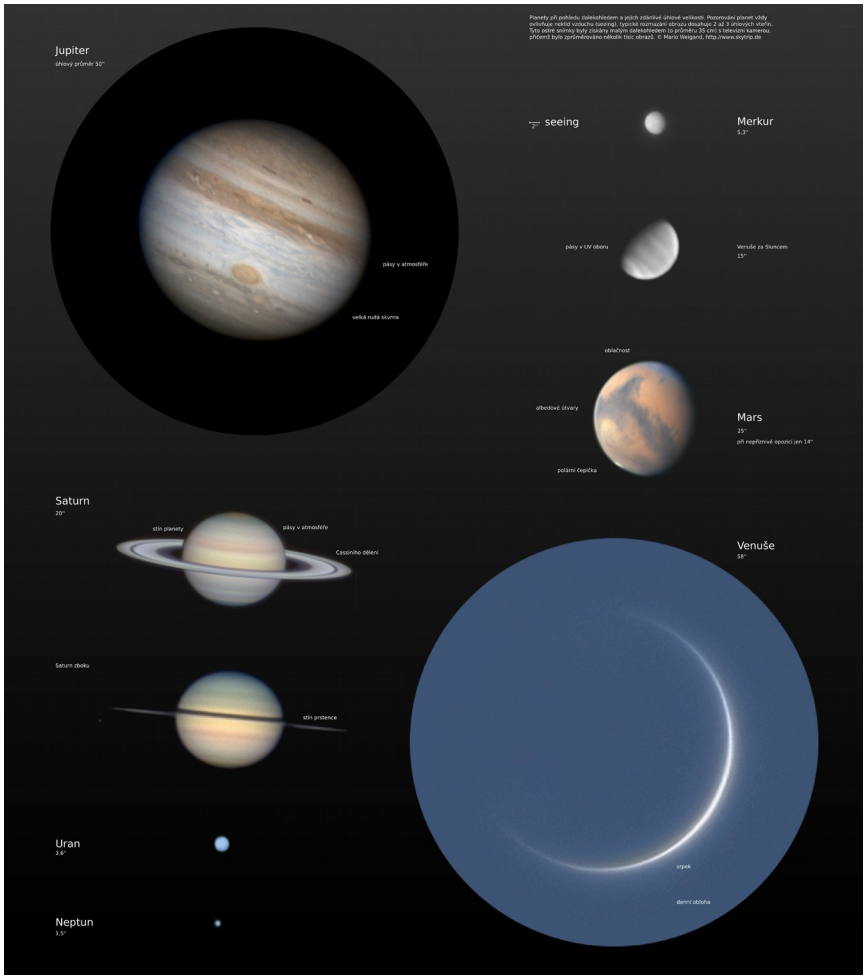
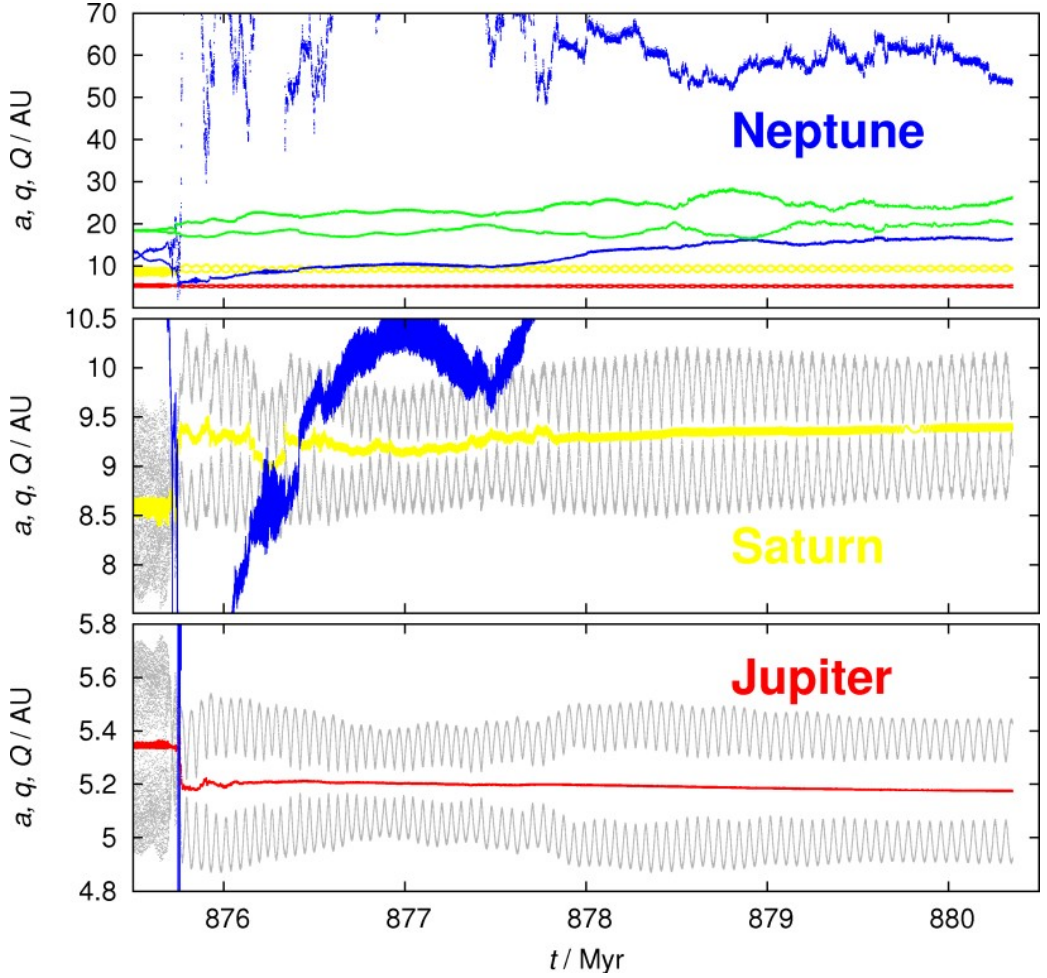
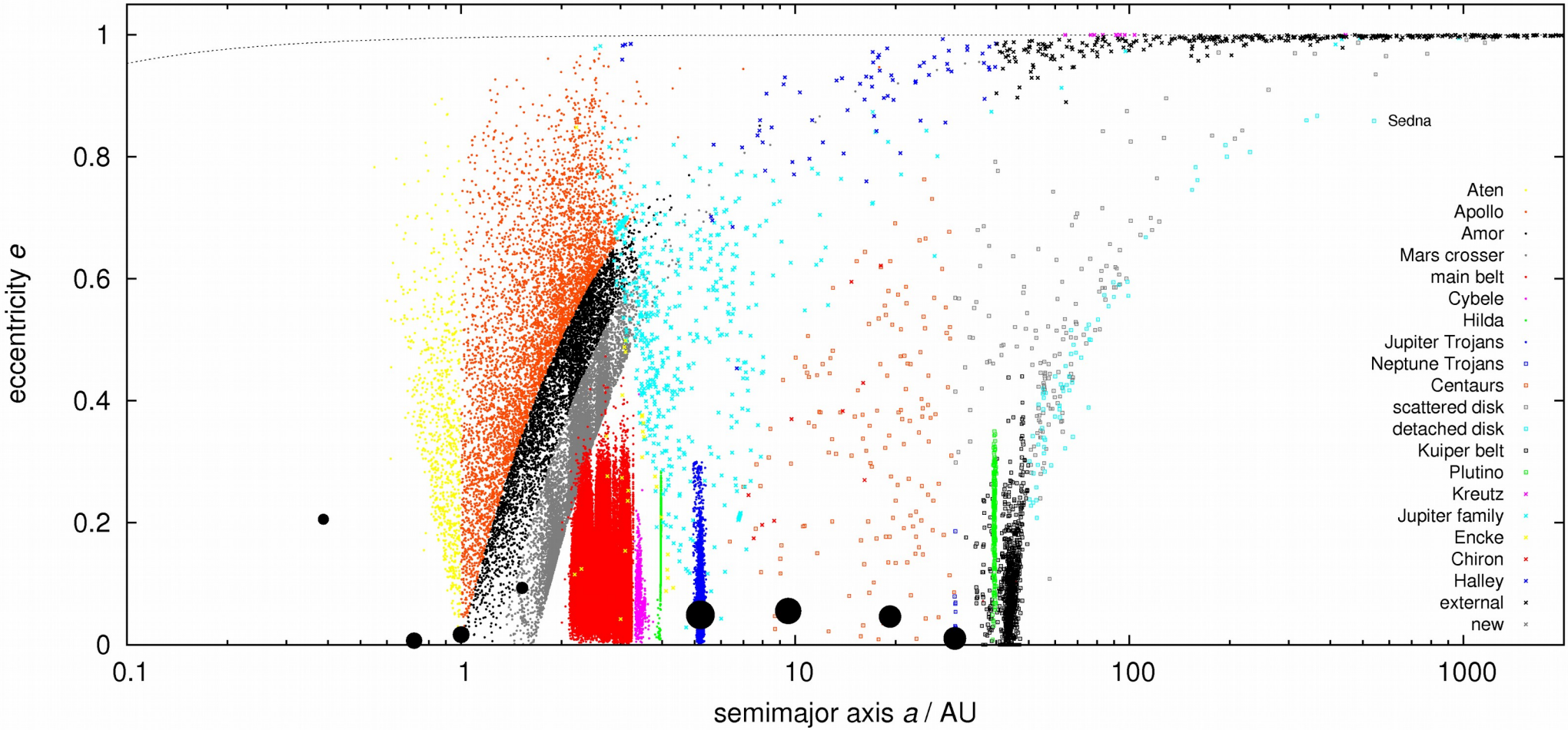
Jak se rodily planety?



