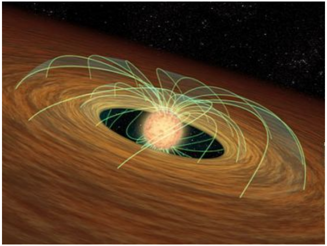
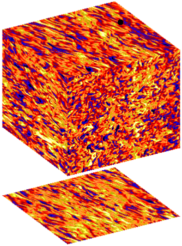
Lecture 2:
Protoplanetary discs



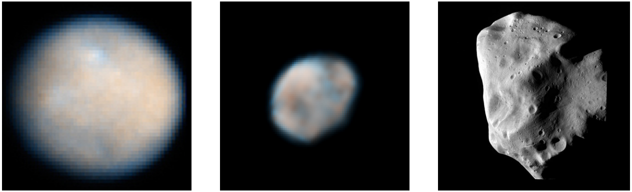


“Planet formation”

April 2016

Bertram Bitsch (Lund Observatory)

Asteroids and meteorites

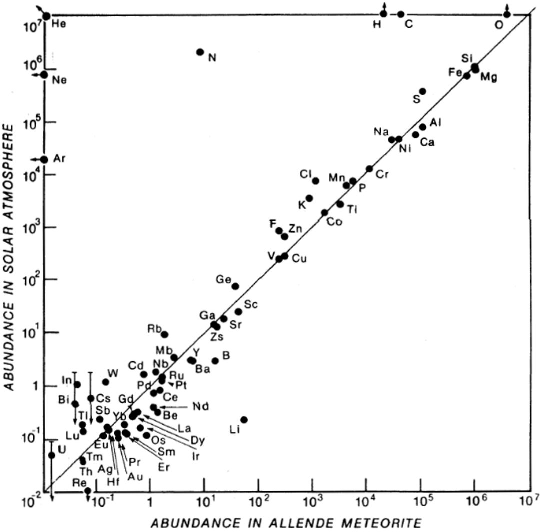


- Asteroid belt between the orbits of Mars and Jupiter
- Left-over planetesimals from the planet formation process
- Fragments of asteroids land on Earth as meteorites

⇒ Best evidence we have for conditions during planet formation

Abundances in meteorites

- Elemental abundances of CI carbonaceous chondrites are very similar to the Sun's photosphere
- N, H, C, O too low in CI meteorites – volatiles
- Li too low in the Sun – destroyed as part of H fusion



⇒ *The planets and the Sun formed from the same material*

⇒ *Planet material was not expelled from the Sun*

Chronology of meteorite parent bodies

- Need ^{26}Al to heat meteorite parent bodies
- Half-life of ^{26}Al is only 0.72 Myr

⇒ *Melting of meteorite parent bodies (planetesimals) by radioactive decay of ^{26}Al puts meteorite parent bodies in close connection with star formation*

-4.567 Gyr: CAIs

- First condensations in the *solar nebula*

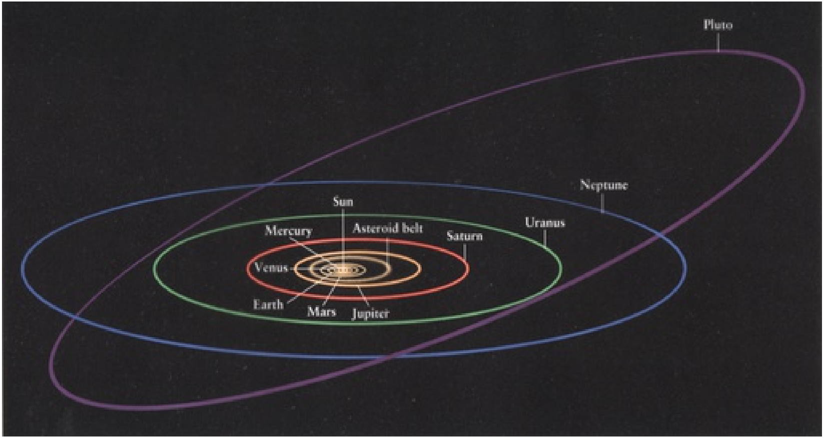
-4.566 Gyr: Differentiated parent bodies

- First $>$ 30 km asteroids (or planetesimals) to form
- Melted and differentiated by decay of ^{26}Al

-4.565 Gyr: Chondrules

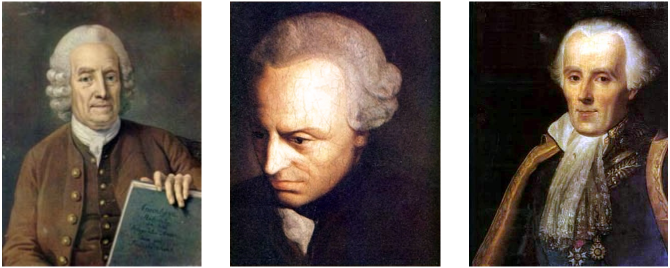
- Chondrite parent bodies formed when ^{26}Al no longer abundant enough for melting?
- Chondrules formed as molten asteroids collide in liquid rock splashes?
- Droplets solidify into chondrules that are accreted on differentiated parent bodies
- Chondrules could also form by shock heating or lightning

