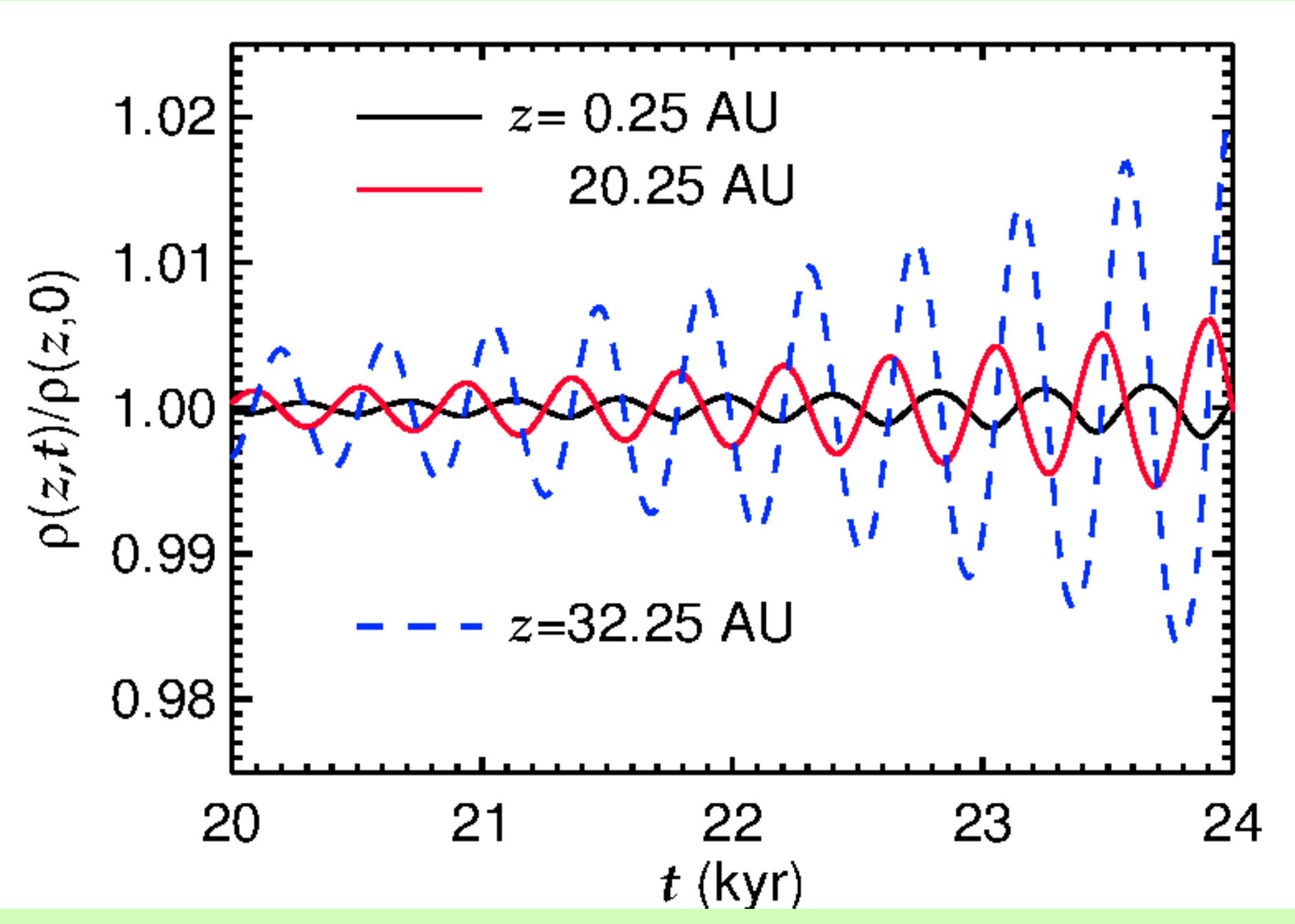
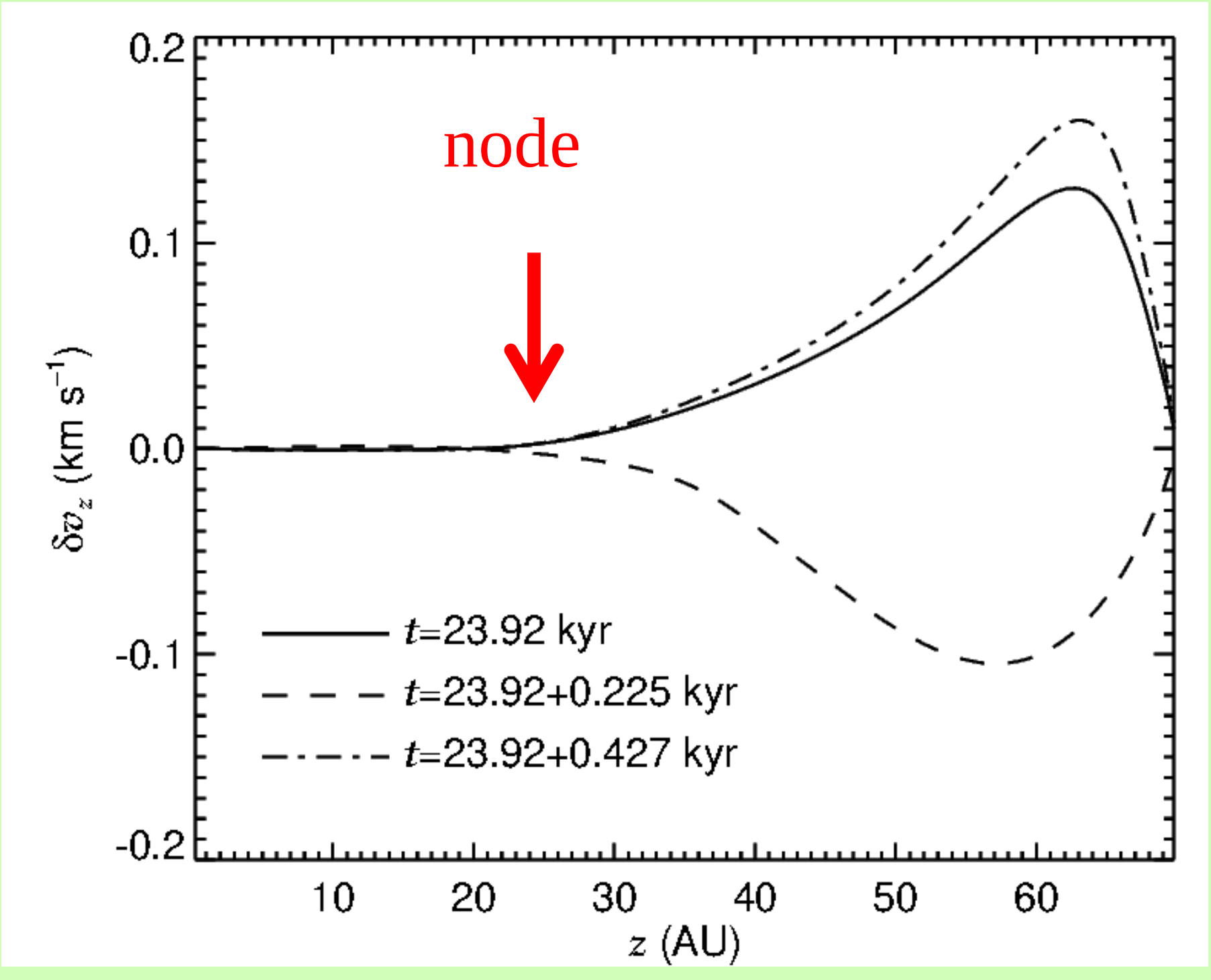