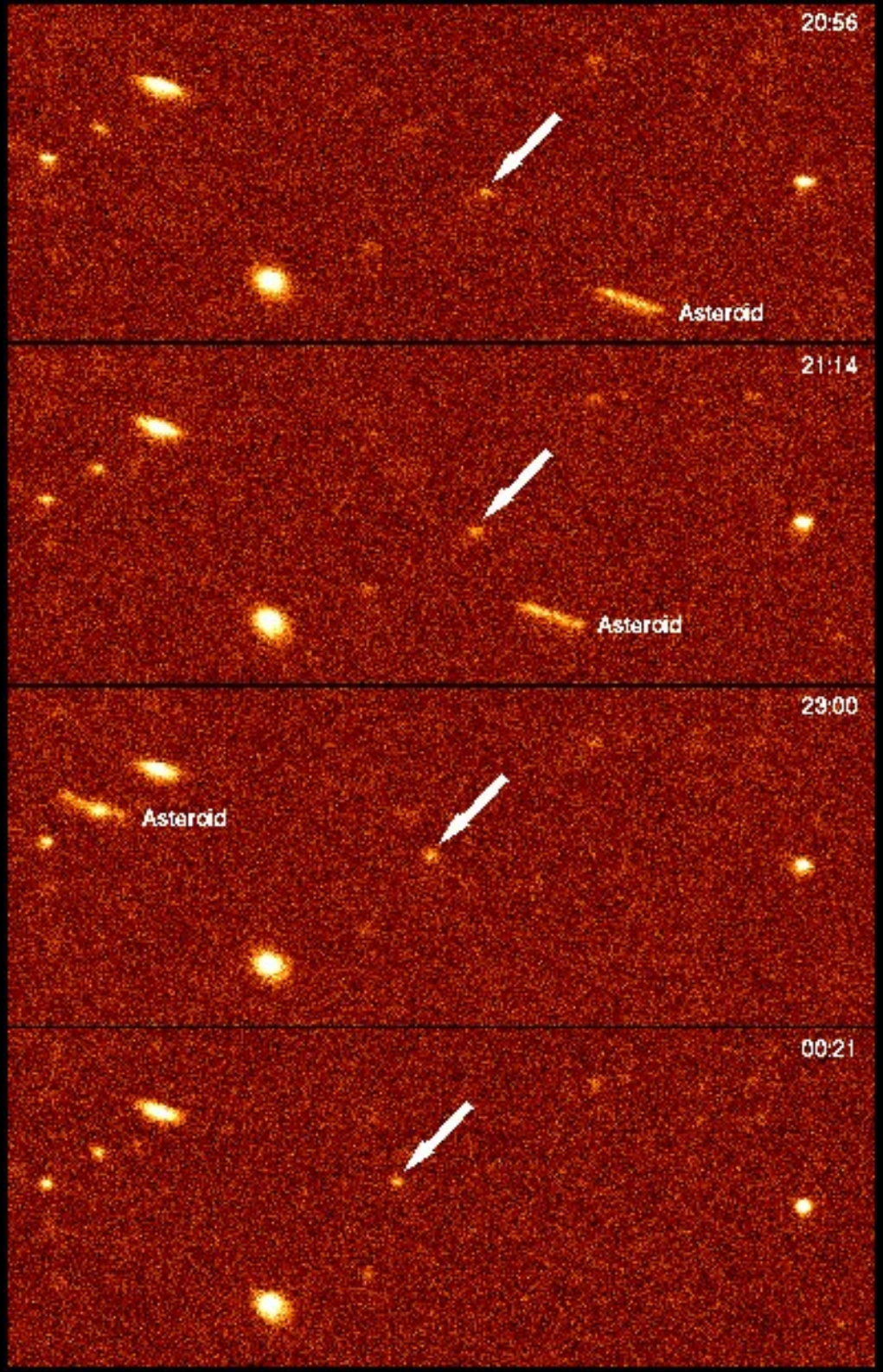


Miroslav Brož, Astronomický ústav MFF UK, mira@sirrah.troja.mff.cuni.cz

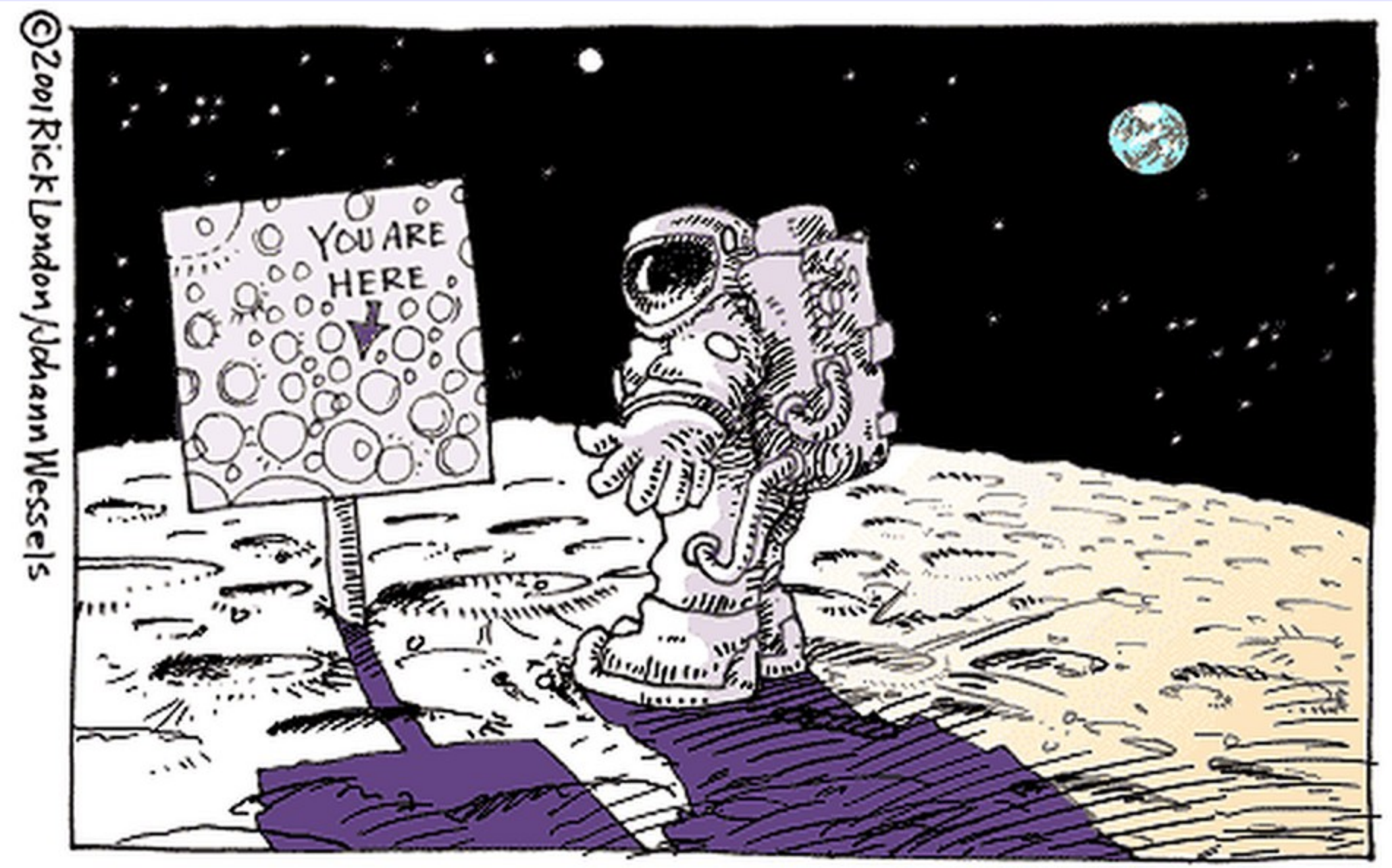
Dráhy planet, asteroidů a komet



data Minor Planet Center

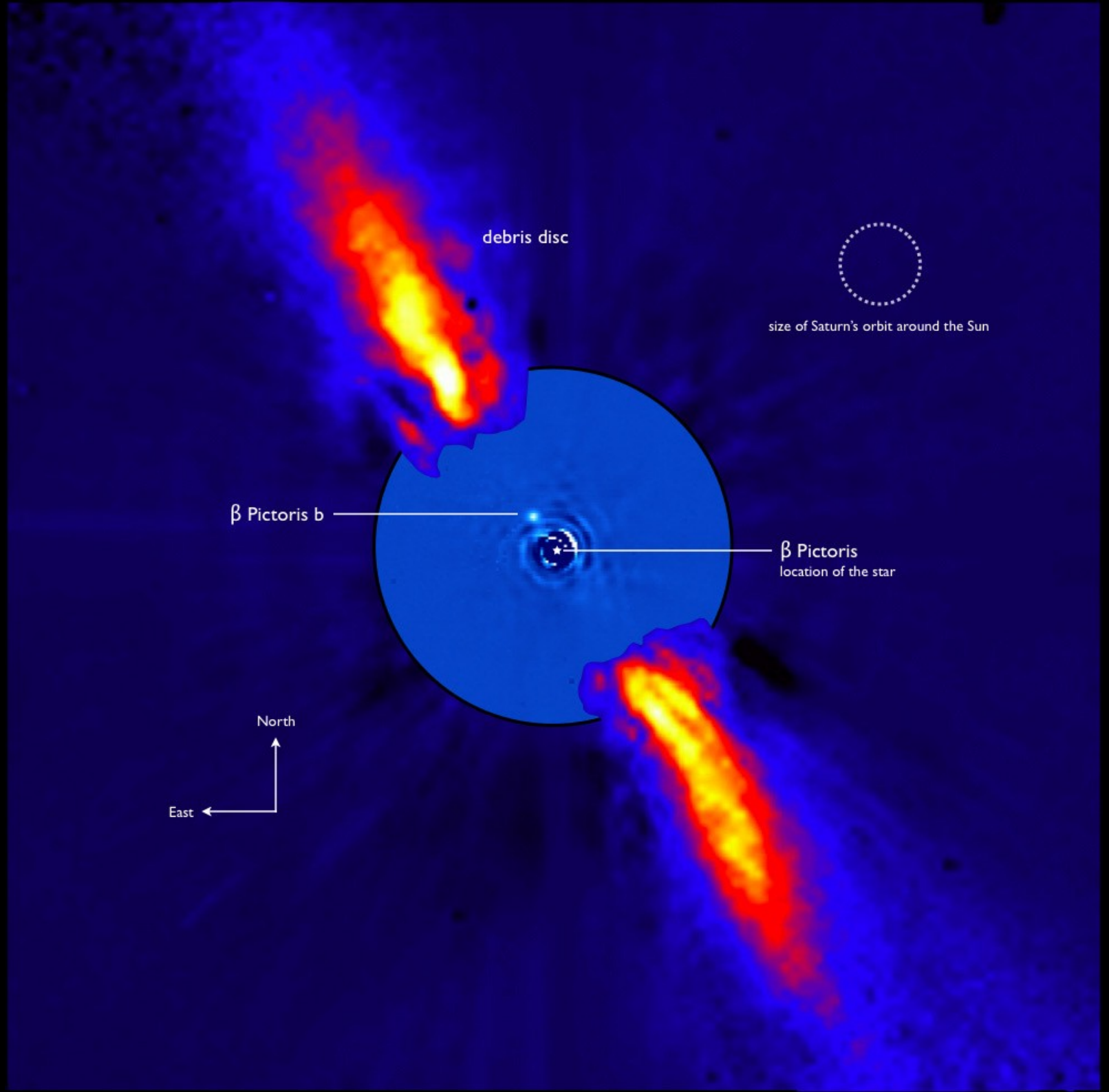


1992 QB1
Jewitt & Luu (1992)



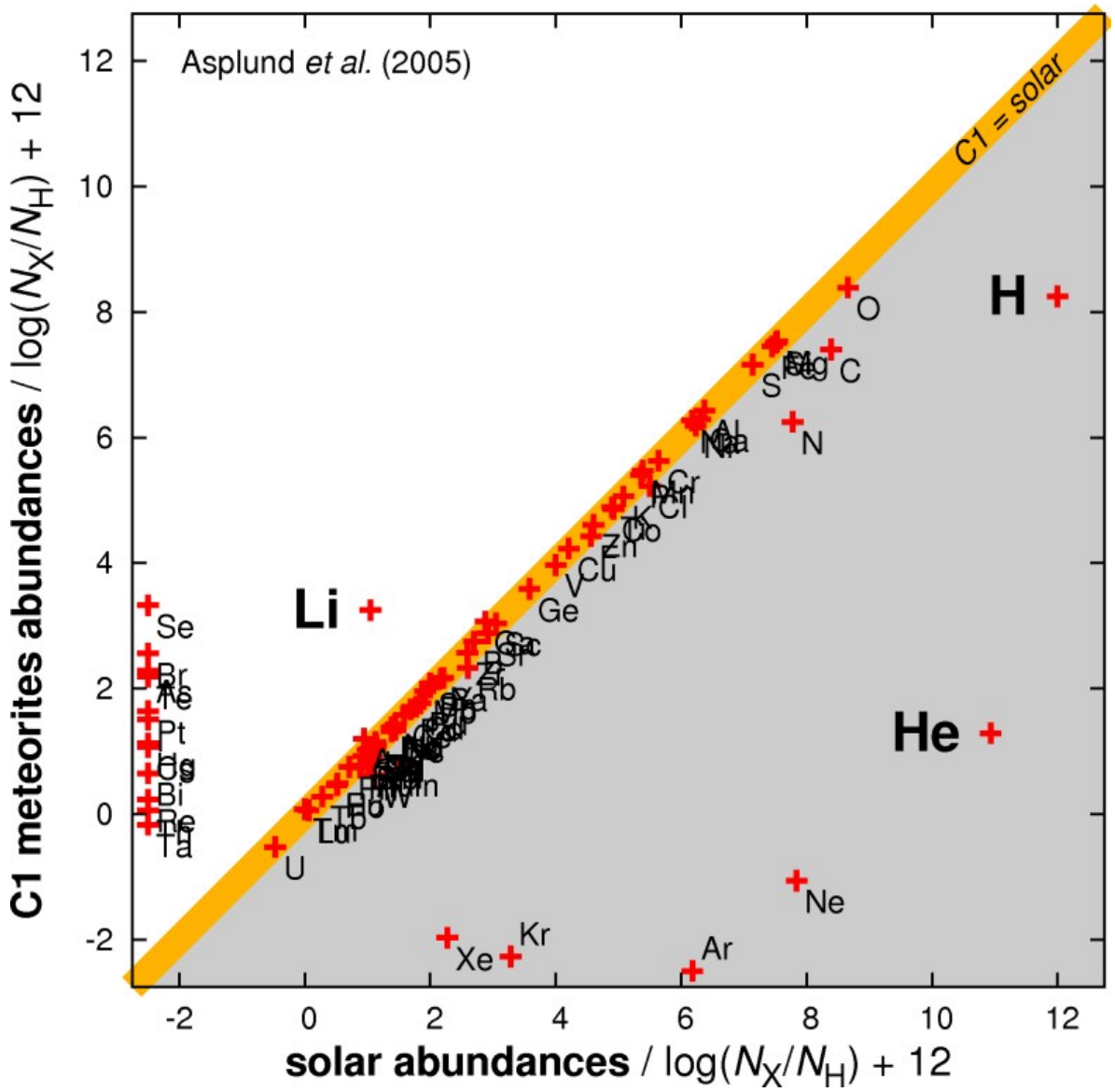
kráterování & impakty

mlhovina M42
© NASA, ESA

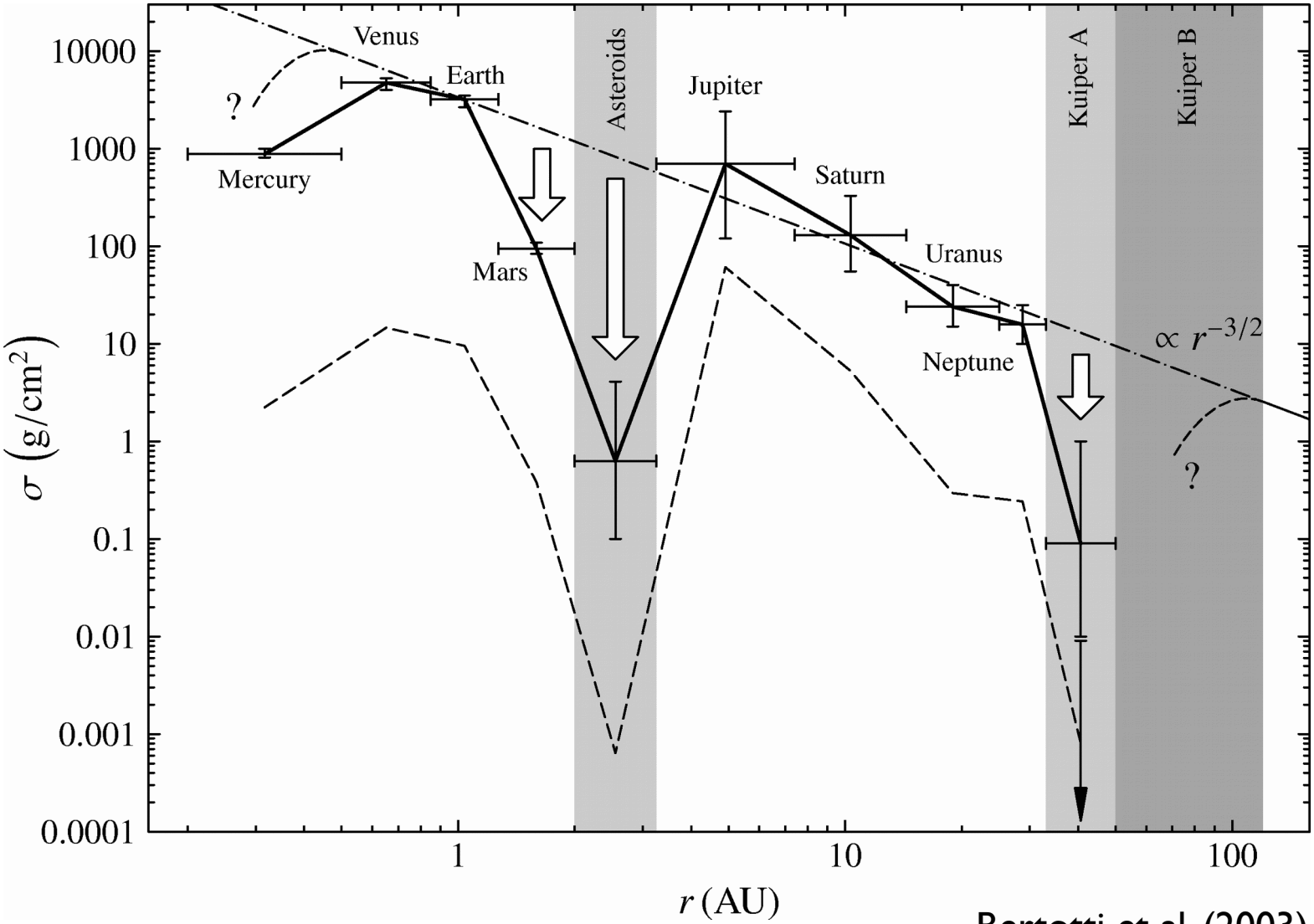


β Pictoris
© ESO

Chemické složení meteoritů a Slunce



Protoplanetární disk



Bertotti et al. (2003)

Hydrodynamické rovnice

rovnice kontinuity (neboli zákon zachování hmoty, např. v jednotkách $\mathrm{kg{\cdot}m^{-3}{\cdot}\,s^{-1}}$):[1]

$$\overbrace{\frac{\partial \rho}{\partial t} + \boldsymbol{v} \cdot \nabla \rho}^{\text{derivace } f(\boldsymbol{r},t)} = \overbrace{-\rho \nabla \cdot \boldsymbol{v}}^{\text{zředění}}, \tag{1}$$

Navierova–Stokesova rovnice (též pohybová, $\mathrm{m{\cdot}s^{-2}}$):

