Initial stages of circumstellar disc formation and following evolution. Physical model.

Valeriy Snytnikov
Olga Stoynovskaya

Novosibirsk, Russia
Boreskov Institute of Catalysis, SB RAS

MOLECULAR CLOUDS
Astrochemistry

Abundance of Elements in the Space

H, He, O, C, Ne, N, Mg, Si, Fe, S, Ar,…

I. ***H + He*** – **98%,**
Another elements – **1-2%,** *among them*

II. ***Organics*** (**H, O, C, N,**…) **> 90%**

III. ***Inorganics*** (**Mg, Si, Fe, O,** …) **< 10%**

H_2, He, H_2O, CH_4, Ne, NH_3, MgH_2, SiH_4, FeH, H_2S, Ar,…

H, O, C, N, S, … - ***elements for organic compounds syntheses***

H_2O, MgH_2, SiH_4, FeH,… – ***compounds for inorganic phase syntheses***

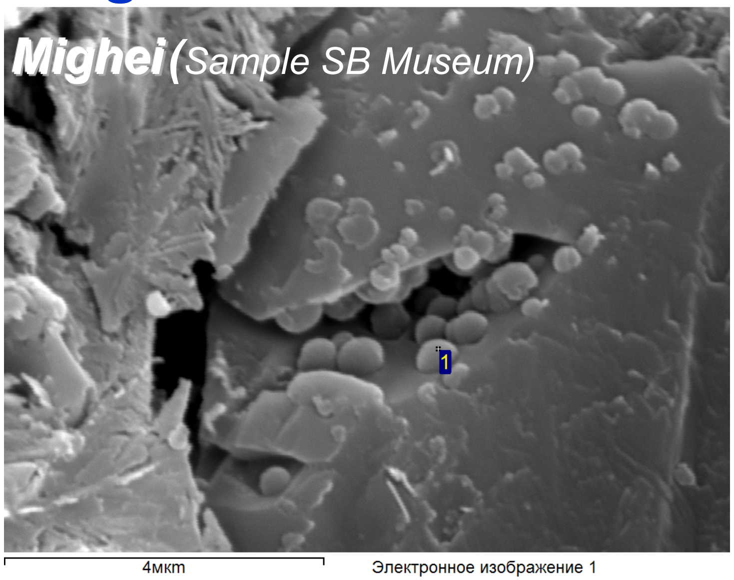
$MgH_2 + SiH_4 + FeH + H_2O$ --> $(Mg,Fe)_2SiO_4$ and $(Mg,Fe)_6Si_4O_{10}(OH)_8$

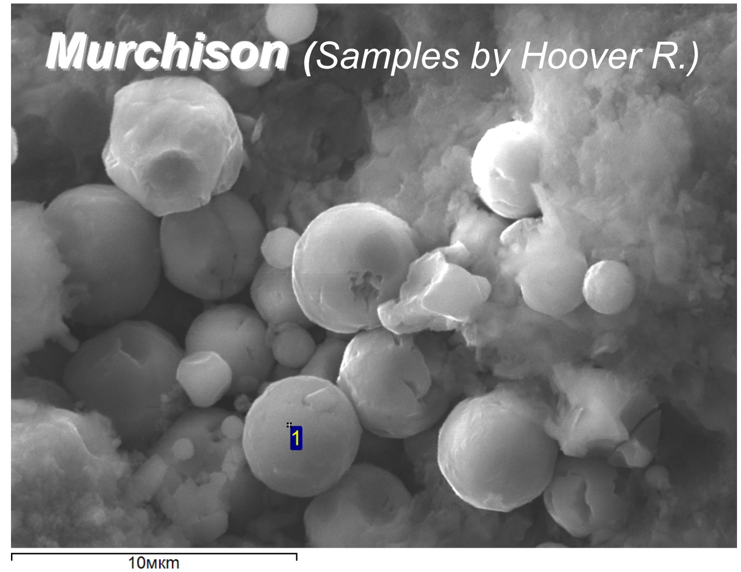
- Primary Clay (carbonaceous chondrites)

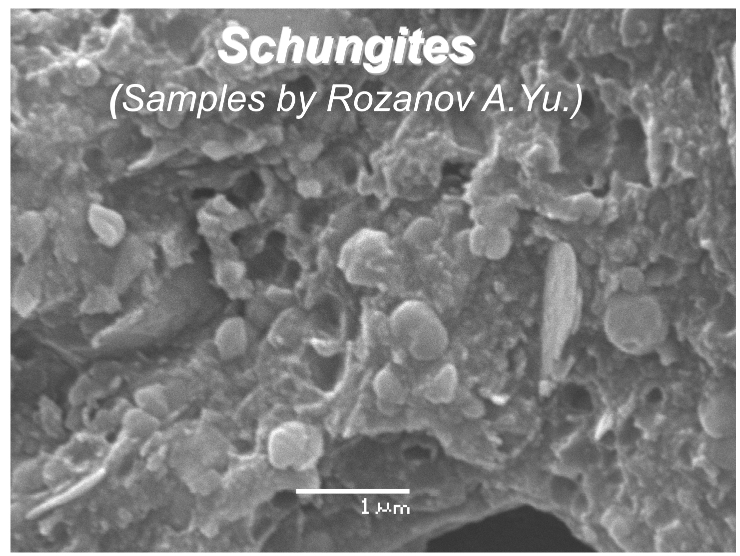
What is the function of the main organic compounds during star formation?

METEORITES

Indigenous Microfossils in Carbonaceous Chondrites CM



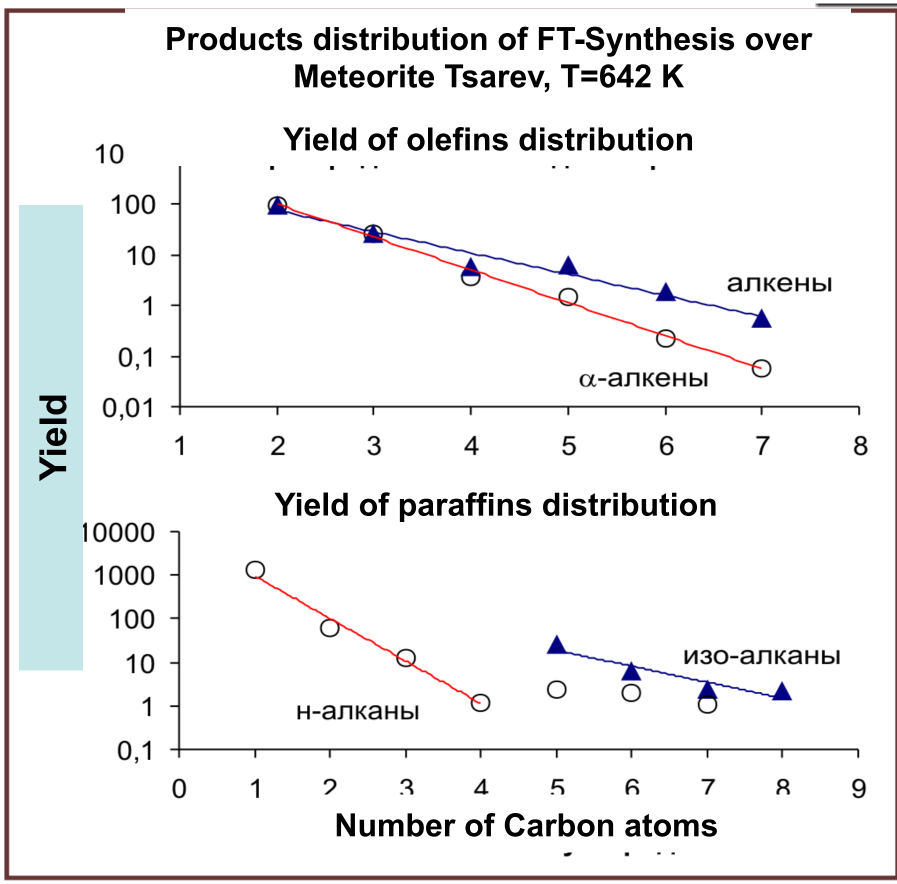




Scanning Electron Microscope, BIC SB RAS (Study by N.A. Rudina)

“FT” Synthesis -Slurry reactor and fixed bed reactor

$$CO + H_2 \rightarrow C_xH_y + H_2O$$



Catalytic active nanomaterials

	Meteorite Tsarev	Dolerit
SiO_2	40,6	41,6
TiO_2	0,12	1,04
Al_2O_3	2,5	12,2
Cr_2O_3	0,5	0,02
FeO_x	**14,0**	**25,3**
MnO	0,34	0,18
MgO	25,2	9,0
CaO	2,0	6,3
Na_2O	0,7	1,0
K_2O	0,10	0,47
P_2O_5	0,3	0,09
S	1,92	0,98
Fe (сулф.)	3,36	0
Fe^0	**6,51**	0
Ni	**1,08**	**0,17**
Co	**0,048**	0
Cu	0,013	0,13

Chemical reactions

Syntheses of active molecules (C_2H_4, NH_3, HCN, H_2O…)

$CO + H_2 \rightarrow H_2CO$ (gas discharge of low pressure)

$CO : H_2 = 1 : 8$, $H_2CO : CO = 7:100$ (plasma-chemical reactions) *Rusanov V.D., Fridman A.A., 1984*

$CO + H_2 \rightarrow H_2CO$ MgO, T<500-600K *Hattory H., Wang G.W., 1984*

$N_2 + 3H_2 \rightarrow 2NH_3$ Fe, Ni

$CO + NH_3 \rightarrow HCN + H_2O$

Reactions of polymerization with mass increasing

H_2O with organic matter, T< 800°C

$n(C_2H_4) \rightarrow (C_2H_4)_n$, Fe, UV

$n(HCN) \rightarrow (HCN)_n$

$n(H_2CO) \rightarrow (H_2CO)_n$, OH^-, Me^{2+} (Mg^{2+}, …)

……………………………………………………………………

CO/H_2 for molecular clouds not equal to CO/H_2 in discs!!!

Collision of two bodies

Collision of two Bodies with speed V1 and V2:

- V1-V2 < Cs (in solid body) aggregation or destruction
- V1-V2 > Cs (in solid body) only destruction