Solar system orbits



- The orbits of the eight planets lie in well-defined plane (variation in inclination is a few degrees)
- Asteroids and Kuiper belt objects (Pluto) have a larger variation, but that is due to gravitational encounters

Nebular hypothesis



Nebular hypothesis:

- **The planets of the solar system formed from a disc of gas and dust particles orbiting the newly born Sun**

⇒ Explains why the planets orbit in the same direction as the Sun's rotation and why the planets orbit in the same plane

- *The nebular hypothesis* was developed by Emanuel Swedenborg (1688-1772), Immanuel Kant (1724-1804) and Pierre-Simon Laplace (1749-1827)

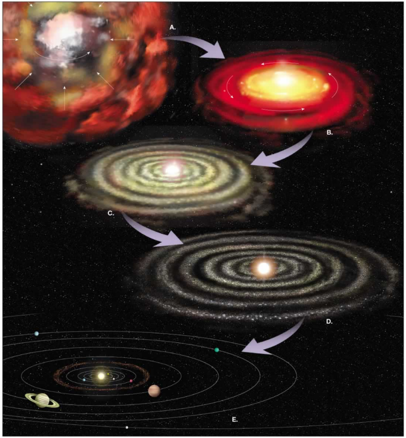
Outdated picture of planet formation

a Sun forms from rotating gas cloud

b Cloud cools down and forms flattened disc orbiting the Sun

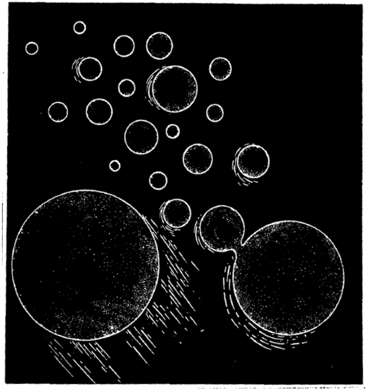
c-d Disc breaks up into rings

e Each ring forms a planet



⇒ **Warning:** steps c-e are interesting for historical reasons, but are no longer considered correct

Very outdated picture of planet formation



← Illustration from slide found in the basement of Lund Observatory:

"Whirled into swift rotation by a passing star, our sun tossed off matter into space. The hot sun material, rounded up in space, cooled down and finally, after gathering in other wandering sun matter, formed the planets."

Two outdated planet formation theories:

- A *star* passes close to the Sun and pulls out material which forms the planets
- A *comet* passes close to the Sun and pulls out material which forms the planets

Meteorite clues to planet formation

1. *The planets formed somewhere else and were captured by the Sun*
2. *The planets formed from material extracted from the Sun by a passing star (or comet!)*
3. *The planets formed together with the Sun, in a disc of material orbiting the young Sun*

- Hypothesis 1 does not work because it would be very unlikely to capture planets in circular orbits and with orbital planes aligned with the solar equator
- Hypothesis 2 would not work either, because Li is burned in the Sun, and the carbonaceous chondrites contain Li
- Hypothesis 3 can explain both the similarity between meteorite and solar photosphere abundances and circular orbits of the planets

⇒ Without the meteorites we would have no way to date the formation of the planets and the Sun and to connect them

Minimum Mass Solar Nebula

Nebular hypothesis:

- **The planets of the solar system formed from a disc of gas and particles which orbited the newly born Sun**

⇒ Explains why the planets orbit in the same direction as the Sun's rotation and why the planets orbit in the same plane

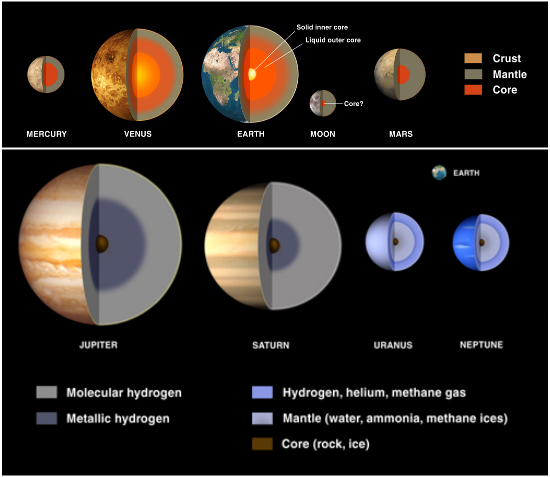
IDEA: Reconstruct the solar nebula by smearing out the planets

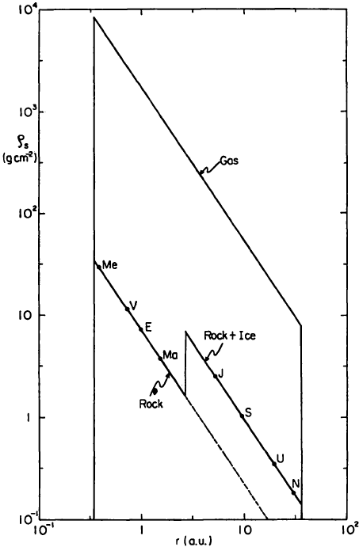
⇒ *Minimum Mass Solar Nebula* or *Hayashi nebula*