$$\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v} \cdot \nabla \boldsymbol{v} = -\frac{1}{\rho} \nabla P - \overbrace{\nabla \Phi}^{\text{gravitace}} + \frac{1}{\rho} \overbrace{\frac{1}{\mu_{\mathrm{vac}}} (\nabla \times \boldsymbol{B}) \times \boldsymbol{B}}^{\text{Lorentz}} + \frac{1}{\rho} \overbrace{\left[\nabla \cdot \mu_1 \nabla \boldsymbol{v} + \nabla (\mu_1 + \mu_2) \nabla \cdot \boldsymbol{v} \right]}^{\text{viskozita}}, \tag{2}$$

[1] pro připomenutí, operátor gradientu jest $\nabla \equiv \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right)$, divergence $\nabla\cdot$ (tj. skalární součin), rotace $\nabla\times$ (vektorový součin); mějme na paměti jejich české významy: stoupání, rozbíhavost a stáčení

rovnice tepelné rovnováhy (1. věta termodynamická, $\mathrm{J\cdot m^{-3}\cdot s^{-1}}$):

$$\frac{\partial U}{\partial t}+\boldsymbol{v}\cdot\nabla U=-U\nabla\cdot\boldsymbol{v}-\overbrace{P\nabla\cdot\boldsymbol{v}}^{\text{práce}}-\overbrace{\kappa_{\mathrm{P}}\rho\frac{\sigma}{4}T^4}^{\text{emise}}+\overbrace{\kappa_{\mathrm{P}}\rho cE_{\mathrm{rad}}}^{\text{absorpce}}-\overbrace{\nabla\cdot F_\star\hat{r}}^{\text{ozáření}}+\overbrace{\nabla\cdot K\nabla T}^{\text{vedení}}, \quad (3)$$

rovnice přenosu záření ($\mathrm{J\cdot m^{-3}\cdot s^{-1}}$):[2]

$$\frac{\partial E_{\mathrm{rad}}}{\partial t}=\overbrace{\nabla\cdot\frac{c\lambda_{\mathrm{lim}}}{\kappa_{\mathrm{R}}\rho}\nabla E_{\mathrm{rad}}}^{\text{difuze}}+\overbrace{\kappa_{\mathrm{P}}\rho\frac{\sigma}{4}T^4}^{\text{emise}}-\overbrace{\kappa_{\mathrm{P}}\rho cE_{\mathrm{rad}}}^{\text{absorpce}}, \quad (4)$$

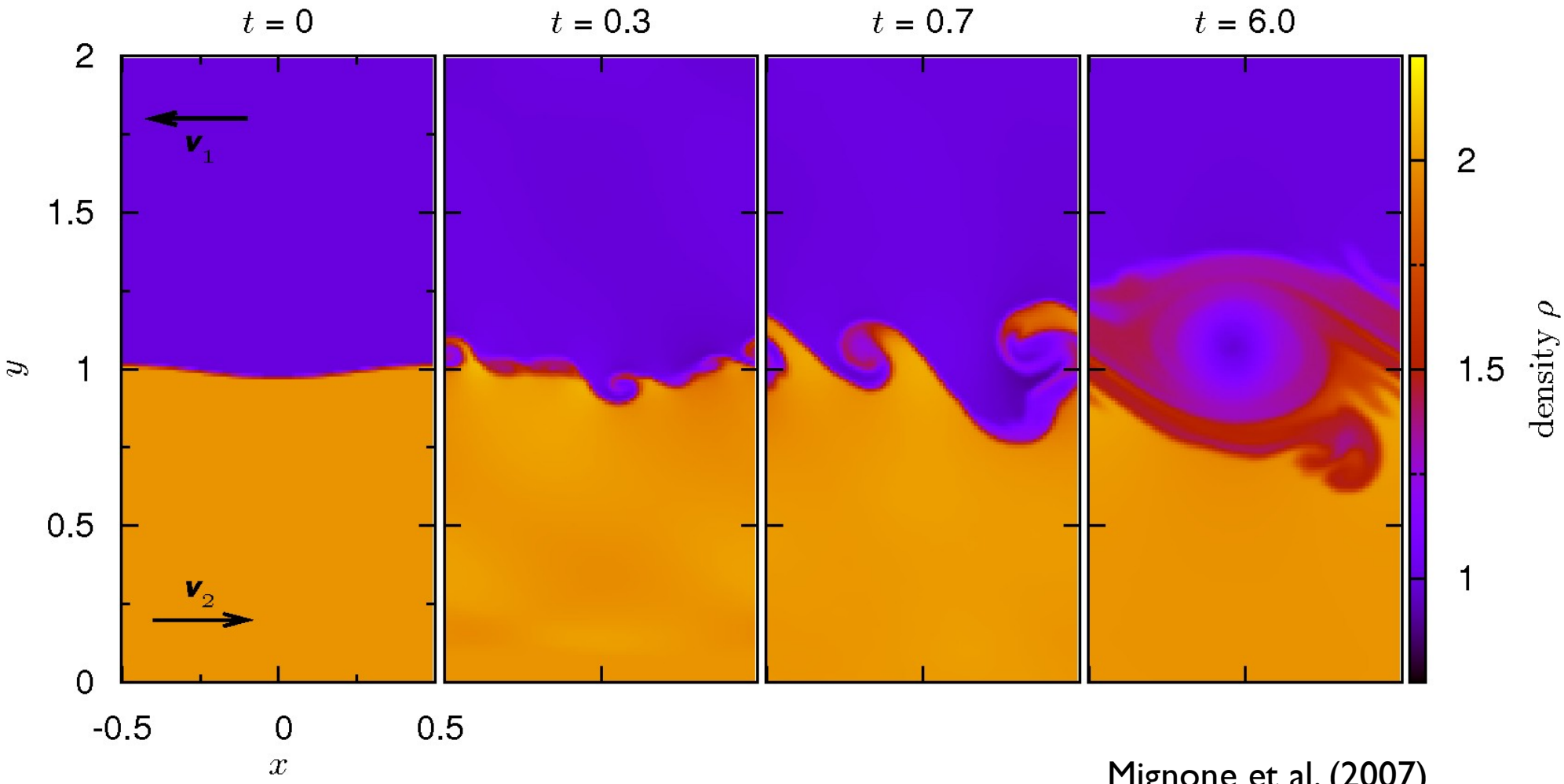
indukční rovnice ($\mathrm{T\cdot s^{-1}}$):[3]

$$\frac{\partial\boldsymbol{B}}{\partial t}=\overbrace{\nabla\times(\boldsymbol{v}\times\boldsymbol{B})}^{\text{advekce}}+\overbrace{\nabla\cdot\eta_{\mathrm{mag}}\nabla\boldsymbol{B}}^{\text{difuze}}, \quad (5)$$