V1-V2 > Cs if about 1 collision on orbit

Size of bodies in massive disk were up to 1-10 meter due to organic matter

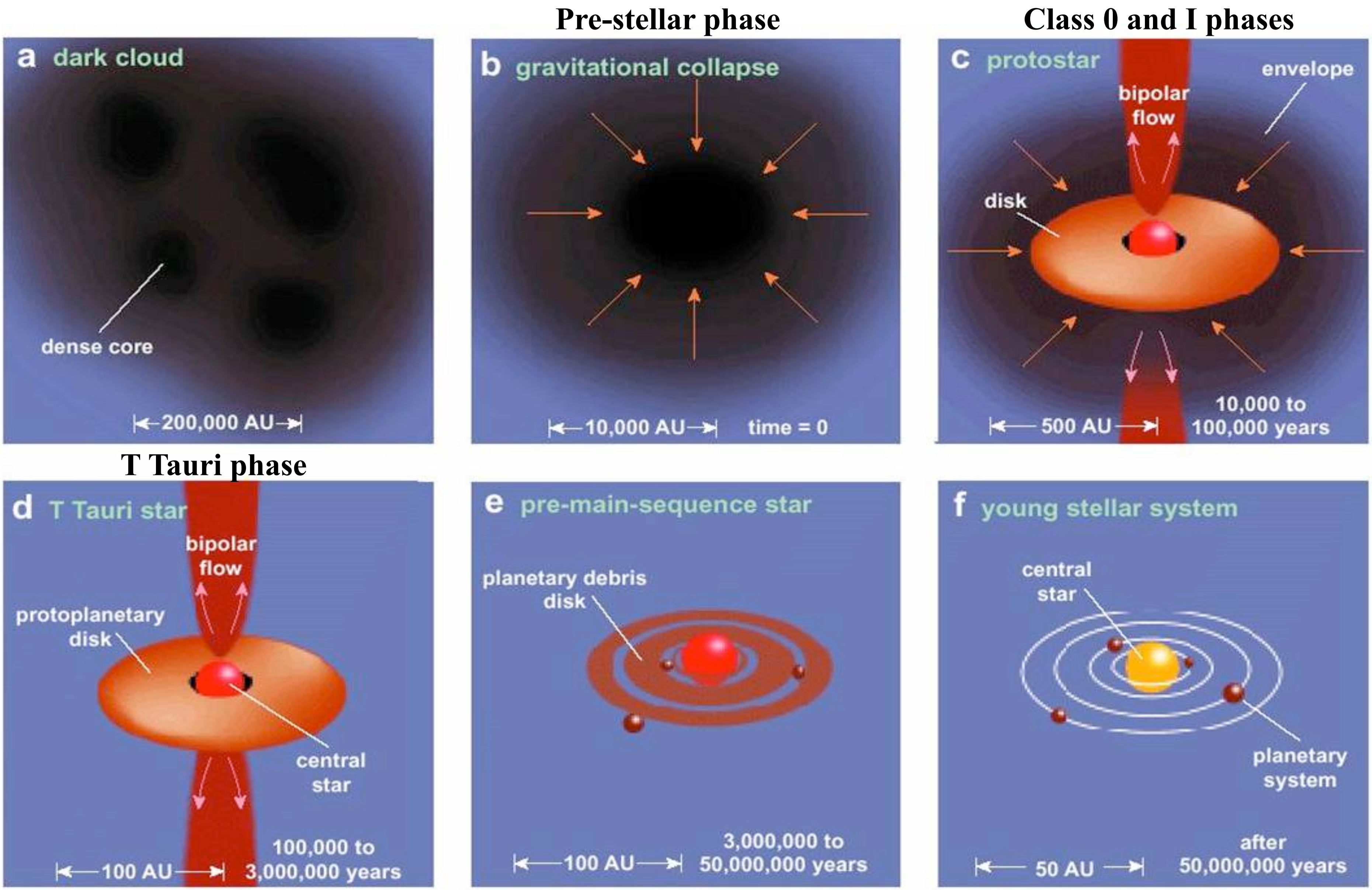
First conclusion

Disk:

- C and O (CO) is in the dust
- Ratio CO/ H_2 is less than 10^{-4}
- Observable disks can be **more massive** than they are ordinarily considered
- Primary bodies were plasticine type with part of inorganic matter
- Size of bodies appeared due to collisions were up to 1-10 meter

Slide from report Olga Zakhozhay

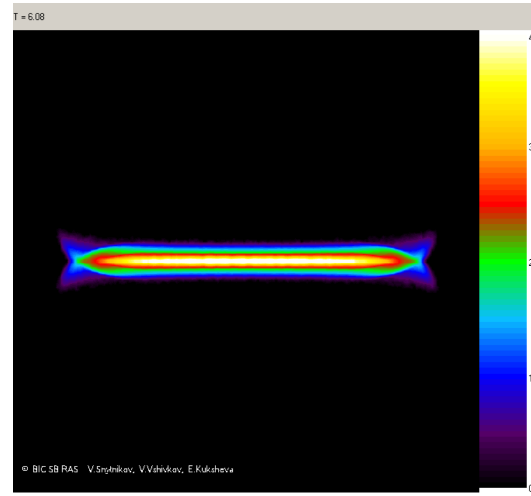
Main stages of protostellar disk evolution

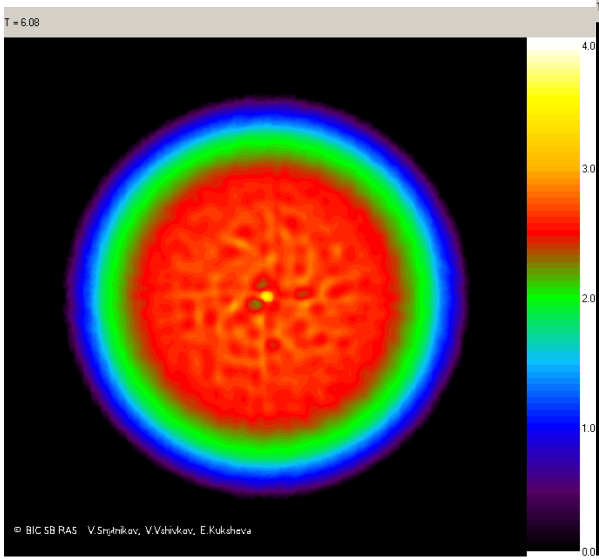


Gravitational dynamics of body in disk. Jeans instability

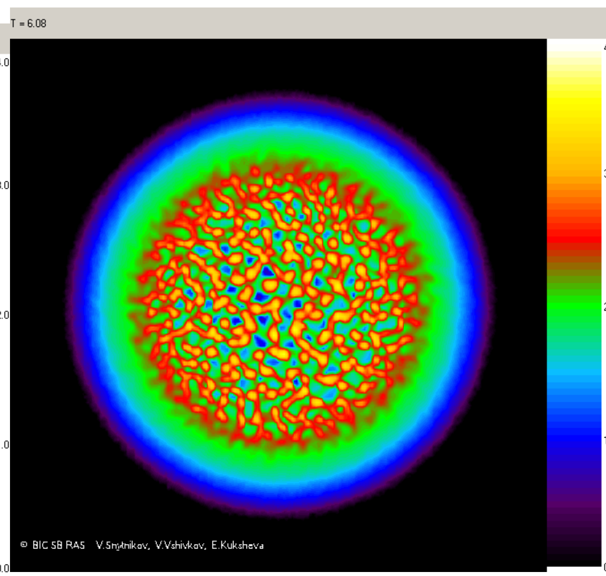
$$\frac{\partial f}{\partial t} + \vec{u}\frac{\partial f}{\partial \vec{r}} - \nabla\Phi\frac{\partial f}{\partial \vec{u}} = 0$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\partial \Phi}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 \Phi}{\partial \varphi^2} + \frac{\partial^2 \Phi}{\partial z^2} = 4\pi G\rho$$

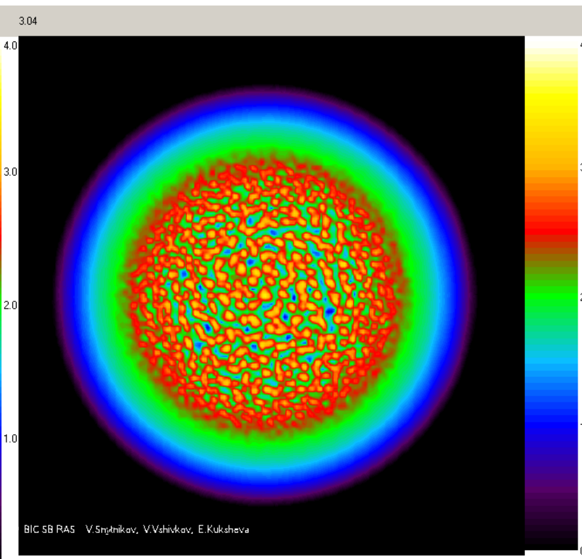




Mesh 128^3
Number of particles 10^8



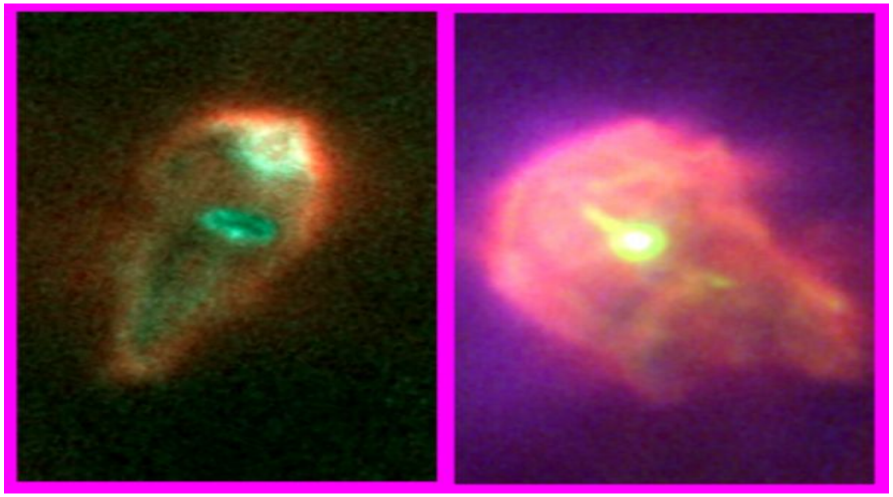
Mesh 256^3
Number of particles 10^8



Mesh 1024^2x 256
Number of particles 10^9

STAR and DISK FORMATION

Observations



Lengths:

Radius of Stars ↔ 10000 AU

Times:

Years ↔ Millions Years

H_2 + He ***are the matter for the stars.***

3D Computer simulation

Gravitational Gas Dynamics

$$\frac{\partial \rho}{\partial t} + div\left(\rho \vec{v}\right) = 0$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \rho\left(\vec{v}\,\vec{\nabla}\right)\vec{v} = -grad\left(p\right) - \rho\, grad\Phi$$

$$\frac{\partial \rho E}{\partial t} + div\left(\rho E \bar{v}\right) = -div\left(p \bar{v}\right) - \left(\rho\, grad\Phi, \bar{v}\right)$$

$$\Delta\Phi = 4\pi\rho$$

$$p = \left(\gamma - 1\right)\rho\varepsilon$$

Collapse

$$\gamma < 4/3 \text{ - collapse}, \ \gamma > 4/3 \text{ - stability}$$

New structures formation (star formation, protostellar disks, double-stars with circumstellar disks,)

Stationary bodies (spherically symmetric bodies, disks, torus…)

Gas bodies stability

Stationary body - nonuniform isothermal gas

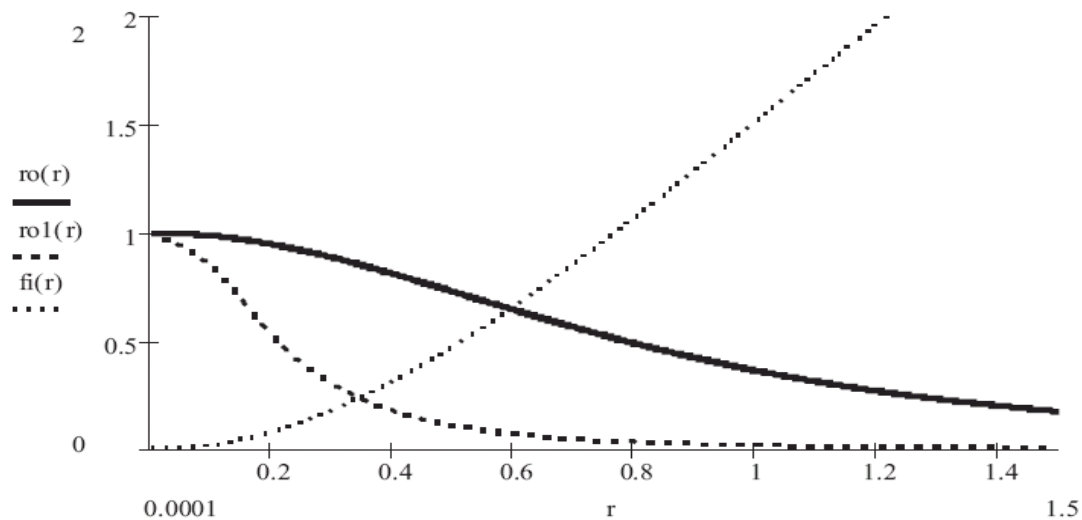
Is it stable?

Bonnor-Ebert sphere

Dimensionless parameters:
G, L, ρ_0

$$r\frac{\partial^2\rho}{\partial r^2} + 2\frac{\partial\rho}{\partial r} - \frac{r}{\rho}\left(\frac{\partial\rho}{\partial r}\right)^2 + \frac{4\pi r\rho^2}{T} = 0$$

$$\rho\Big|_{r=0} = 1, \qquad \frac{\partial\rho}{\partial r}\Big|_{r=0} = 0$$



Distribution of density $\rho_0(r)$-(solid line) and potential $\phi_0(r)$ (dot line) under $T = 1.5$ and $\rho_0(r)$ under $T = 0.11$-(dash line).