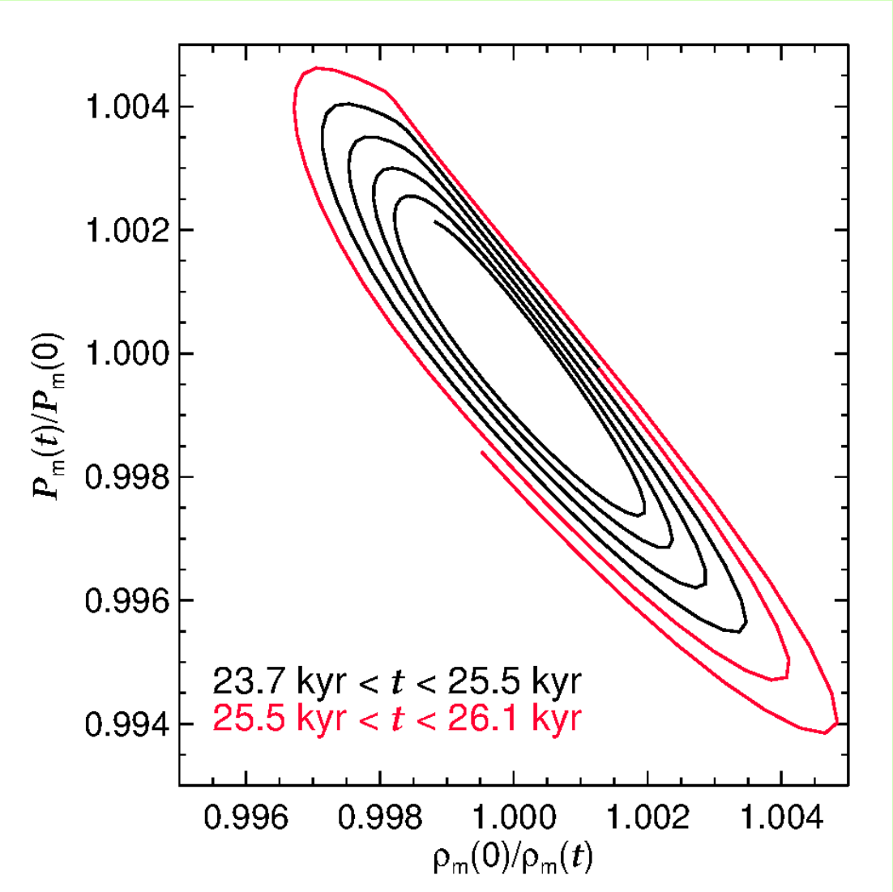
Fig. 4. The density variation at several heights in the early phase in the model of Σ = 7 g cm^{-2}.