Poissonova rovnice ($\mathrm{J\cdot kg^{-1}\cdot m^{-2}}$):

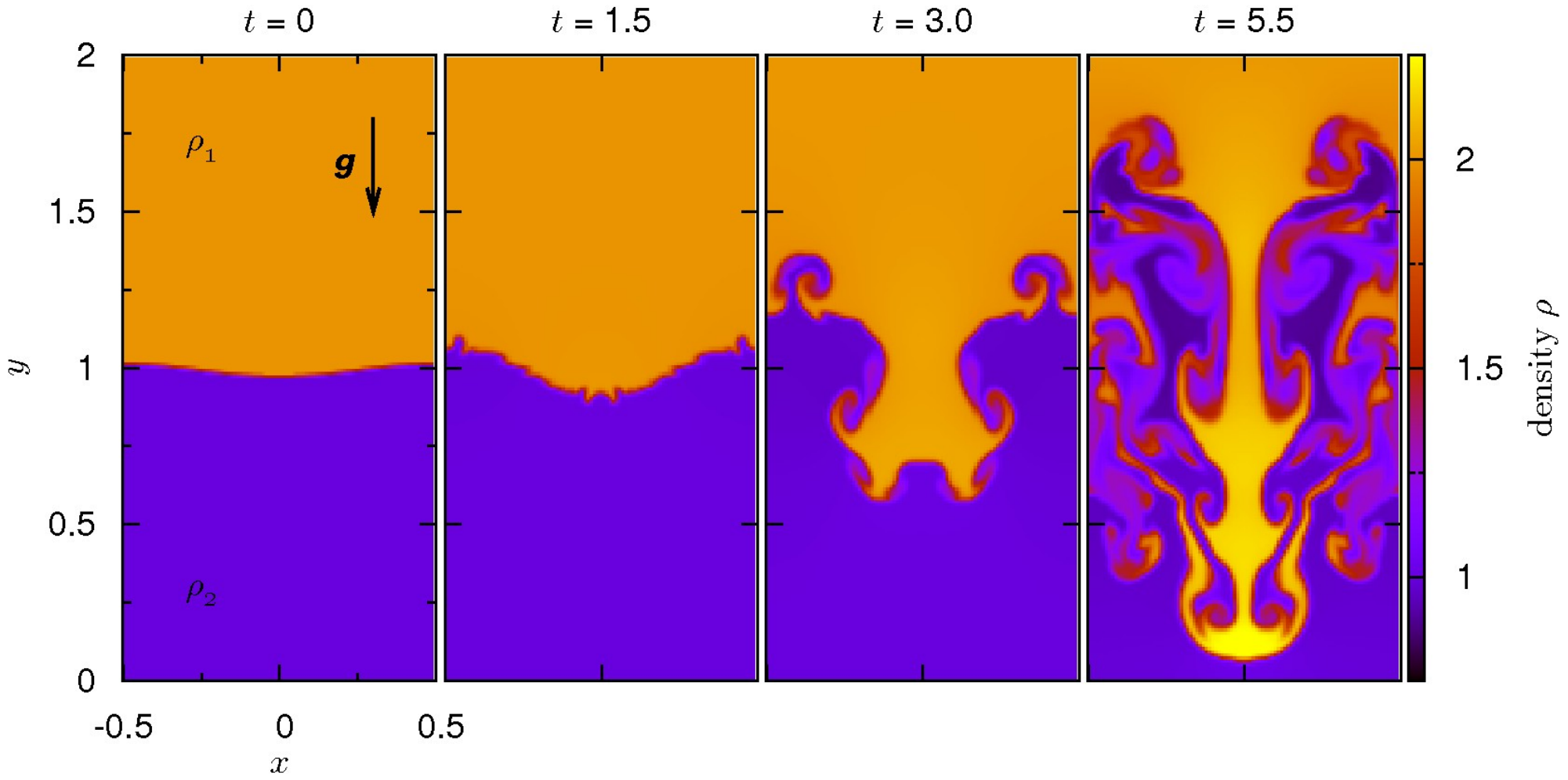
$$\nabla^2\Phi_{\mathrm{disk}}=4\pi G\rho\,, \quad \Phi=-\frac{GM_\star}{r}+\Phi_{\mathrm{planet}}+\Phi_{\mathrm{disk}}\,, \quad (6)$$