Linear variance analysis

System, linearized regarding to stationary solution

$$\rho_0(x), \quad \phi_0(x) \quad \rho_0' = \frac{\partial \rho_0}{\partial x} \qquad \tilde{F}(x,t) = \tilde{F}_0 e^{i(\omega t - kx)}$$

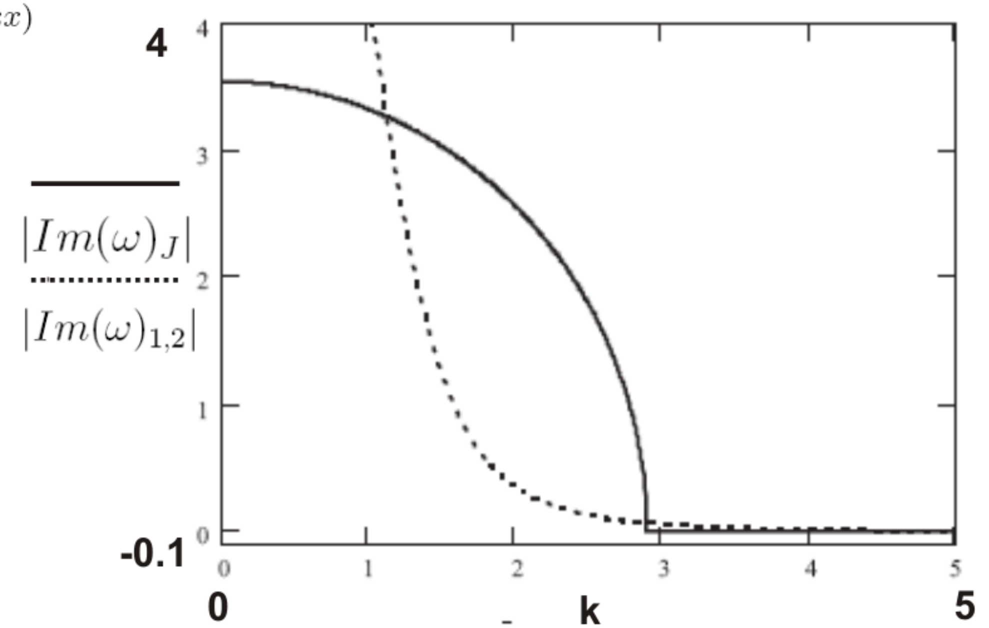
$$\frac{\partial \tilde{\rho}}{\partial t} + \frac{\partial \rho_0 \tilde{v}_x}{\partial x} = 0,$$

$$\rho_0 \frac{\partial \tilde{v}_x}{\partial t} + T\frac{\partial \tilde{\rho}}{\partial x} + \tilde{\rho}\frac{\partial \phi_0}{\partial x} + \rho_0 \frac{\partial \tilde{\phi}}{\partial x} = 0,$$

$$\frac{\partial^2 \tilde{\phi}}{\partial x^2} = 4\pi\tilde{\rho}.$$

Dispersion relation

$$\omega^2 = Tk^2 - 4\pi\rho_0 + \frac{T(\rho_0')^2}{\rho_0^2} - i4\pi\frac{\rho_0'}{k}$$



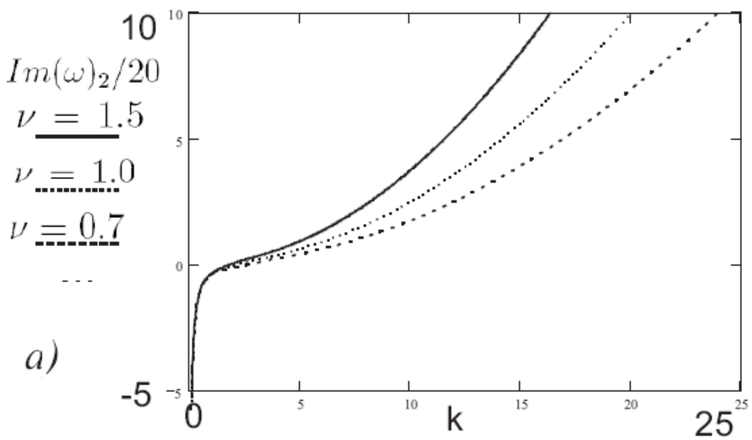
Conclusion: Nonuniform gravitational gas distributions is **unstable!**

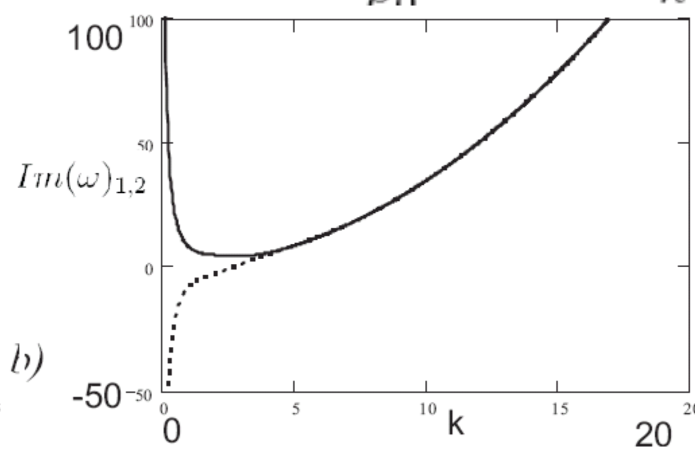
Snytnikov V…Astronomy Letter, 2011

Model of viscous isothermal gas

$$\frac{\partial \rho \vec{v}}{\partial t} + \left(\vec{v} \cdot \vec{\nabla}\right) \rho \vec{v} = -T grad\left(\rho\right) - \rho grad \phi + \rho \nu \Delta \vec{v},$$

Dispersion relation $$\omega^2 = Tk^2 - 4\pi\rho_0 + \frac{T(\rho_0')^2}{\rho_0^2} - i4\pi\frac{\rho_0'}{k} + i\omega\nu k^2$$



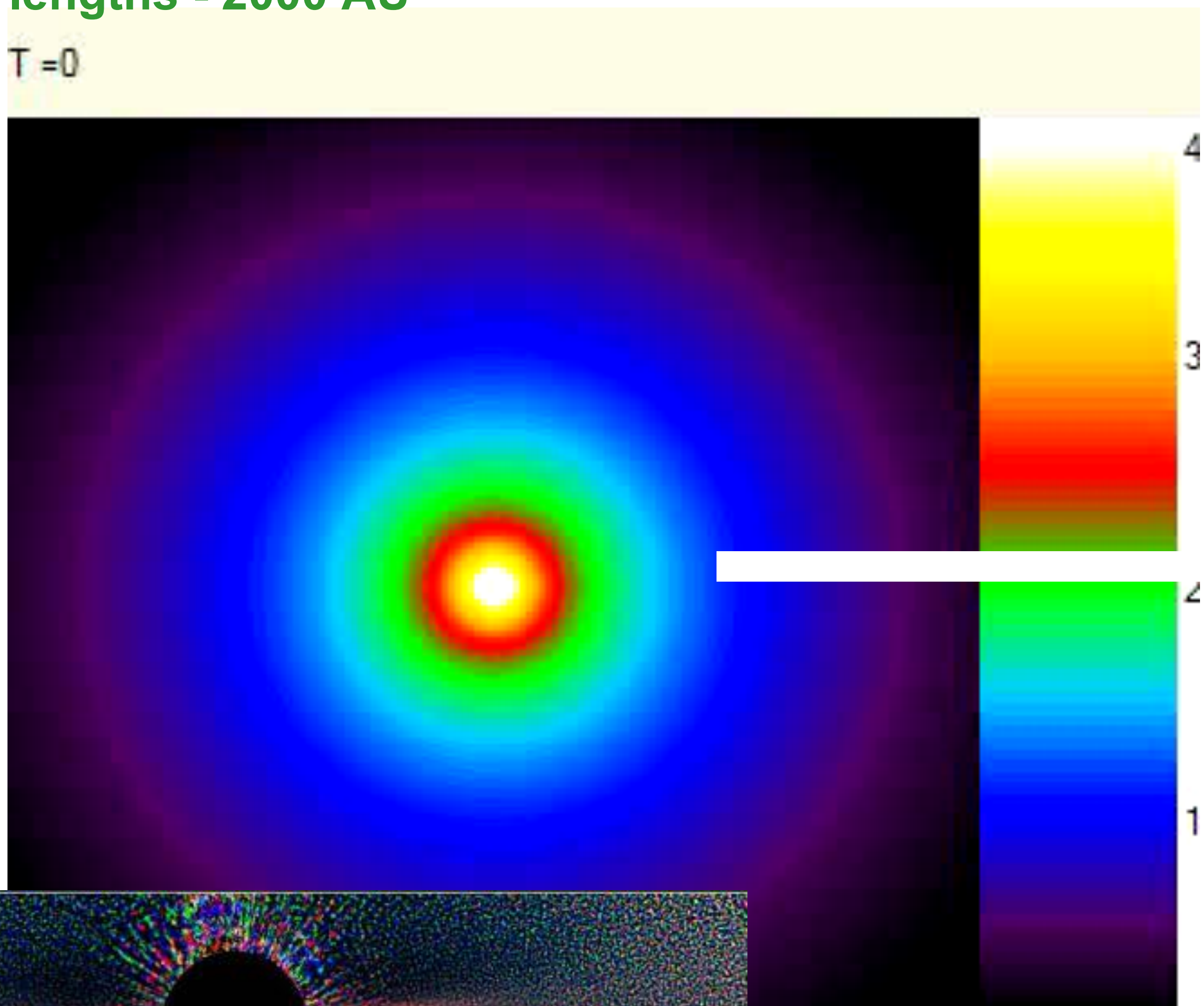


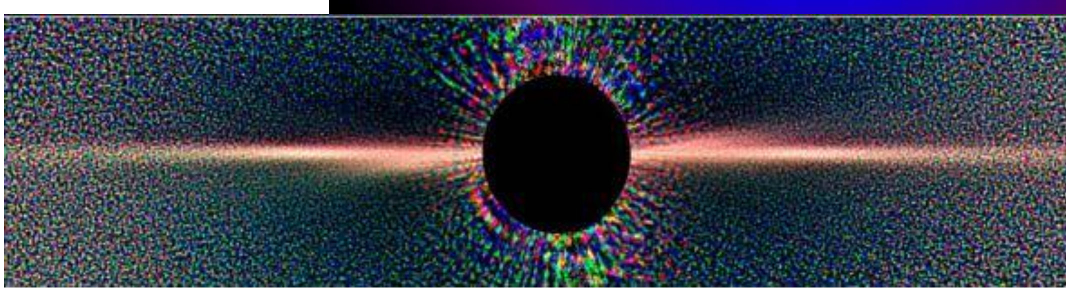
a) Dependence $Im(\omega)_2/20$ on wavenumber k under different values of viscosity coefficients ν. Solid line - under $\nu = 1.5$, dash line - under $\nu = 1.0$, dash-dot - under $\nu = 0.7$, $|\rho_0'| \approx 0.84$ - maximum value of derivative under $T = 1.5$; b) Dependence $Im(\omega)_1$ (solid line) and $Im(\omega)_2$ (dot line) on wavenumber k under $\nu = 0.7$.

Long-waves are unstable!