Hot surface layer expands while cold disk main body is compressed (Fig. 5).



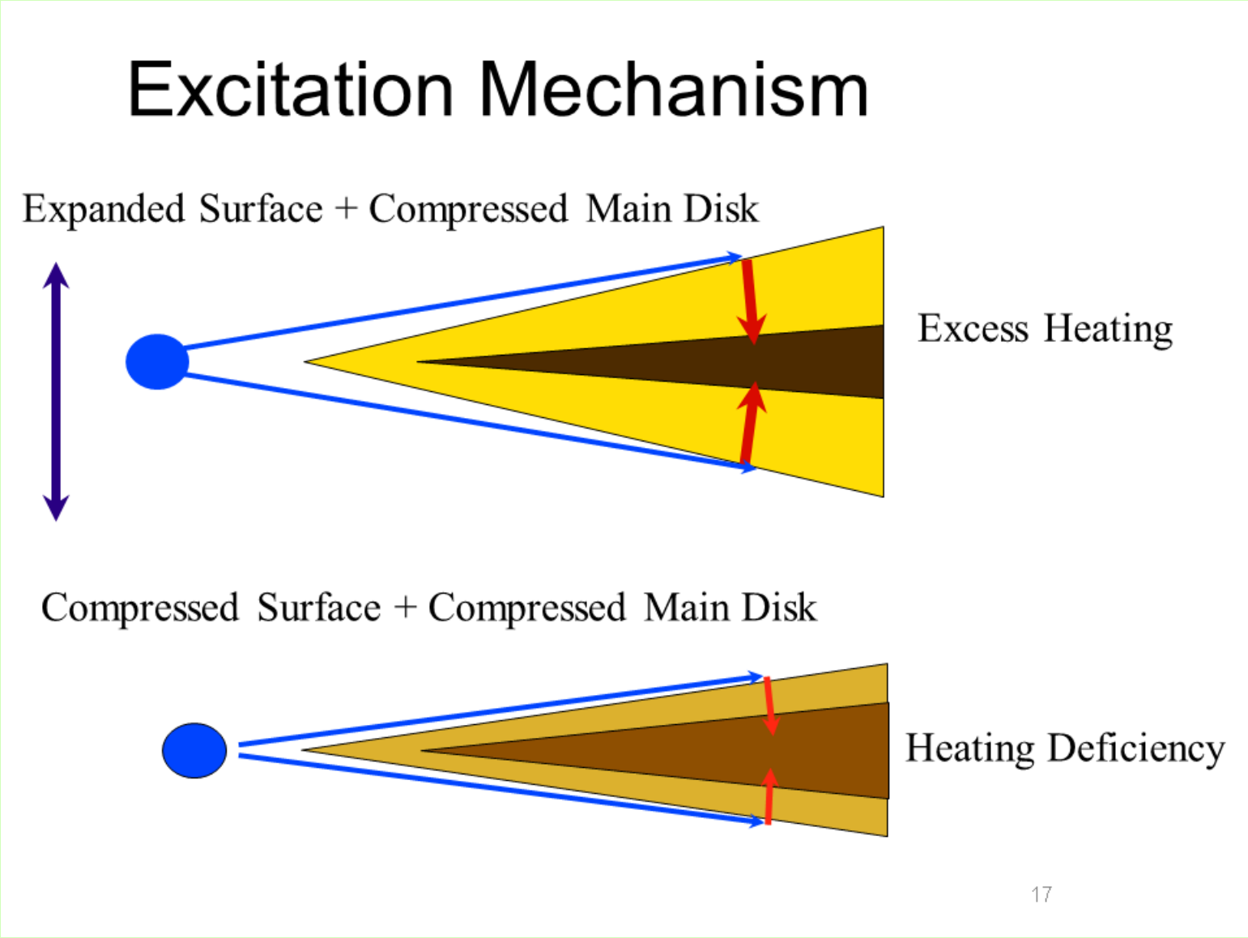
Fgi.5 The velocity oscillation in the early phase of the model of . Σ = 7 g cm^{-2}.