? Current dust-to-gas ratio in the solar system is much higher than 0.01

- Assumption: the dust was incorporated very efficiently into planets, while most of the gas was accreted by the Sun or photoevaporated
- Take the total icy and rocky component of the solar system and multiply by 100 to get gas *(Kusaka, Nakano, & Hayashi 1970; Weidenschilling 1977; Hayashi 1981)*

Rock and ice in the solar system





Column density in the Minimum Mass Solar Nebula

- Spread rock and ice in the solar system planets evenly over the distance to the neighbouring planets
- Assume rock and ice represent ≈1.8% of total material ⇒ original gas contents when multiplied by ≈100

$$\begin{aligned}
\Sigma_{\rm r}(r) &= 7\,{\rm g\,cm^{-2}}\left(\frac{r}{\rm AU}\right)^{-3/2} \quad {\rm for} \quad 0.35 < r/{\rm AU} < 2.7 \\
\Sigma_{\rm r+i}(r) &= 30\,{\rm g\,cm^{-2}}\left(\frac{r}{\rm AU}\right)^{-3/2} \quad {\rm for} \quad 2.7 < r/{\rm AU} < 36 \\
\Sigma_{\rm g}(r) &= 1700\,{\rm g\,cm^{-2}}\left(\frac{r}{\rm AU}\right)^{-3/2} \quad {\rm for} \quad 0.35 < r/{\rm AU} < 36
\end{aligned}$$

- Total mass of Minimum Mass Solar Nebula

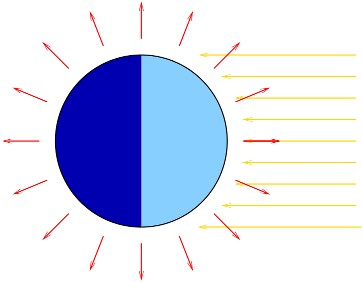
$$M = \int_{r_0}^{r_1} 2\pi r \Sigma_{\rm r+i+g}(r){\rm d}r \approx 0.013 M_\odot$$

Temperature in the solar nebula

- Much more difficult to determine the temperature in the solar nebula
- Several energy sources: solar irradiation, viscous heating, irradiation by nearby stars
- Simplest case: only solar irradiation in optically thin nebula

$$F_\odot = \frac{L_\odot}{4\pi r^2}$$

$$P_{\rm in} = \pi \epsilon_{\rm in} R^2 F_\odot \qquad P_{\rm out} = 4\pi R^2 \epsilon_{\rm out} \sigma_{\rm SB} T_{\rm eff}^4$$



$$T_{\rm eff} = \left[\frac{F_\odot}{4\sigma_{\rm SB}}\right]^{1/4}$$

$$T = 280\,{\rm K}\,\left(\frac{r}{\rm AU}\right)^{-1/2}$$

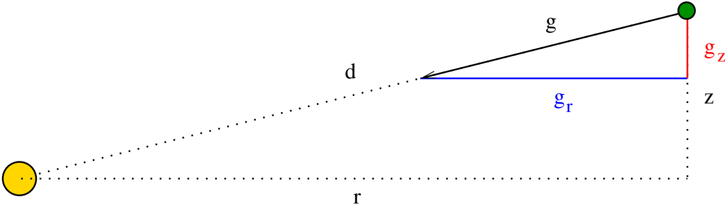
Vertical gravity

Radial density structure solar nebula

$$\Sigma(r) = 1700\,\mathrm{g\,cm^{-2}}(r/\mathrm{AU})^{-1.5}$$

- What about the vertical structure?

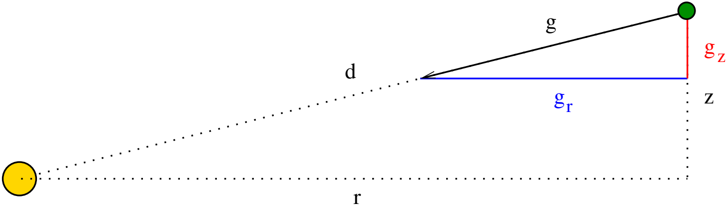
⇒ Hydrostatic equilibrium between gravity and pressure



- The distance triangle and the gravity triangle are *similar triangles* ⇒ $g_z/g = z/d$

$$g_z = g\frac{z}{d} = -\frac{GM_\star}{d^2}\frac{z}{d} \approx -\frac{GM_\star}{r^3}z = -\Omega_{\mathrm{K}}^2 z$$

Hydrostatic equilibrium structure



- Equation of motion for fluid element at height z over the disc mid-plane:

$$\frac{\mathrm{d}v_z}{\mathrm{d}t} = -\Omega_{\mathrm{K}}^2 z - \frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}z}$$

- For constant temperature T we can write $P = c_{\mathrm{s}}^2\rho$ (isothermal equation of state with sound speed c_{s}=const)
- Look for hydrostatic equilibrium solution:

$$0 = -\Omega_{\mathrm{K}}^2 z - c_{\mathrm{s}}^2\frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}z}$$

Scale height

- Hydrostatic equilibrium condition:

$$0 = -\Omega_{\mathrm{K}}^2 z - c_{\mathrm{s}}^2 \frac{\mathrm{d}\ln\rho}{\mathrm{d}z}$$