DISK

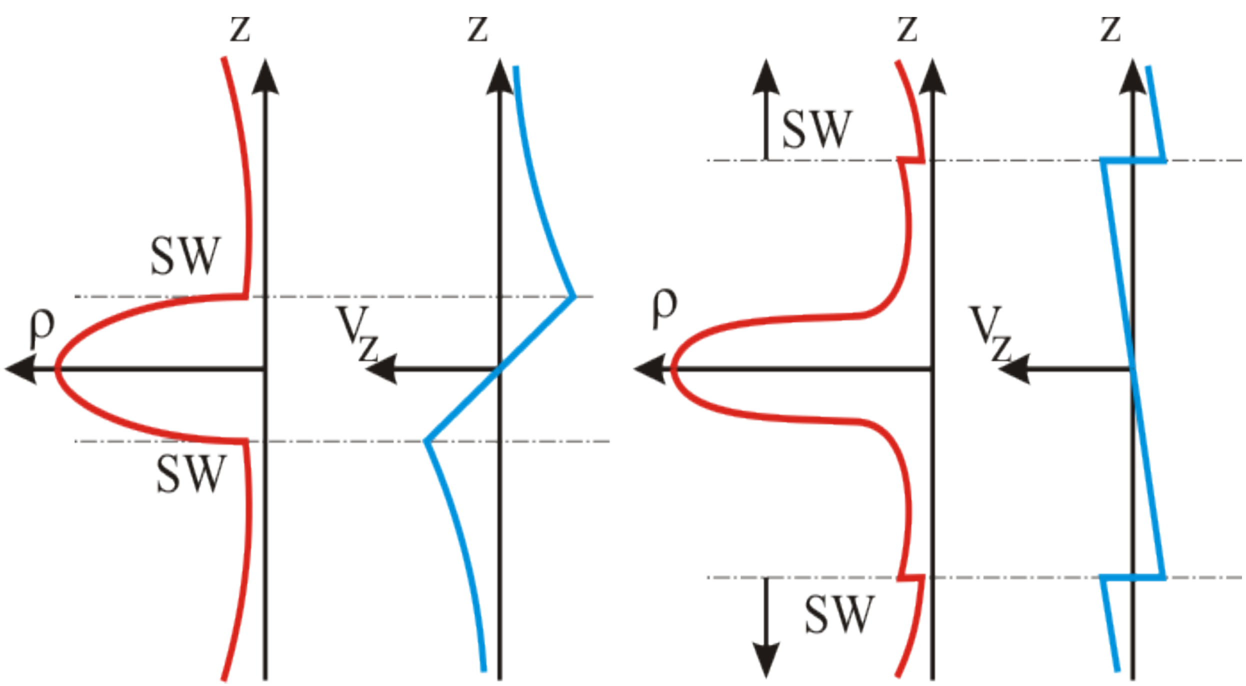
Density in meridional plane
Axial lengths - 2000 AU





Disk of Beta-Pictures, Hubble Telescope

Formation of massive gas-dust disc by the collision of the opposing streams during the molecular cloud collapse

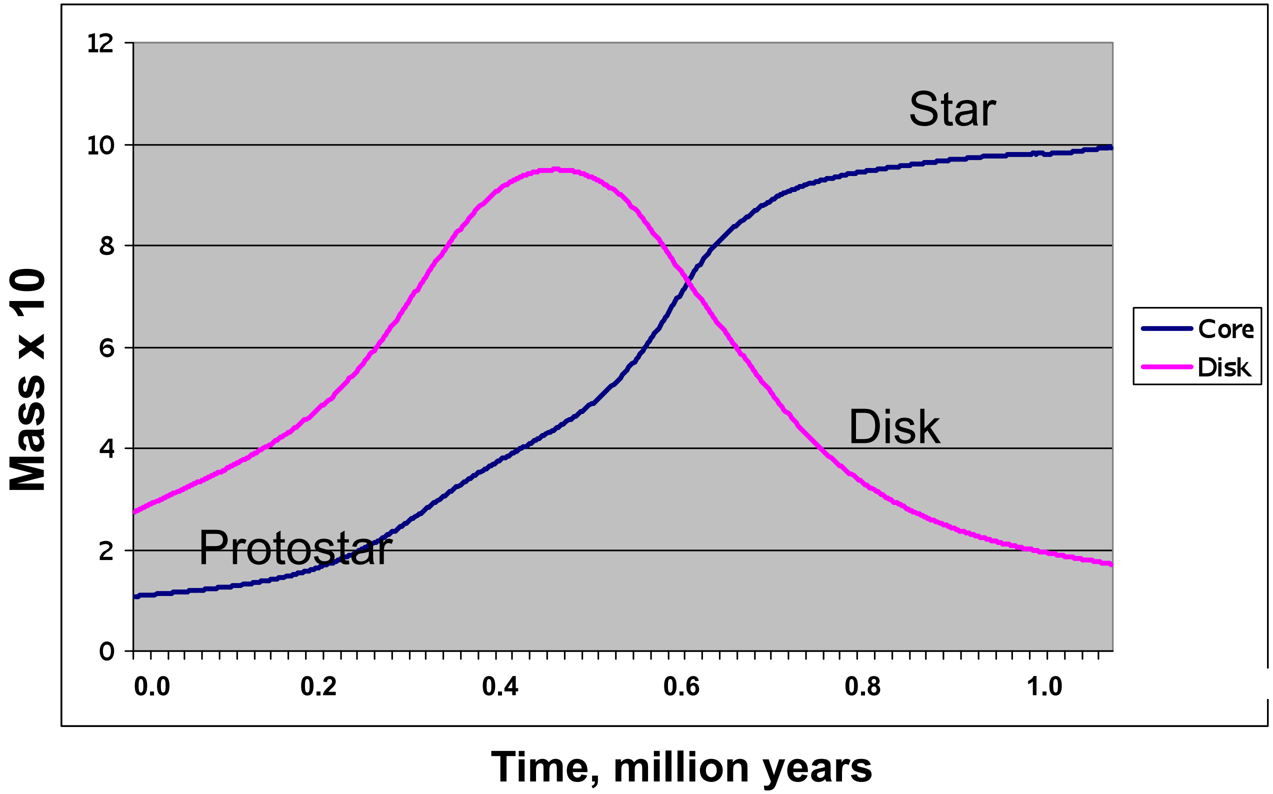


Ratio dust/gas > 0.02

Temperature in massive disk – firstly increases then falls

Formation of the bodies of organic composition with radius up to 1- 10 m

Protostar’s and its disk mass change Times about 1 Million Years



Toomre and Jeans gravitational instability for multi-phase system.

Jeans length for continuum and collision-less medium in "plane" assumption

$\Lambda_{gas} = T_{gas}/G\ \mu\ \sigma_{gas}$

$\Lambda_{par} = T_{par}/G\ m\ \sigma_{par}$

Jeans length for hybrid system – nonlinear combination

$$\frac{1}{\Lambda} = \frac{1}{\Lambda_{gas}} + \frac{1}{\Lambda_{par}}.$$

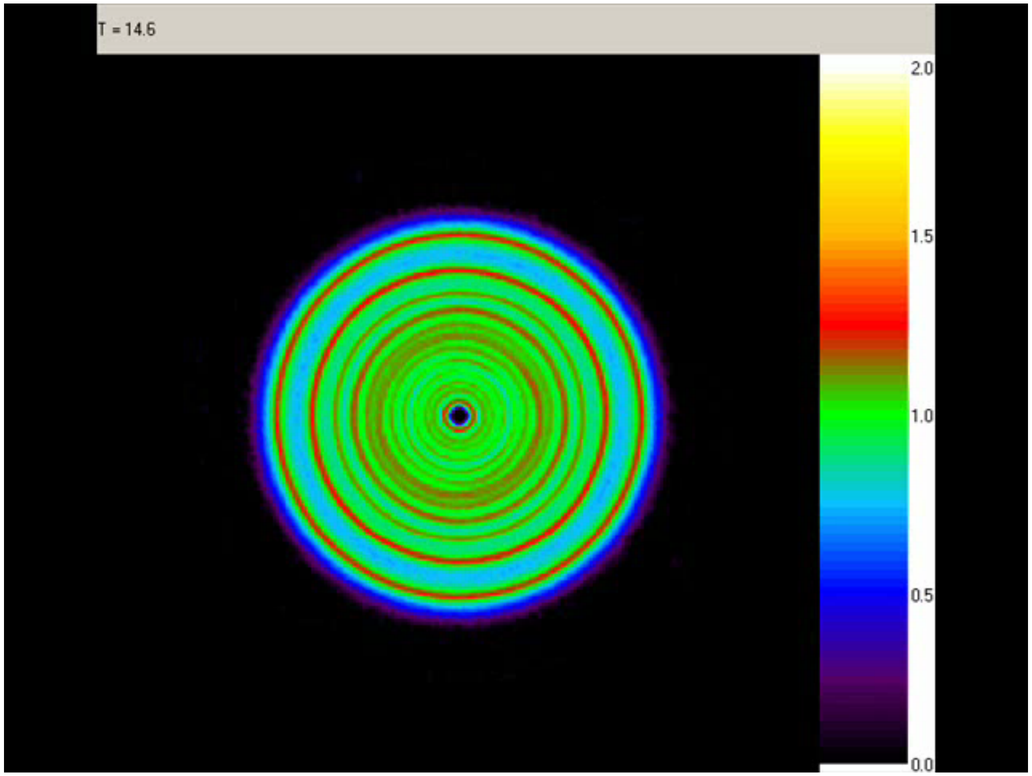
For $T_{gas} = T_{par}$ and

m increasing Λ_{par} decreasing !!!

$$Q = \sqrt{\frac{\Lambda_{par}\Lambda_{gas}}{\Lambda_{gas}+\Lambda_{par}} \frac{\Omega^2}{G(\sigma_{gas}+\sigma_{par})}}.$$

Snytnikov, Stoyanovskaya, MNRAS 2012 ,accepted

SUBDISK
RNA World



Gravitational instability
(O. Stoyanovskaya report)
Time of the Clump was 1-10 years
RNA World was during 1 Million Years

Creation of primary bodies with size about 1 and more kilometers

Catalysts and organics compounds

Drastic change of physical and chemical conditions

RNA world

Ancient RNA world was a precursor of the Life on the Earth

Ribonucleic acids are capable to perform all basic functions characteristic of both DNA and proteins.

Inelastic collisions modeling

$$\frac{\partial f(m_1,t)}{\partial t} = \frac{1}{2}\int_0^{m_1} \Phi(m_1 - m, m) f(m_1 - m, t) dm - f(m_1,t)\int_0^{\infty} \Phi(m_1, m) f(m,t) dm,$$

For $0 \leq m_1, m \leq \infty$, $t > 0$

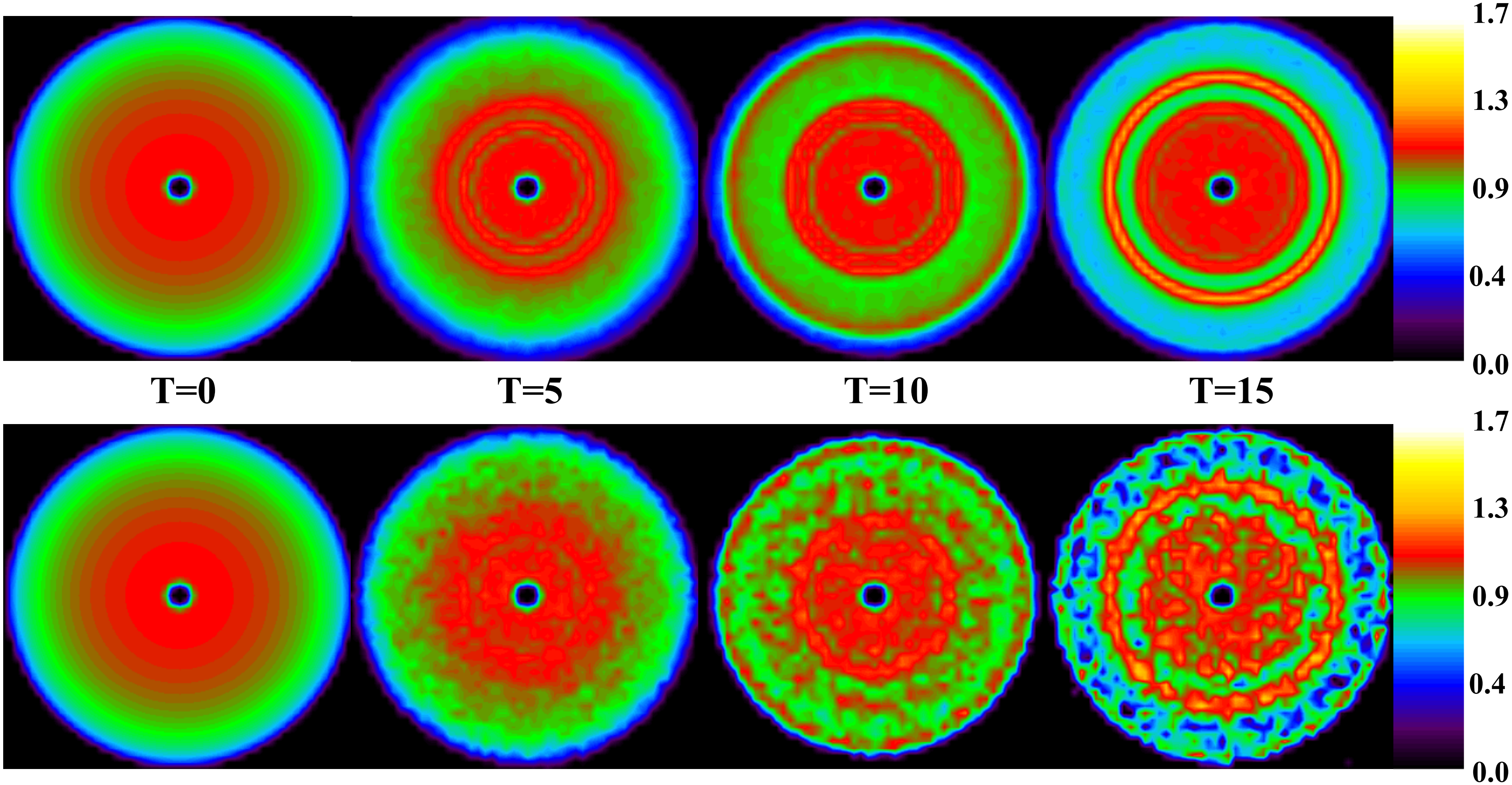
$$\tau_k \approx \frac{2}{K_0 N}$$ – dynamical time for collision

$$P = \tau_k(N) N \Phi(m_i, m_j), P < 1$$

Parameters of new body formed due to inelastic pair collision

$$\begin{cases} m = m_1 + m_2 \\ r = \dfrac{m_1}{m} r_1 + \dfrac{m_2}{m} r_2 \\ u = \dfrac{m_1}{m} u_1 + \dfrac{m_2}{m} u_2 \\ \dfrac{m_1 |u_1|^2}{2} + \dfrac{m_2 |u_2|^2}{2} = \dfrac{m |u|^2}{2} + Q \end{cases}$$