The disk has a higher pressure in the expansion phase than in the contraction (Fig. 6).. Thus, it is a heat engine to push the hot surface layers outwards.



$$\oint PdV > 0$$

Fgi.6. The motion of the gas element on the midplane in P-V plane.



Excitation Mechanism

Fig. 7. Schematic diagram for overstability.

Our model shows limit cycle oscillation in the late phase. As shown in Fig. 8, the high velocity suggests mass ejection. The variation in the brightness shown in Fig. 9 may be seen as bright arcs in the disk image.

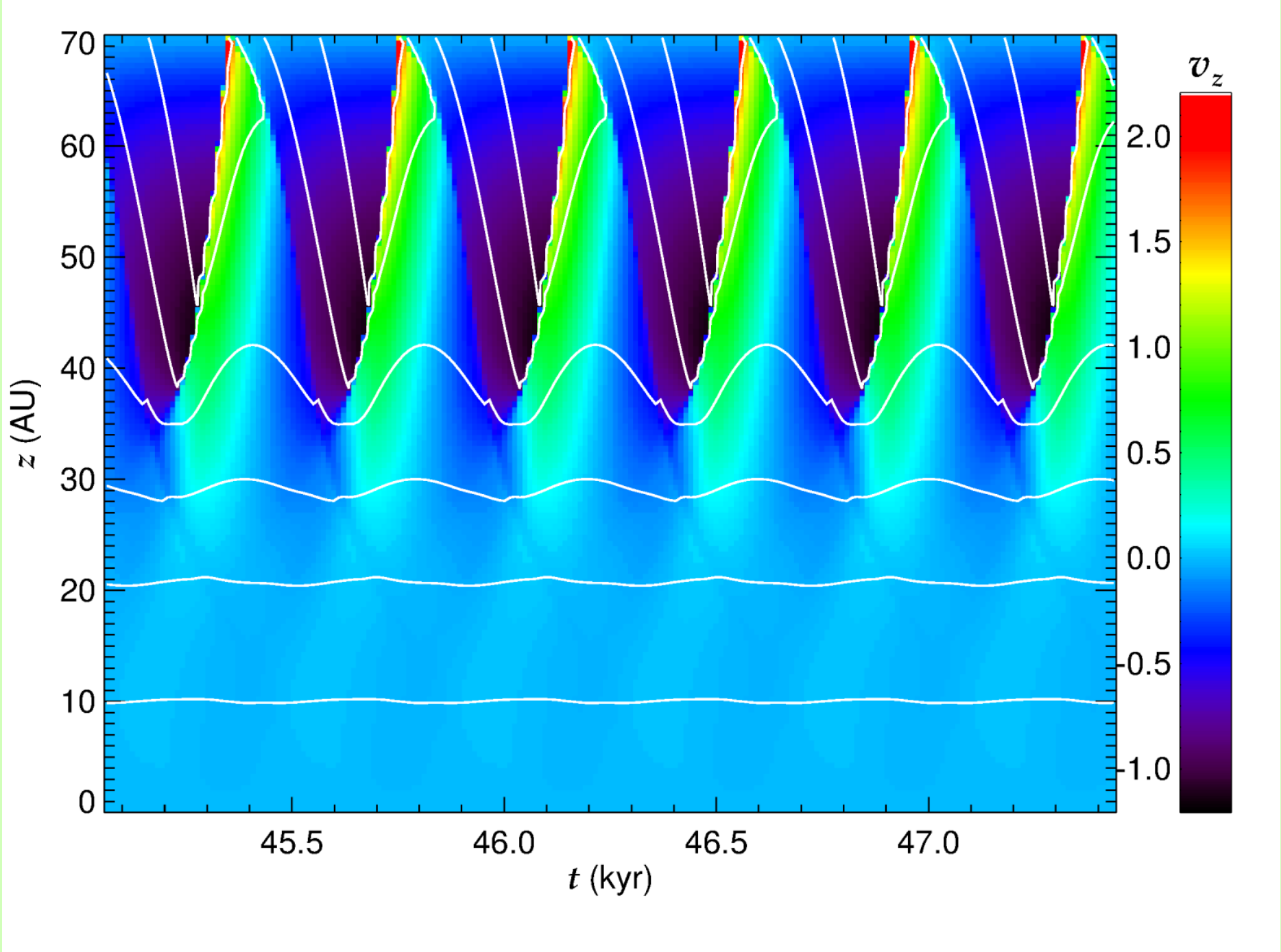


Fig. 8. Velocity evolution in the late phase of model of Σ = 7 g cm^{-2}..