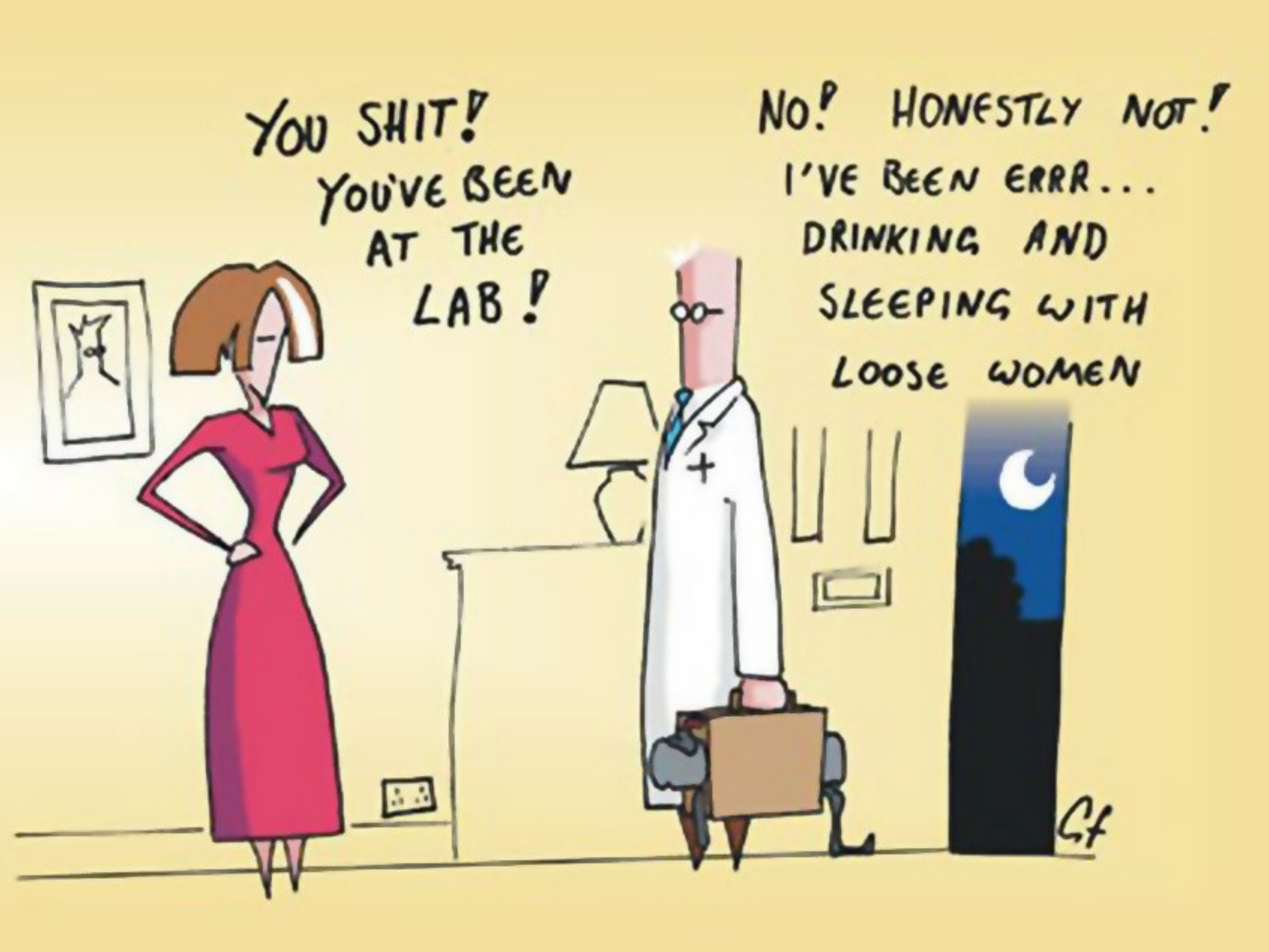
Kelvinova-Helmholtzova nestabilita



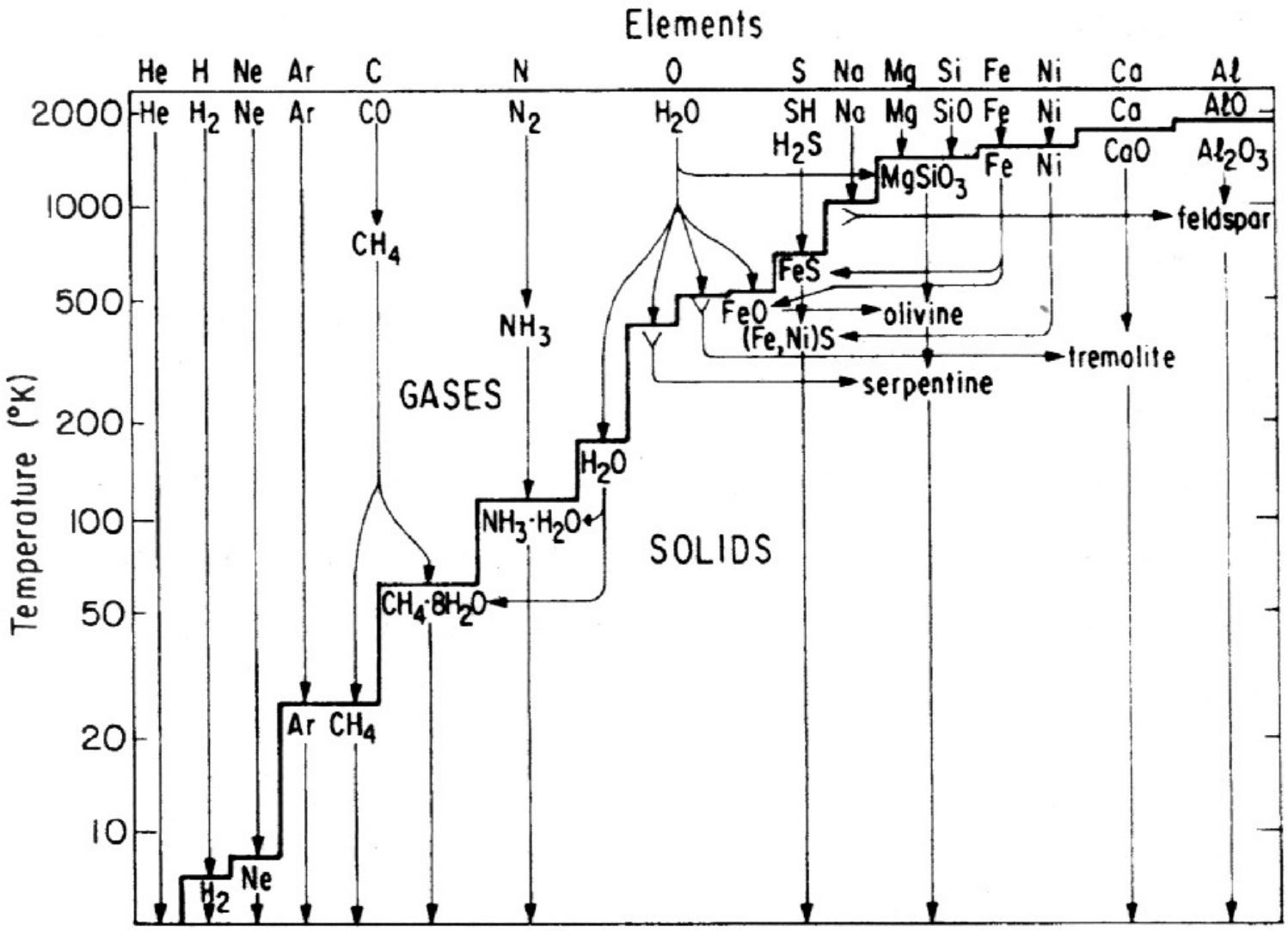
Mignone et al. (2007)