Decreasing of Λ_{par} due to inelastic collisions of solids



Logarithm of the solids surface density in the disc.
Top line – without inelastic collisions of bodies,
second line – taking into account inelastic collisions.
1 rotation = 5 in dimensionless time unit.

$$\Phi_0 = V_0^2 = \frac{GM_0}{R_0} \quad \tau = \frac{R_0}{V_0} \quad c_s \approx V_0$$

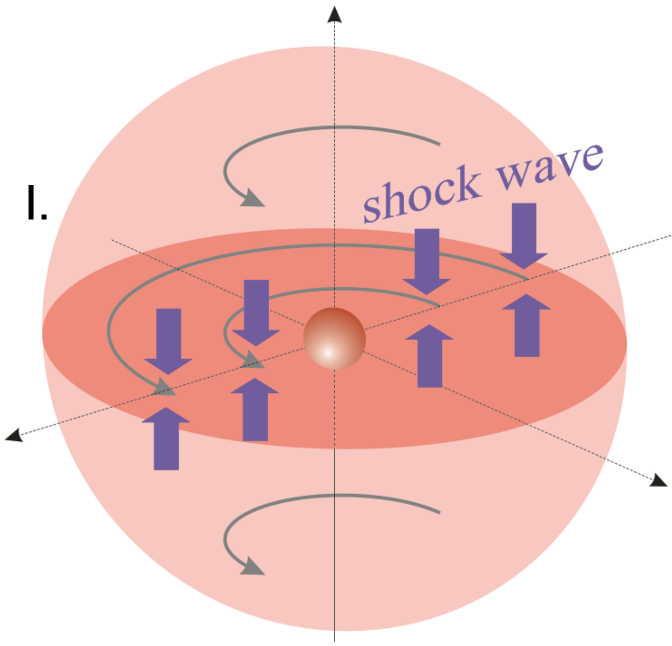
Main Stages

Stages	Duration From the beginning To the end	Physical Stages
I	- 0.1 million years	Protostar > 0.08 M_{sun} Formation
II	0.1 million years – 1 million years	Massive disc > 0.1 and < 1 M_{sun}.
III	0.4 million years– 1.2 million years	Subdisc of condensed matter Gravity unsteady disc
IV observation	1 million years- 10 million years	Star ≈ 1.0 M_{sun} . Medium-massive disc < 0.1 M_{sun}
V observation	5 million years- 60 (100) million years	Protoplanetary disc ≈ 0.001 M_{sun}
Geological unrecorded time	100 million years- 600 million years	Planets. End of bombardment
Geologically recorded time	600 million years- 4 560 million years	Oxidizing atmosphere, oceans, sediments

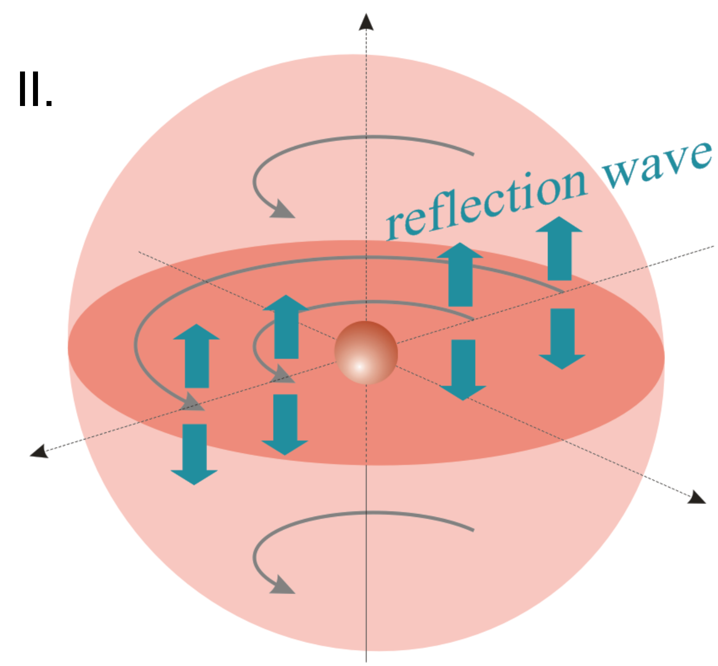
Conclusion

Gravitational instabilities **of multiphase chemically active medium** are promising mechanisms to explain planets formation

Formation of unstable multiphase subdisc



Shock wave **concentrates gas and solids** inside the equatorial plane. **Velocity dispersion of solids decreases** due to collisions with counter-flow wave.



Reflection wave **spreads gas** and causes **gas cooling**. Solids leave in equatorial plane.