- Rewrite slightly and introduce *scale height* $H = c_{\mathrm{s}}/\Omega_{\mathrm{K}}$:

$$\frac{\mathrm{d}\ln\rho}{\mathrm{d}z} = -\frac{\Omega_{\mathrm{K}}^2}{c_{\mathrm{s}}^2} z = -\frac{z}{H^2}$$

- Solution in terms of $\ln\rho$:

$$\ln\rho = \ln\rho_0 - \frac{z^2}{2H^2}$$

- Solution in terms of ρ:

$$\rho(z) = \rho_0 \exp\left[-\frac{z^2}{2H^2}\right]$$

Mid-plane density

Vertical density structure of solar nebula

$$\rho(z) = \rho_0 \exp\left[-\frac{z^2}{2H^2}\right]$$

- $\rho_0 = \rho(r, z = 0)$ is the mid-plane gas density
- Problem: we only know the column density. Connection between Σ and ρ_0 comes from definite integral

$$\begin{aligned} \Sigma &= \int_{-\infty}^{\infty} \rho(z)\mathrm{d}z = \rho_0 \int_{-\infty}^{\infty} \exp[-z^2/(2H^2)]\mathrm{d}z \\ &= \sqrt{2}H\rho_0 \int_{-\infty}^{\infty} \exp[-\zeta^2]\mathrm{d}\zeta = \sqrt{2\pi}H\rho_0 \end{aligned}$$

- This yields the mid-plane density

$$\rho_0 = \frac{\Sigma}{\sqrt{2\pi}H}$$

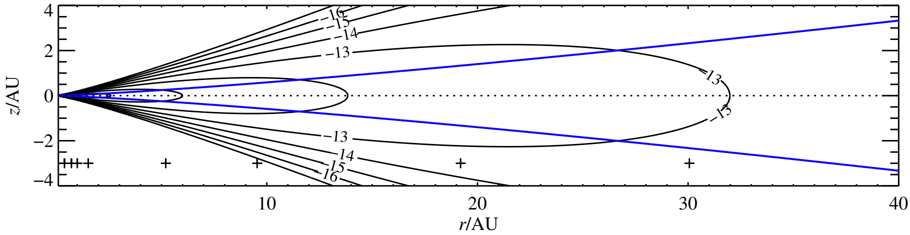
Minimum Mass Solar Nebula overview

- As a starting point for planet formation models we can use the Minimum Mass Solar Nebula model of Hayashi (1981):

$$
\begin{aligned}
\Sigma(r) &= 1700\,\mathrm{g\,cm^{-2}}\left(\frac{r}{\mathrm{AU}}\right)^{-3/2} \\
T(r) &= 280\,\mathrm{K}\left(\frac{r}{\mathrm{AU}}\right)^{-1/2} \\
\rho(r,z) &= \frac{\Sigma(r)}{\sqrt{2\pi}H(r)}\exp\left[-\frac{z^2}{2H(r)^2}\right] \\
H(r) &= \frac{c_\mathrm{s}}{\Omega_\mathrm{K}} \qquad\qquad \Omega_\mathrm{K} = \sqrt{\frac{GM}{r^3}} \\
c_\mathrm{s} &= 9.9\times 10^4\,\mathrm{cm\,s^{-1}}\left(\frac{2.34}{\mu}\frac{T}{280\,\mathrm{K}}\right)^{1/2} \\
H/r &= \frac{c_\mathrm{s}}{v_\mathrm{K}} = 0.033\left(\frac{r}{\mathrm{AU}}\right)^{1/4}
\end{aligned}
$$

Minimum Mass Solar Nebula density

- Density contours in solar nebula:



- Mid-plane gas density varies from 10^{-9} g/cm^3 in the terrestrial planet formation region down to 10^{-13} g/cm^3 in the outer nebula
- Blue line shows location of $z = H$
- Aspect ratio increases with r, so solar nebula is slightly *flaring*

Molecular clouds

Stars form in giant molecular clouds:

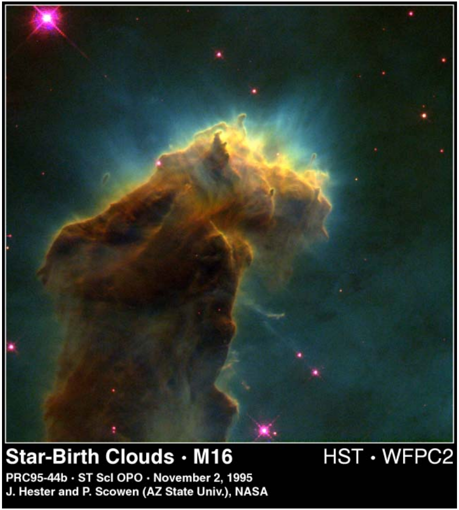
- Consist mainly of H_2 molecules
- Typical masses 10^4–10^6 $M_\odot$
- Typical sizes 10–100 pc
- Typical densities 10^2–10^3 cm^{-3} (average MW: 0.1 cm^{-3})

← Orion (412 pc)