Rayleighova-Taylorova nestabilita

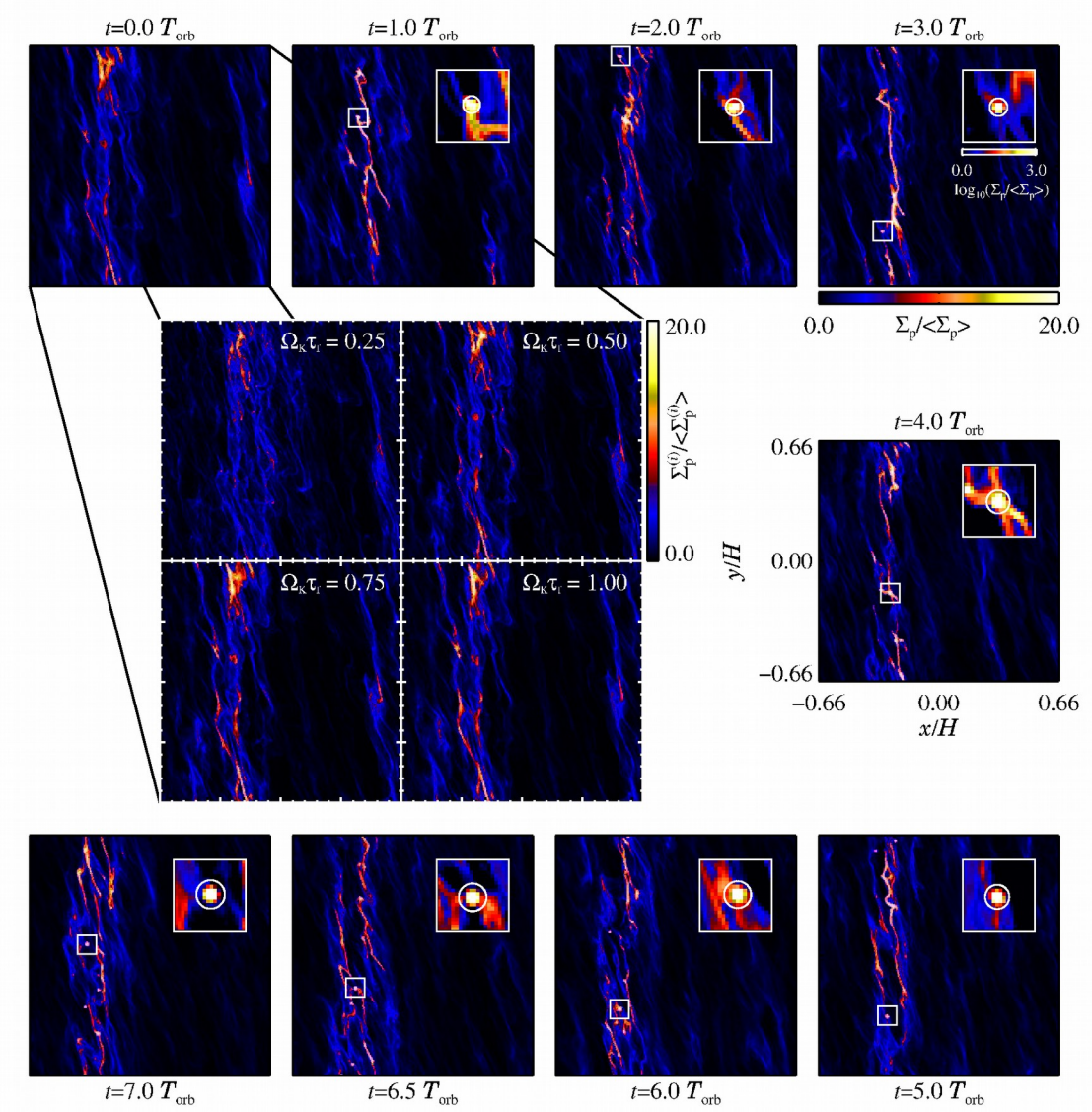



YOU SHIT! YOU'VE BEEN AT THE LAB!
NO! HONESTLY NOT! I'VE BEEN ERRR... DRINKING AND SLEEPING WITH LOOSE WOMEN
Cf

Kondenzační sekvence

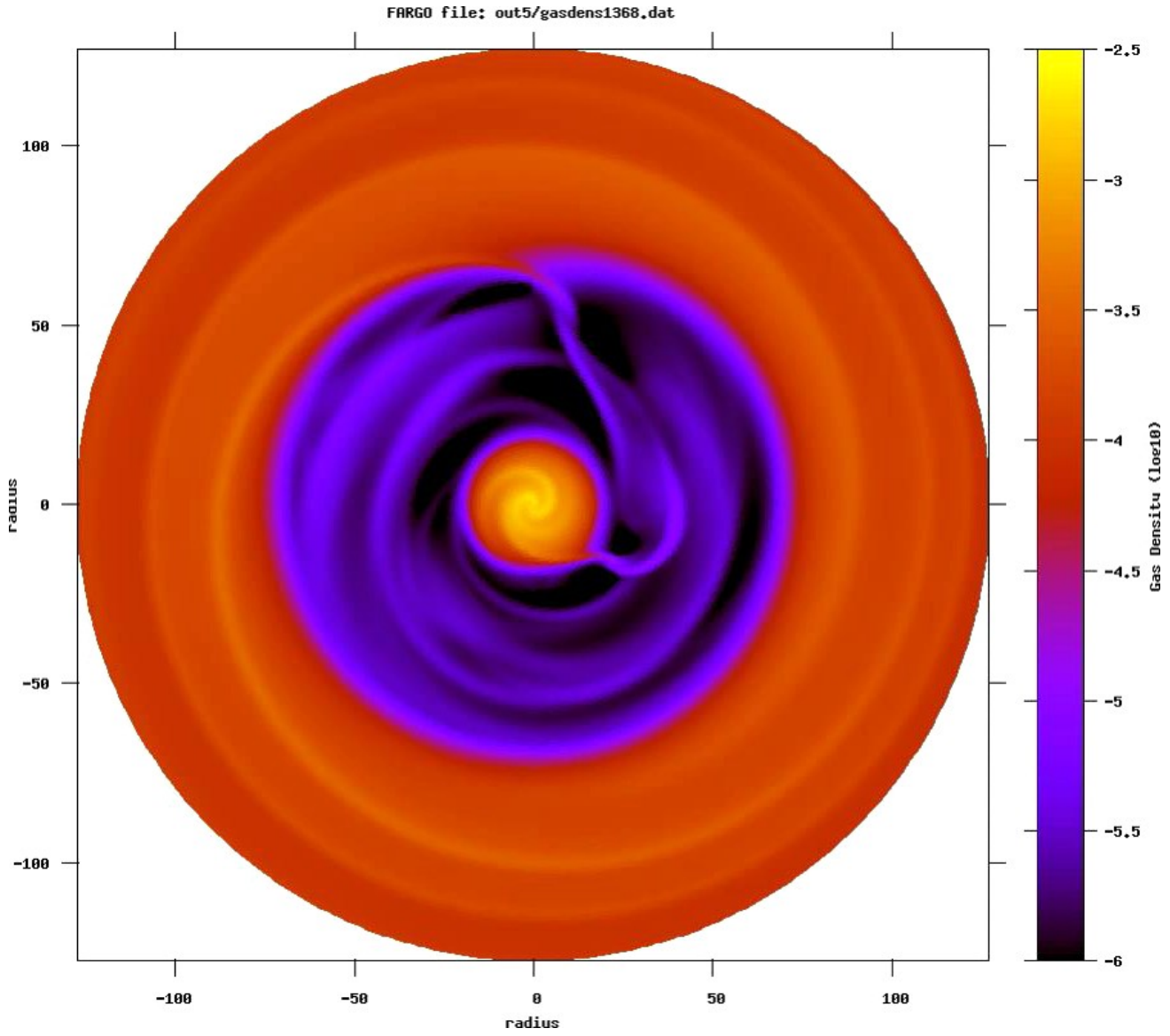


Interakce plynu a prachu



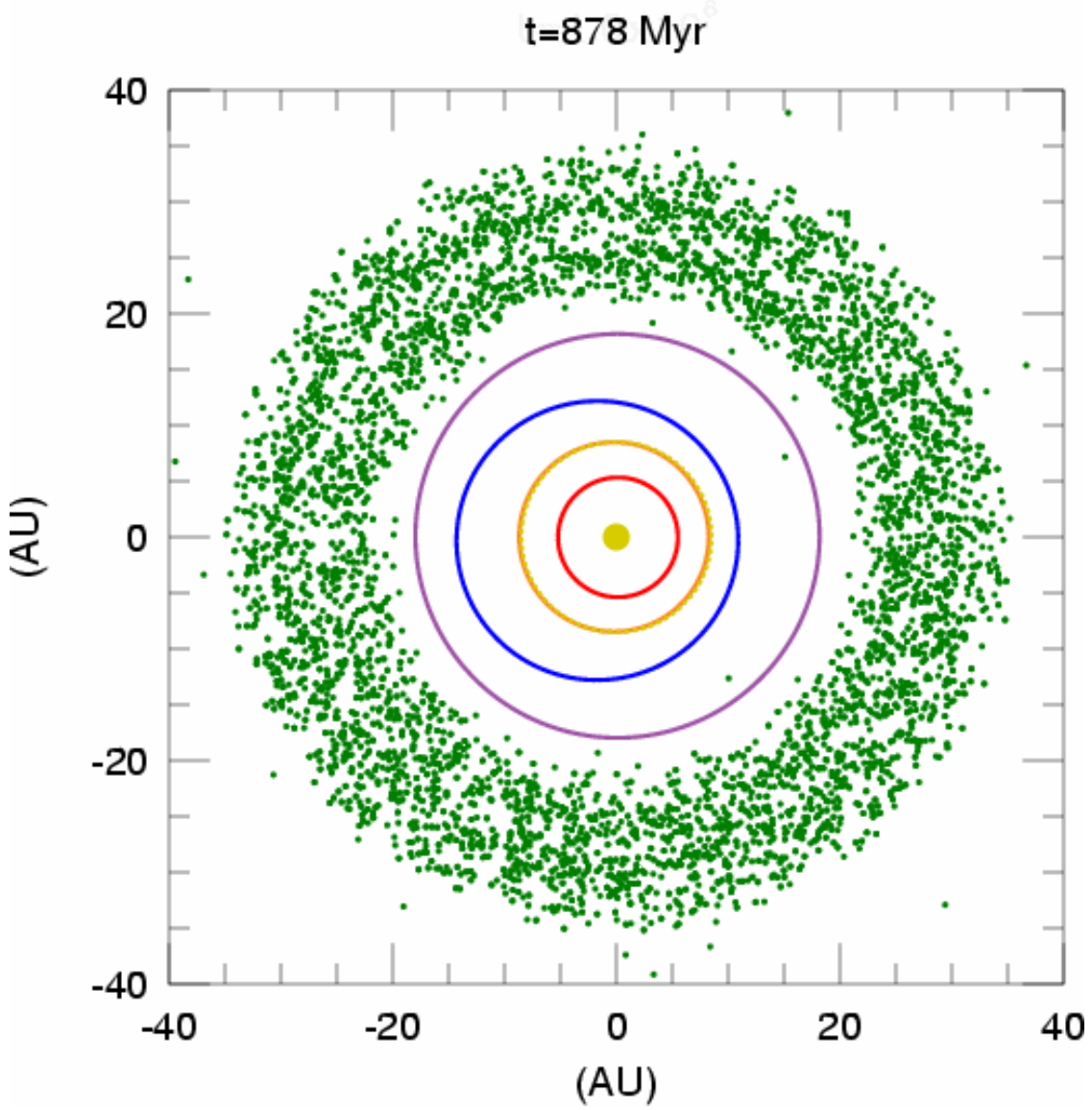
Johansen et al. (2007)

Interakce planet a plynu



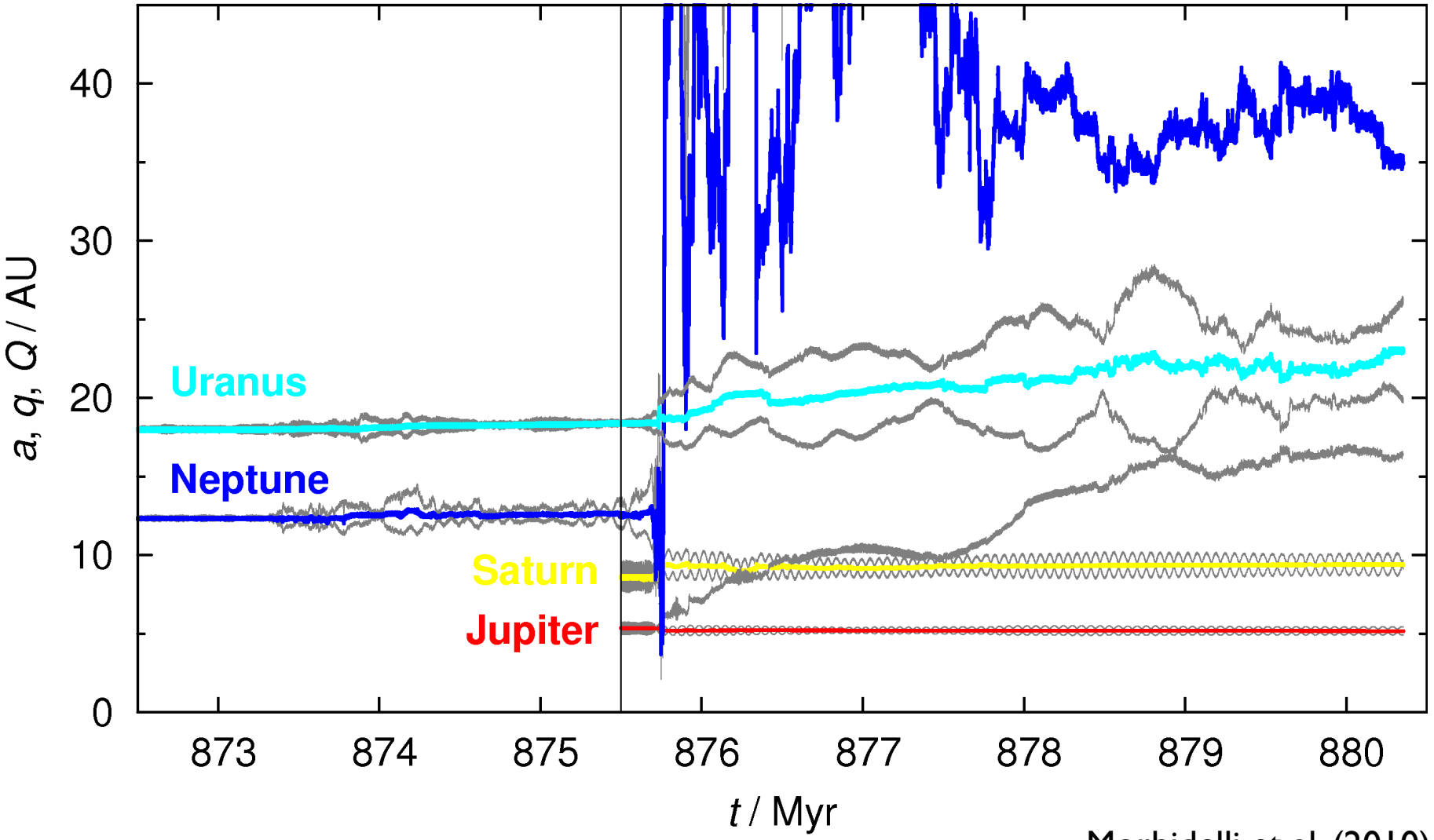
Masset (2000)