Rotating cloud of isentropic gas

$\rho(r) = (1-r)^7$

$v_r = v_\theta = 0$

$v_\varphi = \frac{c}{a} r \sin\theta,\ r \le a$

$v_\varphi = c,\ \ r \ge a$

$R_0 = 10^4\ AU$

$T_c = 20K$

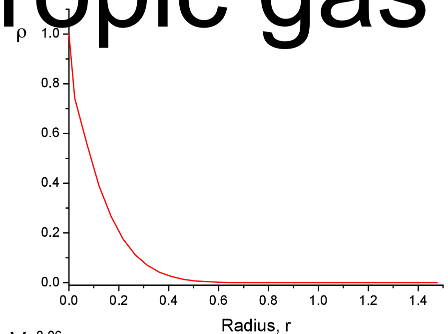
$M = 0.035 \cdot M_\Theta$

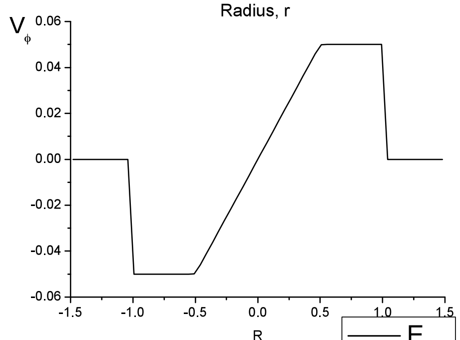
$V_0 \approx 3 \cdot 10^2\ m/\sec$

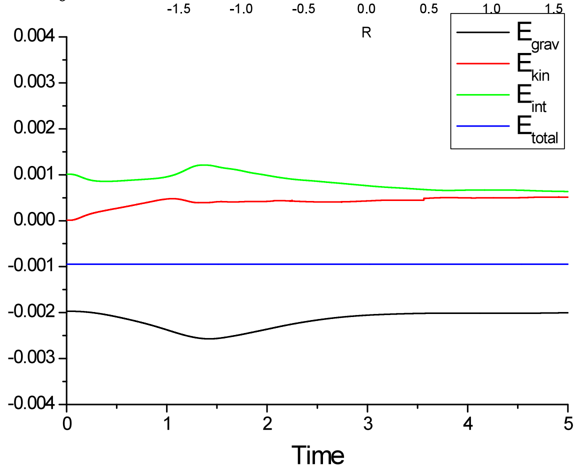
$c = 0.05V_0, a = 0.5R_0$

$\tau = 0.01$

$h \approx 0.023$

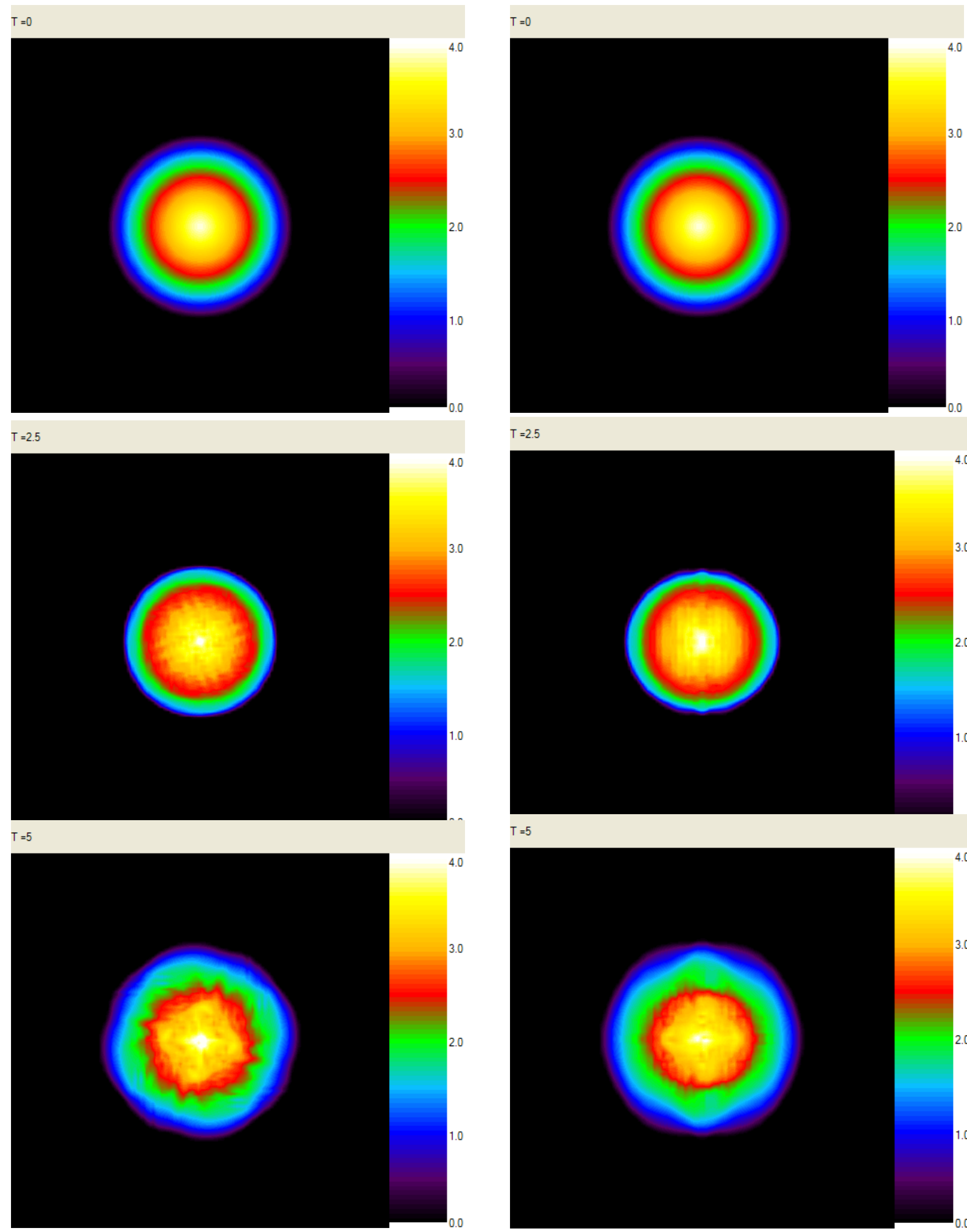






Equatorial section

Meridian section



Collapsing cloud of isoentropic gas. Thick disk

$$\rho(r) = (1-r)^7$$

$$v_\varphi = v_\theta = 0$$

$$v_r = -d \cdot r \cdot |\cos\theta|$$

$$R_0 = 10^4\, AU$$

$$T_c = 20K$$

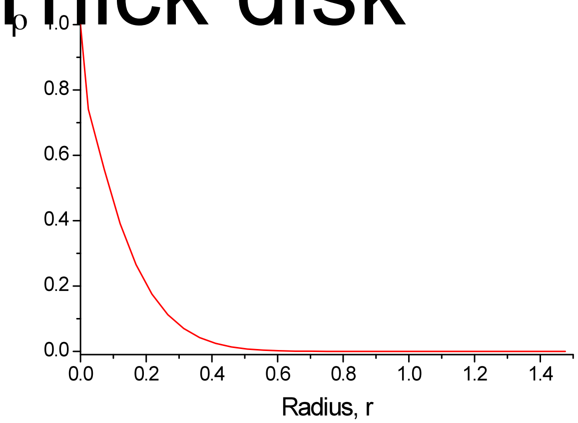
$$M = 0.035 \cdot M_\Theta$$

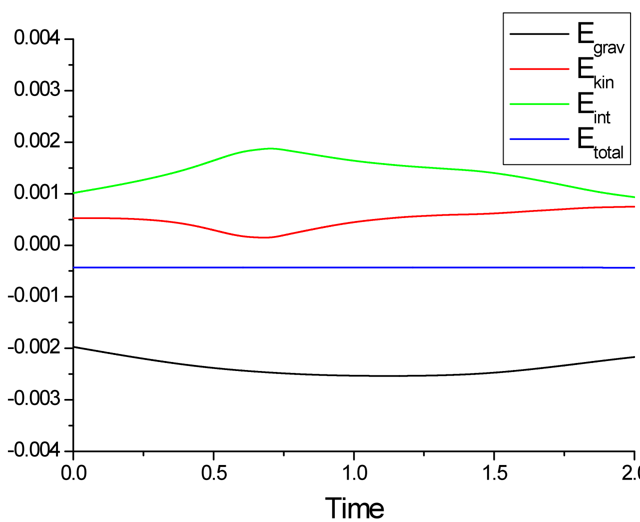
$$V_0 \approx 3 \cdot 10^2\, m/\sec$$

$$d = V_0$$

$$\tau = 0.0005$$

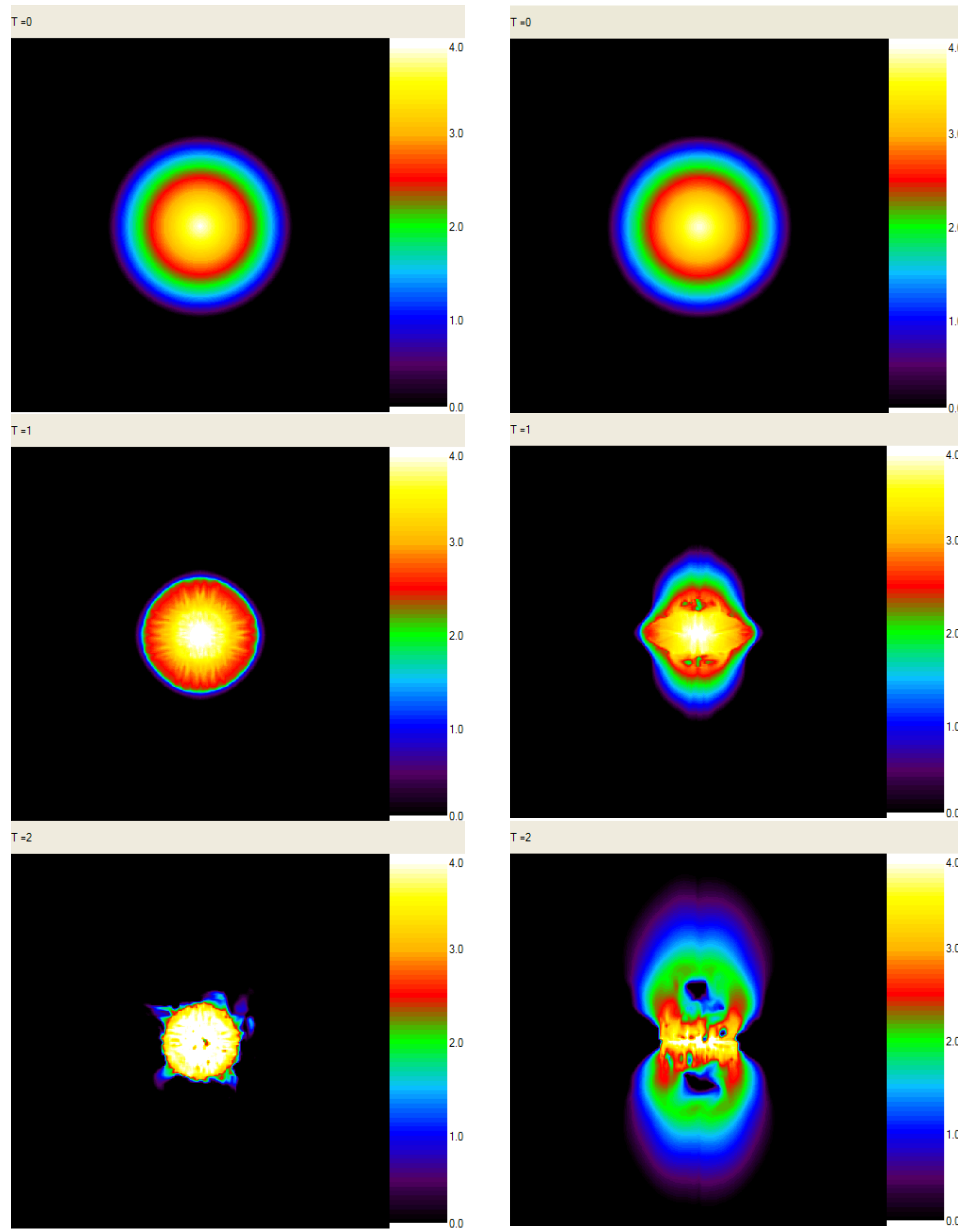
$$h \approx 0.01$$





Equatorial section

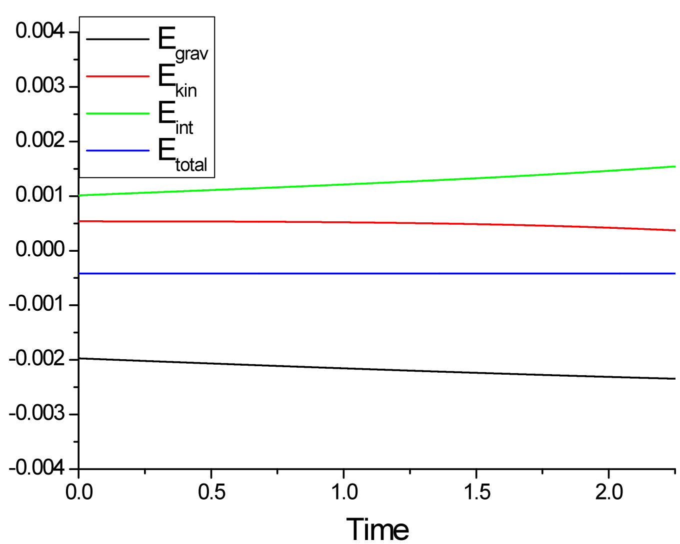
Meridian section



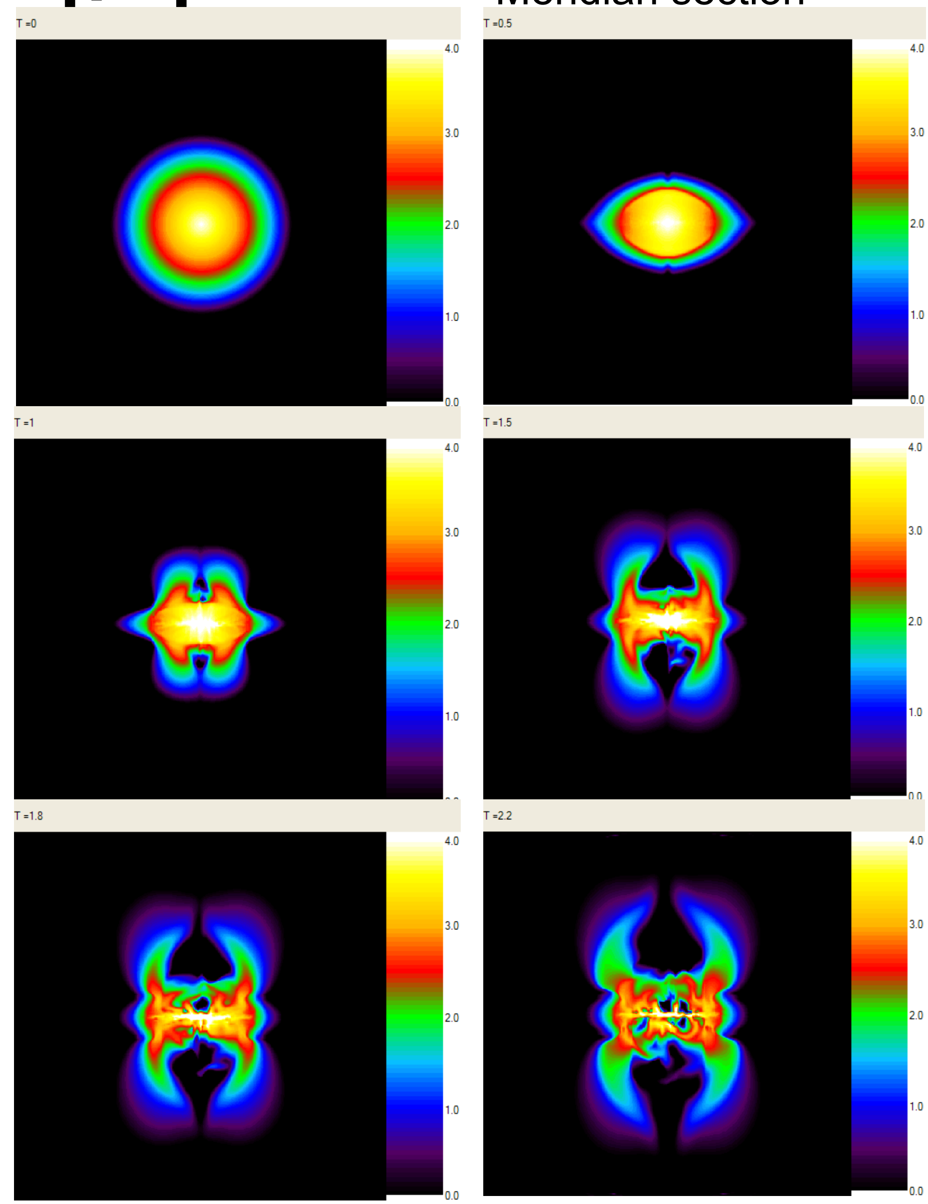
Initial stage of circumstellar disk. Thin

$$\rho = (1-r)^7$$
$$v_\theta = 0$$
$$v_r = -dr \cdot |cos\theta|$$
$$v_\varphi = \frac{c}{a} r \sin\theta,\ r \le a$$
$$v_\varphi = c,\ \ r \ge a$$
$$R_0 = 10^4\ AU$$

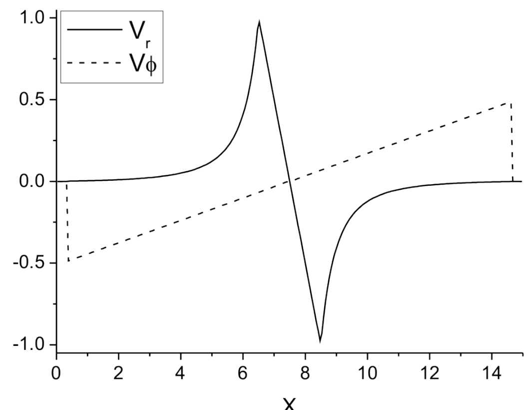
$$T_c = 20K$$
$$M = 0.035 \cdot M_\Theta$$
$$V_0 \approx 3 \cdot 10^2\ m/\sec$$
$$d = V_0, c = 0.05 V_0$$
$$a = 0.5 R_0$$
$$\tau = 0.0005$$
$$h \approx 0.01$$