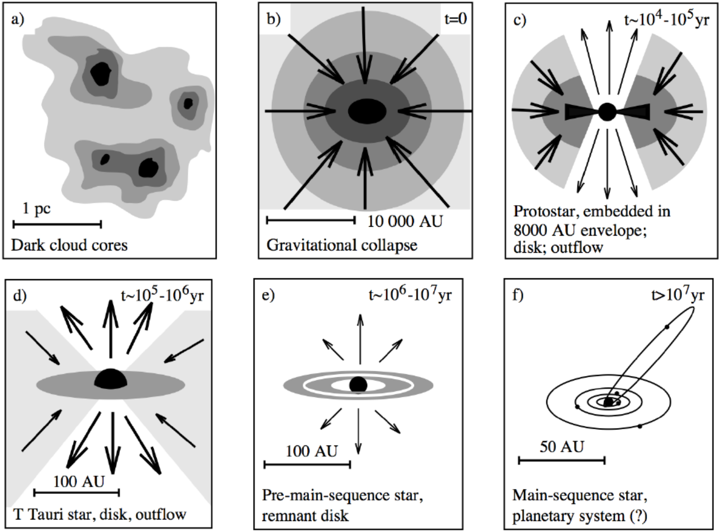
- Taurus (140 pc)
- …

Dark clouds

- Densest parts of giant molecular clouds appear black against the background ⇒ **Dark Clouds**



Star formation (sketch)

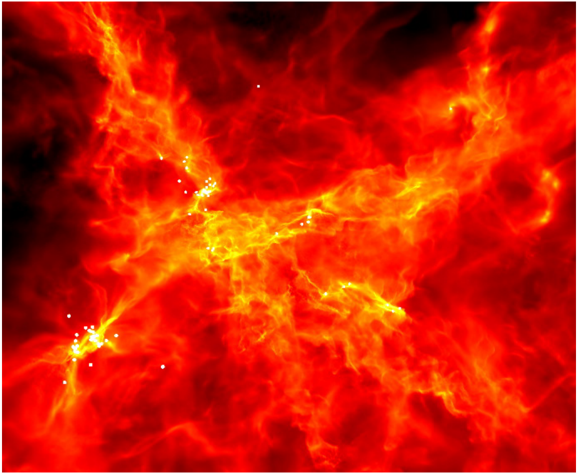


(Shu et al. 1987)

Illustration by Hogerheijde

Nature: Turbulence, magnetic fields, cosmic rays, supernovae, outflows, ...

Computer simulation of star formation



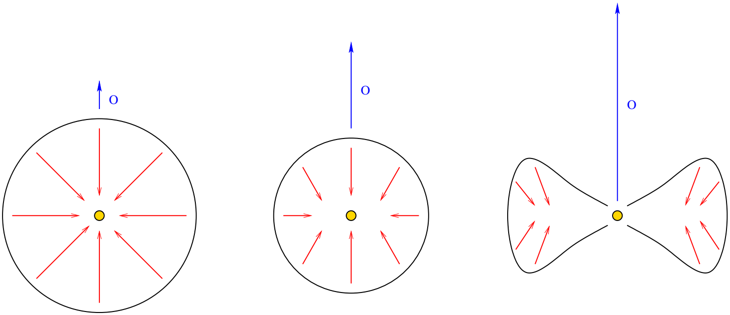
Movie by Matthew Bate

⇒ Supersonic turbulence counteracts self-gravity and prevents collapse

⇒ . . . but turbulence also compresses gas into filaments that collapse into stars

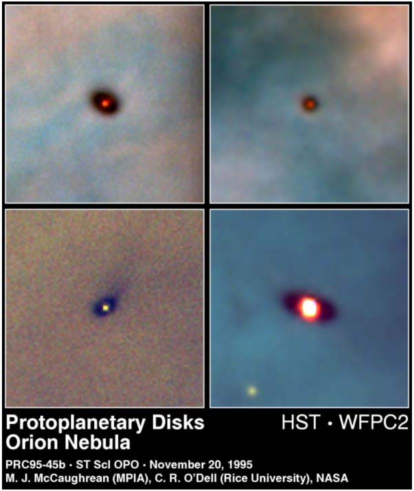
Circumstellar discs

- If dense cores rotate, then material spins up during gravitational contraction
- Specific angular momentum $\mathbf{L} = \mathbf{r} \times \mathbf{v}$ conserved
- Radial collapse stops when $L = L_{\rm Kep} = \sqrt{GM_\star r}$
- Centrifugal radius $r_{\rm c} = L^2/(GM_\star)$



$\Rightarrow$ Further contraction can only happen along $\boldsymbol{\Omega}$, so material lands on the disc rather than on the star

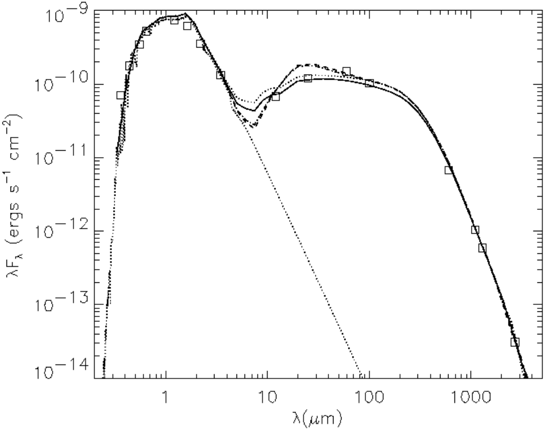
Proplyds



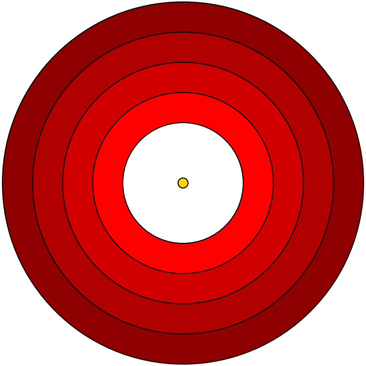
- Protoplanetary discs in Orion appear dark against the bright background