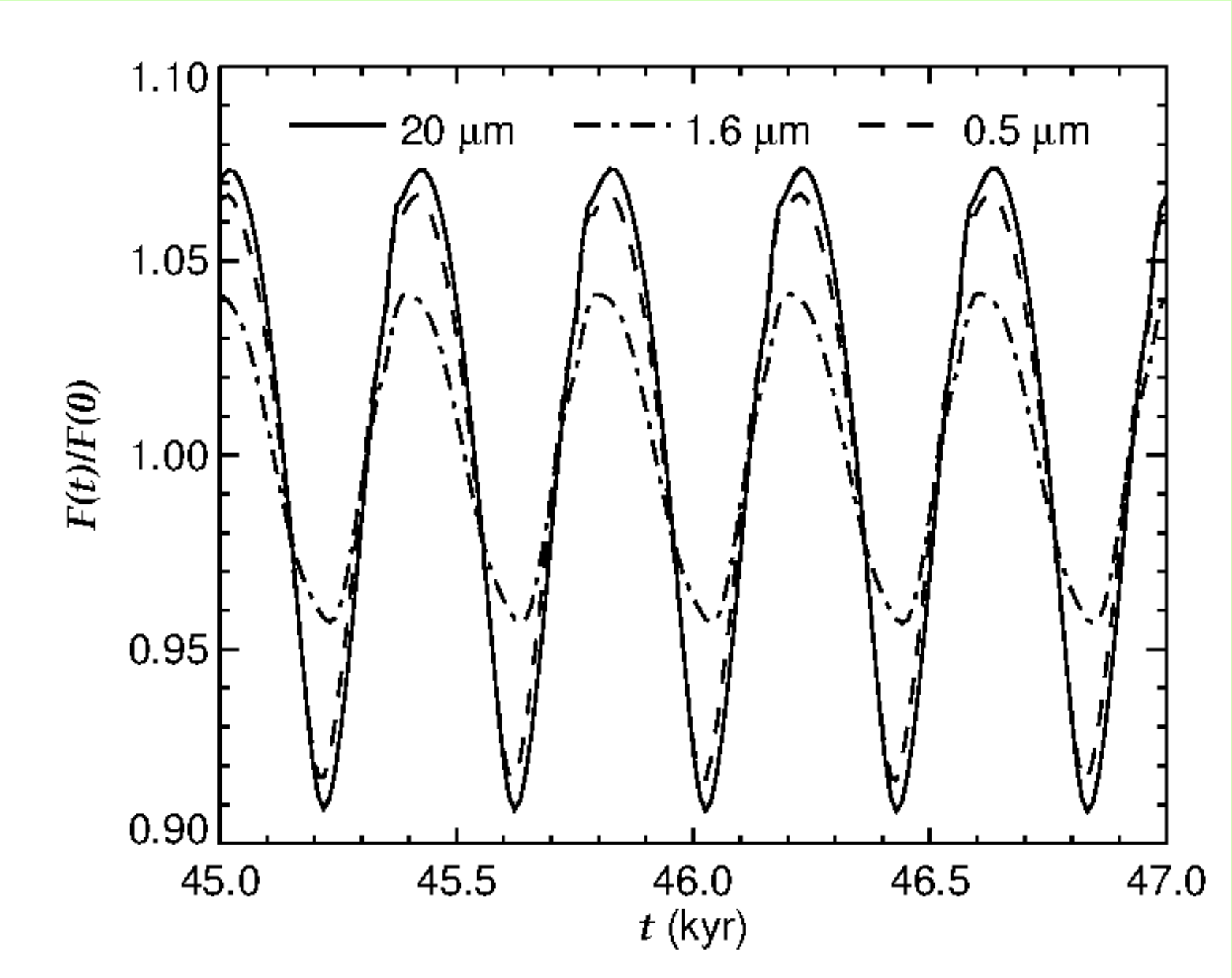


Fig. 9. Light curve for Σ = 7 g cm^{-2}.