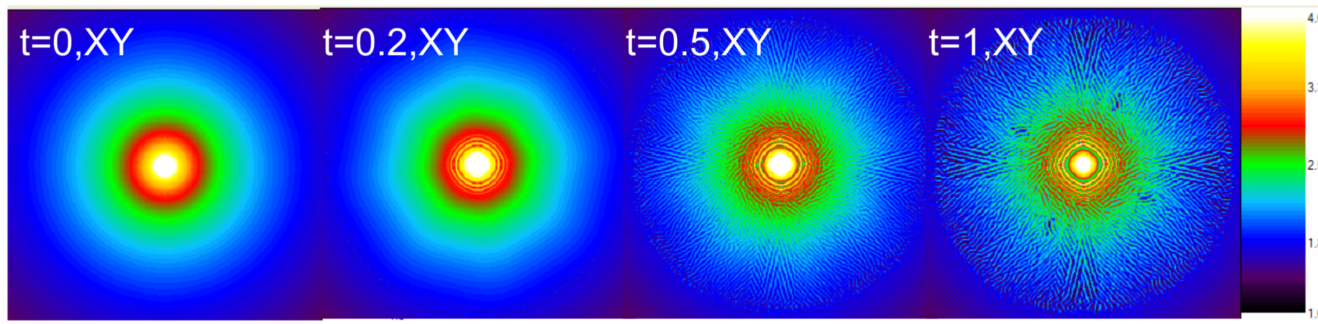


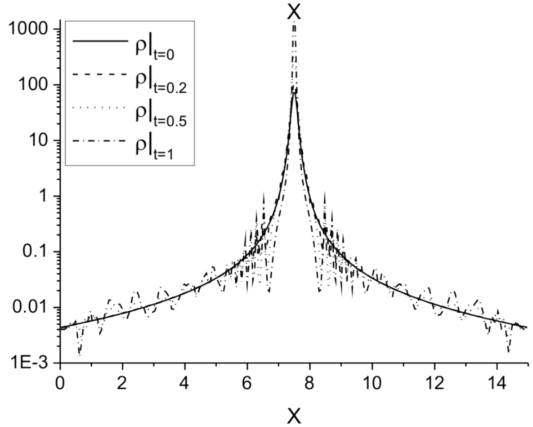
Meridian section

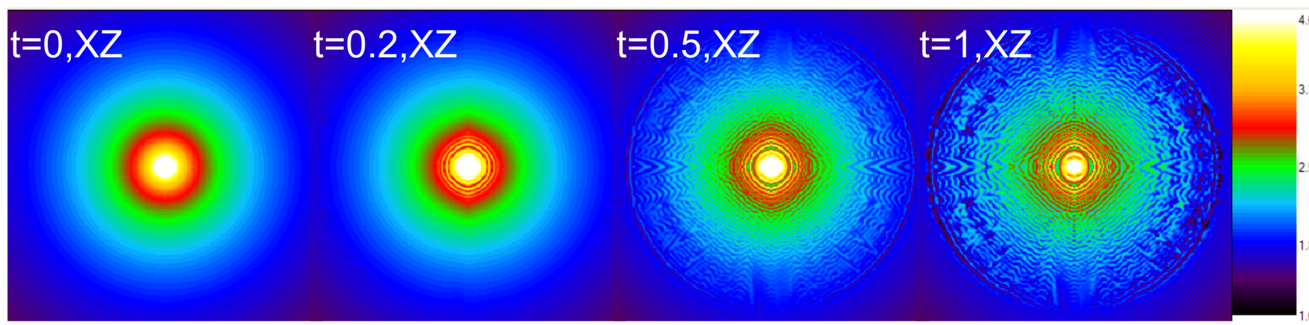


Isothermal gas collapse with rotation
Waves

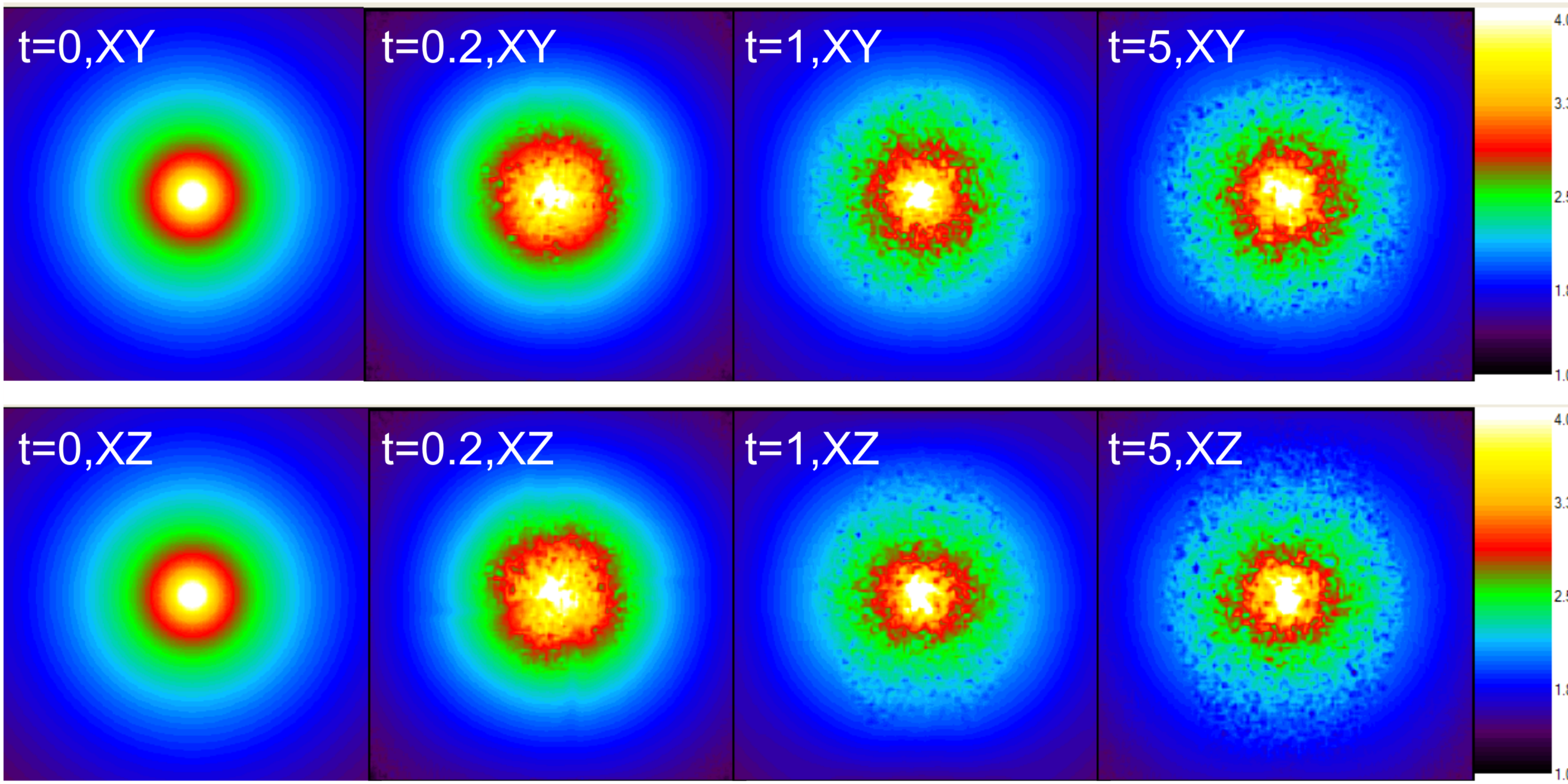




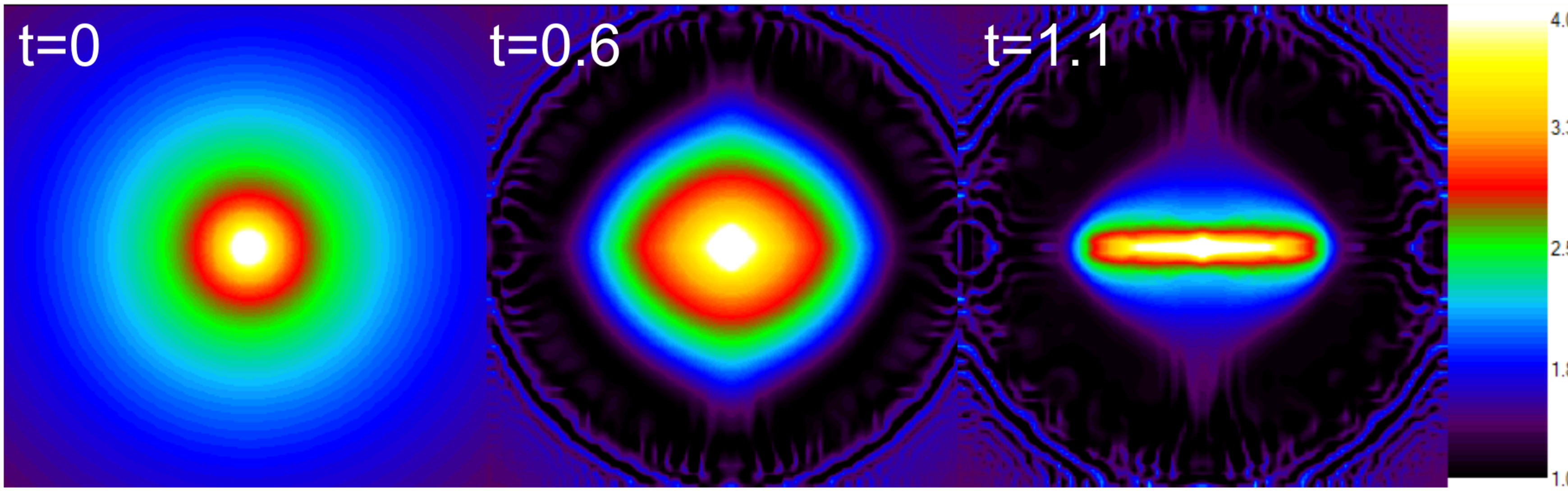


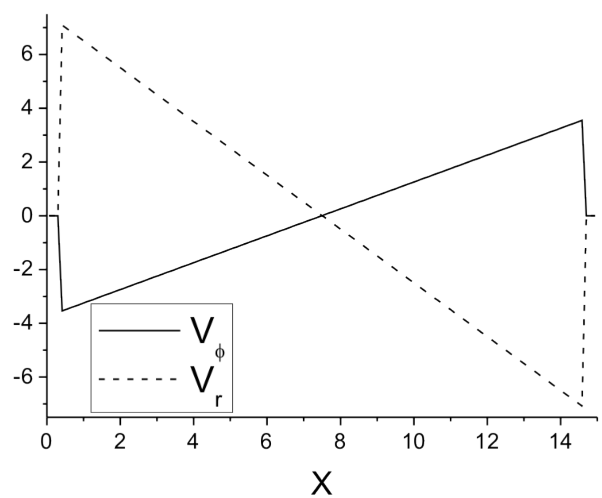


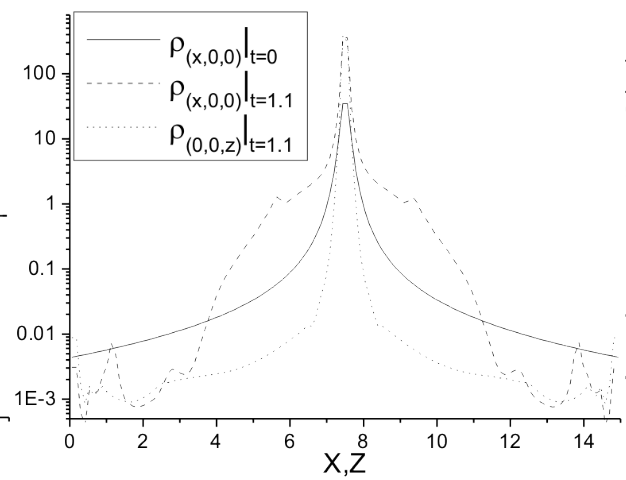
Gas dynamics. Turbulence. gamma=*7/5*

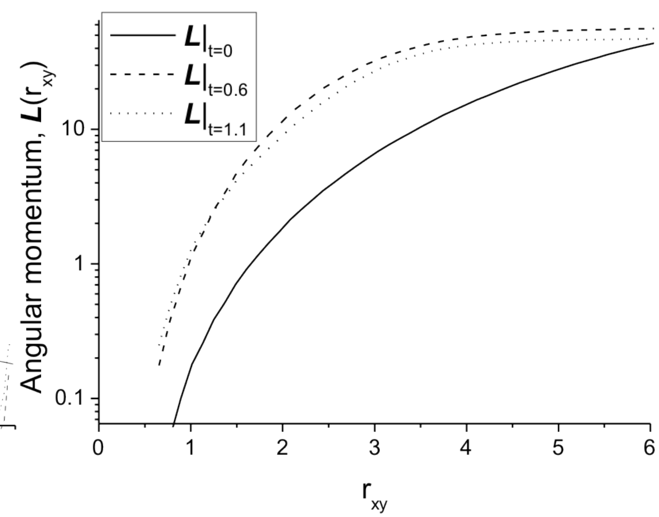


Isothermal gas dynamics.