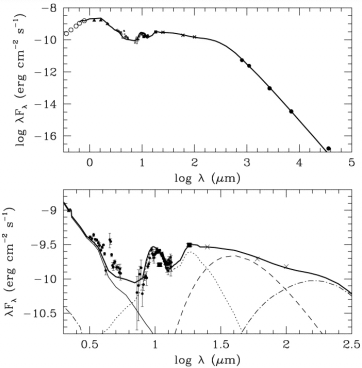
Spectral energy distribution

- The spectral energy distribution of young stars reveals two components: the stellar black body at short wavelengths and emission from warm circumstellar dust at long wavelengths



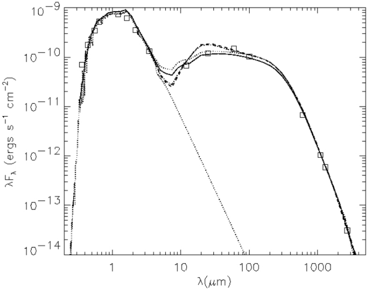
Irradiated dust

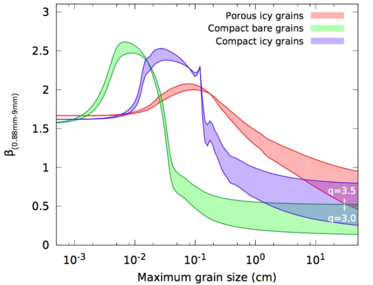




- Each ring radiates like a black body
- Temperature falls as r^{-q} ($q = 1/2$ in optically thin disc)
- Dust is the main opacity in protoplanetary discs
- Hydrogen molecules have *very* low opacity at low (10-100 K) temperatures
  $\Rightarrow$ H_2 very difficult to detect
- Use instead dust mass to find mass of a protoplanetary disc ($M_{\rm disc} \approx M_{\rm dust}/0.01$)

Observed dust growth



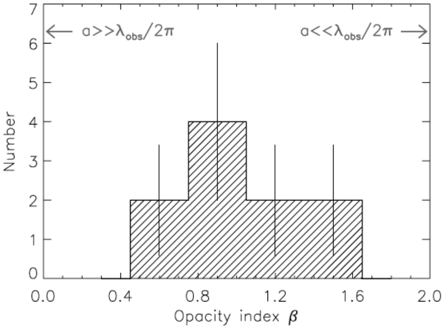


(*Testi et al.*, 2014)

- Dust opacity as a function of frequency $\nu = c/\lambda$:
  - $\kappa_\nu \propto \nu^2$ for $\lambda \gg a$
  - $\kappa_\nu \propto \nu^0$ for $\lambda \ll a$
- $F_\nu \propto \nu^\alpha \propto \kappa_\nu B_\nu \propto \kappa_\nu \nu^2 \propto \nu^\beta \nu^2$
- By measuring α from SED, one can determine β from $\beta = \alpha - 2$
- Knowledge of β gives knowledge of dust size

Opacity index

- Rodmann et al. 2006 observed 10 low-mass pre-main-sequence stars in the Taurus-Auriga star-forming region
- All had $\beta \sim 1$, indicating growth to at least millimeters
- Agrees well with expectation from radial drift barrier and bouncing barrier

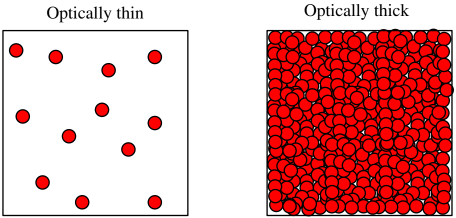


- The disc around TW Hya contains $10^{-3}\ M_{\odot}$ of cm-sized pebbles (Wilner et al. 2005) and more than $0.05 M_{\odot}$ of gas (Bergin et al. 2013)

Dust mass in protoplanetary discs

What is needed to determine the dust mass in a protoplanetary disc?

- The temperature of the dust
- The opacity of the dust
- *The dust emission must be optically thin*



⇒ Optically thin: emission proportional to emitting area of all particles – dust mass known if opacity κ known

⇒ Optically thick: emission proportional to surface area of disc – total dust mass unknown

Measuring the dust mass

What is needed to determine the dust mass in a protoplanetary disc?