Interakce planet a planetesimál

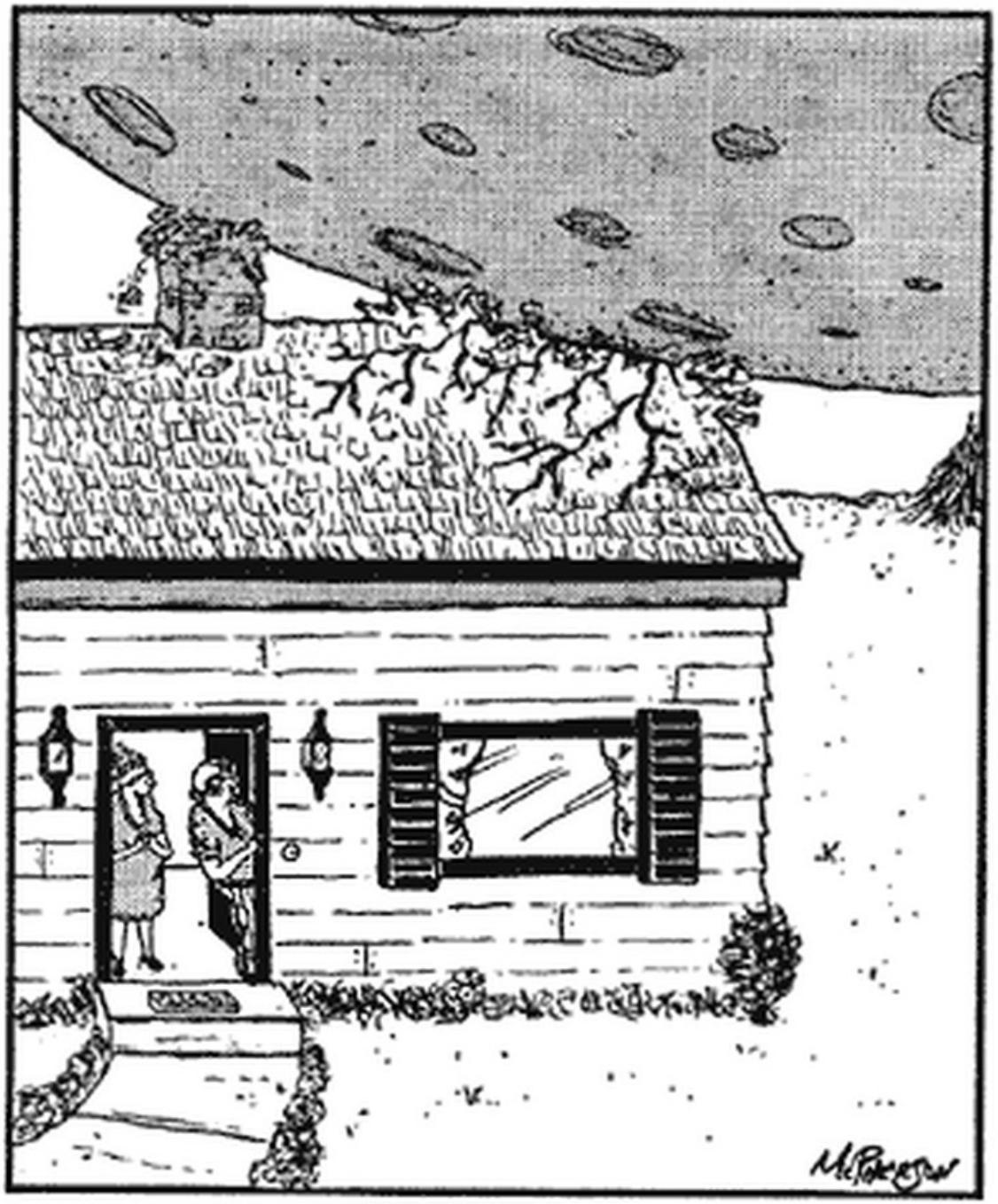


Levison et al. (2009)

Blízká přiblížení planet



Morbidelli et al. (2010)



"They say this is the closest Mars has been to Earth in 60,000 years."

Pátá obří planeta

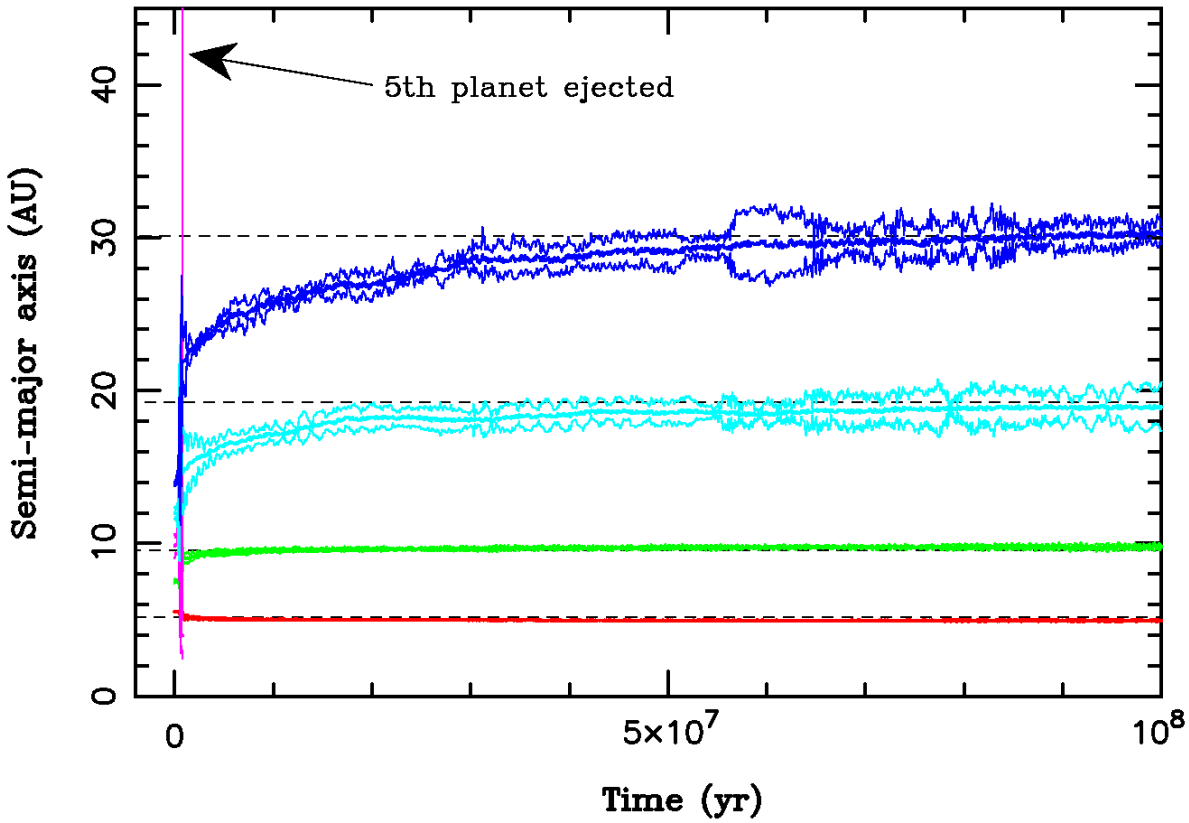


Figure 2. Orbit histories of giant planets in a simulation with five initial planets. The five planets were started in the (3:2,3:2,4:3,5:4) resonances, $M_{\rm disk} = 50\,M_{\rm Earth}$, and $r_{\rm in} = 15$ AU. After a series of encounters with Jupiter the inner ice giant was ejected from the solar system at 8.2×10^5 yr (purple path). The remaining planets were stabilized by the planetesimal disk and migrated to orbits that very closely match those of the outer planets (dashed lines).

Nesvorný (2011)