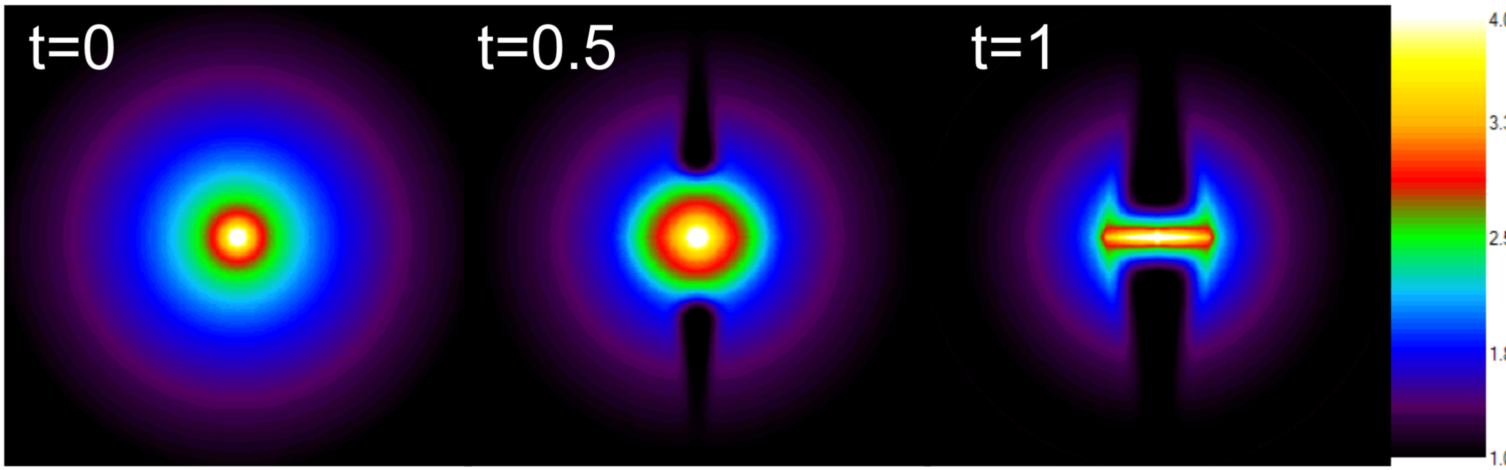


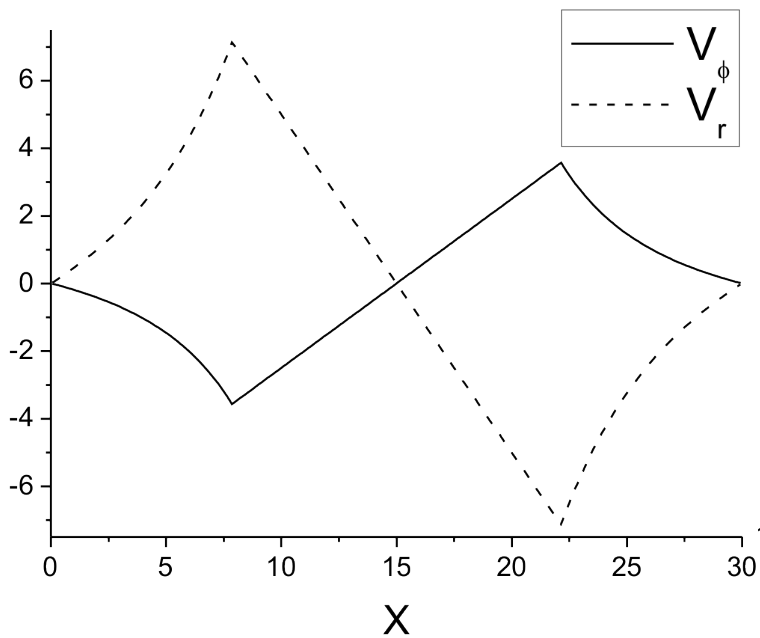


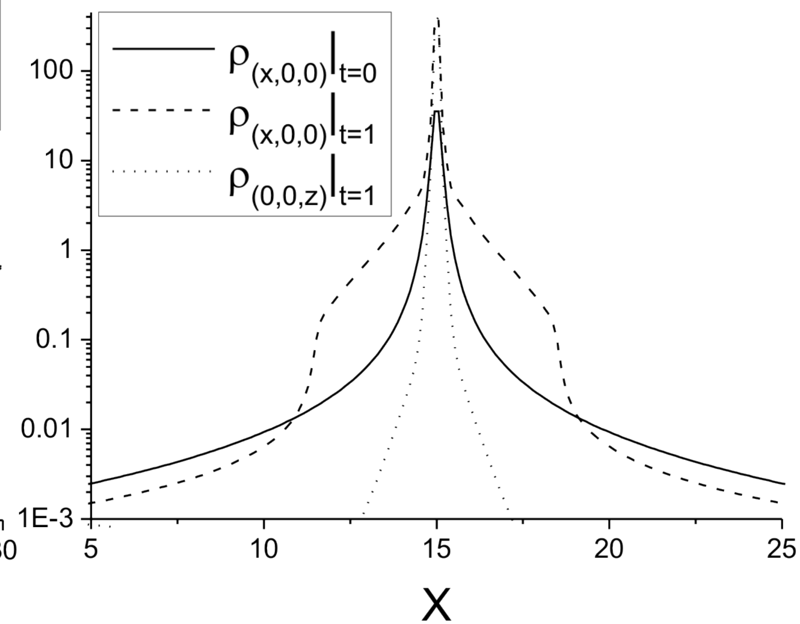




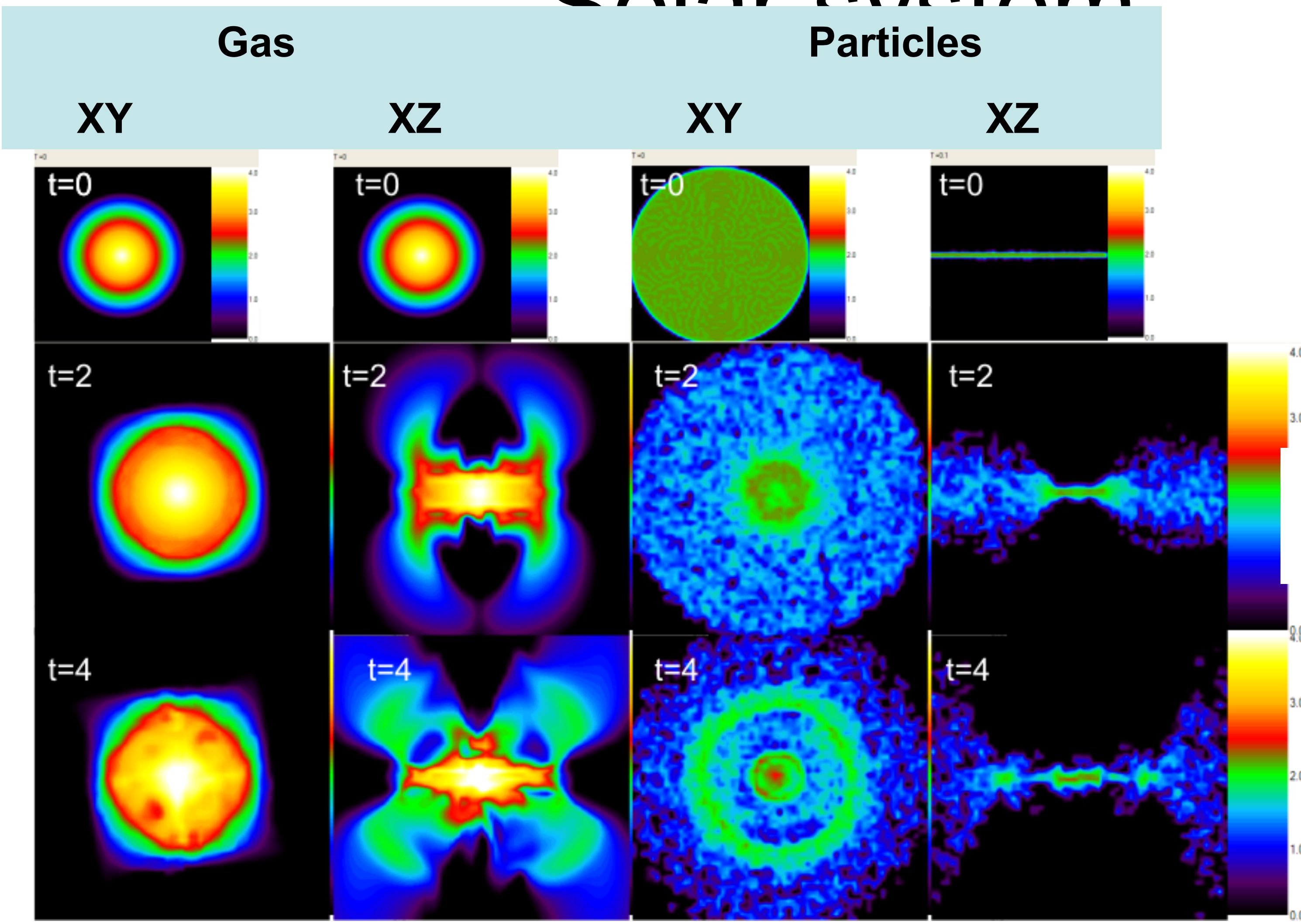
Isothermal gas dynamics.







Gas and Particles in Disk. Solar system



Mesh 128^3

Gas

$\rho(r)=(1-r)^7$

Particles

$\rho(r)=const$

$$\frac{u'^2_\psi}{r} = \frac{\partial \Phi}{\partial r}, \quad u'_r = 0.$$

on r - 0.01
on ϕ - 0.01
on z - 0.1

$$\frac{M_g}{M_p} = 10$$

Supercomputers attributes

Shared memory machines

NKS-160
www2.sscc.ru/ HKC-160
Novosibirsk, Russia

84 computational modules
hp Integrity rx1620

2 processors
Intel Itanium 2 @ 1.6GHz,
RAM 4 G.

MVS-100K
www.jscc.ru
Moscow, Russia

1460 computational modules

2*4-kernel processors -8 kernels
Intel Xeon @ 3 GHz,
RAM 4 G.

Common memory machine

SMP16x256
smp16x256.sscc.ru
Novosibirsk, Russia

4*4-kernel processors -16 kernels
Intel Xeon X7350 @ 2.93GHz
RAM - 256 G

Chemical reactions

Energy transfer

(dust)H + H $\rightarrow$ H_2 + 4.48 eV

$h\nu$ + He $\rightarrow$ $He^*(2^3S_1)$

He +(p,e) $\rightarrow$ $He^*(2^3S_1)$ +(p,e)

He* $\rightarrow$ He + 19.82 eV (~ 10^5s)

Reactions of activation

He^* + H_2 $\rightarrow$ He + H + p + e

He^* + H_2O $\rightarrow$ He + OH + p + e 3.2%

$\rightarrow$ He + OH^+ + H + e 17.9%

$\rightarrow$ He + H_2O^+ + e 77.9%

$\rightarrow$ He + OH + H

He^* + CH_4 $\rightarrow$ He + CH_3 + H