- The temperature of the dust
- The opacity of the dust
- *The dust emission must be optically thin*

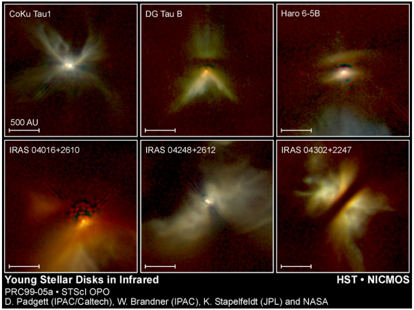
- Dust is optically thin at long wavelengths:
  - Opacity decreases for wavelengths much longer than typical particle size: $\kappa_\lambda \propto \lambda^{-2}$ for $\lambda \gg a$
- Measure energy flux at mm wavelengths:

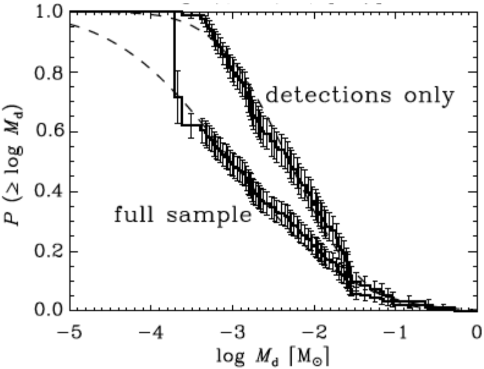
$$F_\nu = M_{\rm dust} \kappa_\nu B_\nu(\nu, T)/d^2$$

- Assume that distance d, dust temperature T and dust opacity κ_ν are known
- The total dust mass is $M_{\rm dust} = \frac{d^2 F_\nu}{\kappa_\nu B_\nu(\nu, T)}$

Disc masses in Taurus-Auriga

- *Taurus-Auriga complex* is one of the nearest active star forming regions ($d = 140$ pc, $M \sim 3.5 \times 10^4 \ M_\odot$)
- Andrews & Williams (2005) monitored 153 young stars for dust emission and found significant dust discs around 93 of them



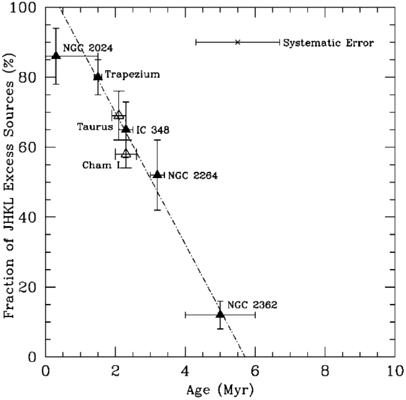


- Minimum mass solar nebula has $M_{\rm disc} = 0.013 \ M_\odot$

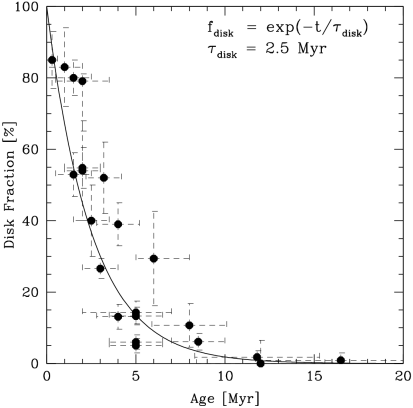
⇒ Solar nebula was a pretty standard protoplanetary disc

Life-times of protoplanetary discs

- Stars in same star-forming region are pretty much the same age
- Compare instead *disc fraction* between regions of different age



Haisch et al. (2001)



Mamajek (2009)

⇒ Protoplanetary discs live for 1–10 Myr

The end of protoplanetary discs

⇒ Dust discs live 1-10 Myr

Why do protoplanetary discs disappear?

1. Dust and gas incorporated into planets?
2. Dust and gas accreted?
3. Gas is photoevaporated?

Accretion luminosity

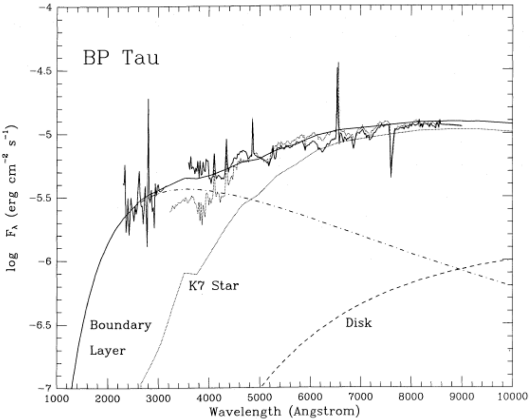


FIG. 6a

(Bertout et al. 1988)

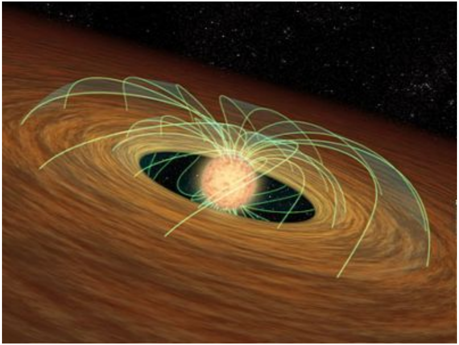
- Many young stars show excess in short-wavelength radiation
- Energy released by matter accreted onto the star

⇒ Signs of accretion tell us that protoplanetary discs are *turbulent*

Young star classification

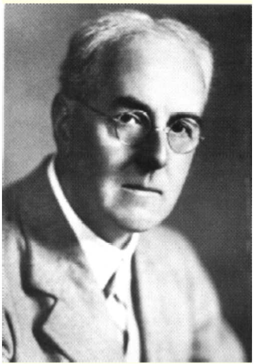
⇒ Young stars are identified by their Li abundance and by non-black-body emission arising as hot material lands on the star

- *T Tauri stars* are young stars that have shed their envelope, but are still accreting mass from a disc
- *Weak Line T Tauri stars* show signs of little accretion

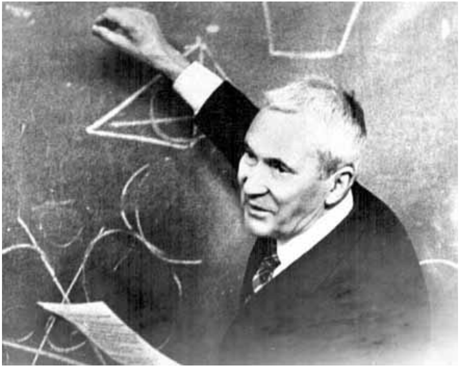


Turbulence

- Two important characters in the development of turbulence theory are



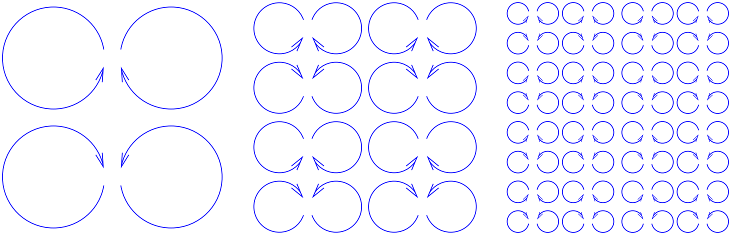
- Lewis Fry Richardson (1881-1953)



- Andrey Kolmogorov (1903-1987)

Turbulence

Lewis Fry Richardson about turbulence: *Big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls and so on to viscosity*



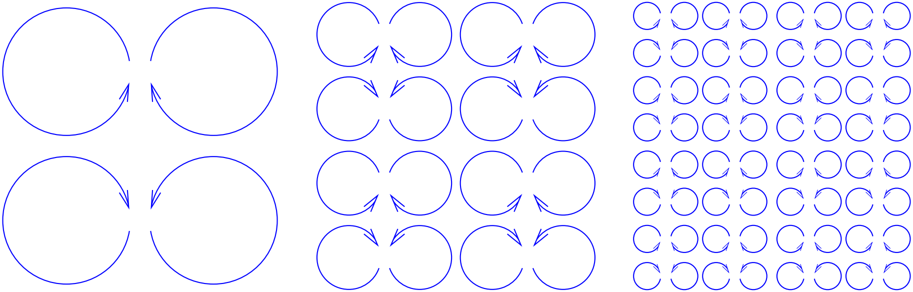
The general concept of turbulence:

- Energy injected at scale L
- Eddies break into smaller eddies which break into smaller eddies etc.
- Energy present at all scales
- Molecular viscosity dissipates energy at *Kolmogorov scale* ($\sim$ 1 km in protoplanetary discs)

Energy cascade

Turbulent eddy

Turbulent eddies at length scale ℓ have velocity u_ℓ and turn-over time-scale $t_\ell \sim \ell / u_\ell$

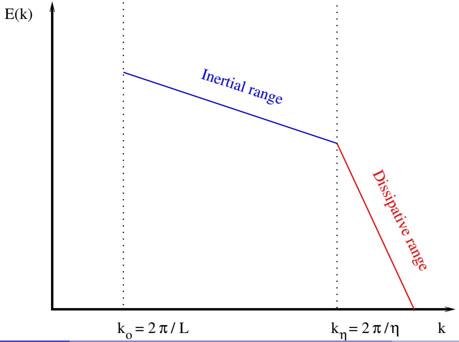


- Assume eddies live for one turn-over time before breaking apart into smaller eddies

$\Rightarrow$ *Energy cascade* $\epsilon \sim u_\ell^2 / t_\ell \sim u_\ell^3 / \ell$

Energy spectrum

- Practical to work with wavenumber k rather than scale ℓ
- Want to determine the energy spectrum $E(k)$ – the kinetic energy per unit wavenumber at scale k
- Relevant scales:
    - L: energy injection scale
    - η: dissipation scale (Kolmogorov scale)
    - $L \gg \ell \gg \eta$: inertial range (constant ϵ)
    - $\ell \ll \eta$: dissipative range



Inertial range

Kolmogorov's assumption:

The energy spectrum in the inertial range where $L \gg \ell \gg \eta$ can only depend on the rate of energy dissipation ϵ and scale k

- Dimensional analysis of $E = \epsilon^a k^b$ gives

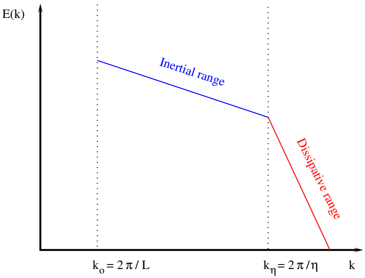
$$\begin{aligned} [E] &= [\epsilon]^a [k]^b \\ m^3 s^{-2} &= (m^2 s^{-3})^a (m^{-1})^b \end{aligned}$$

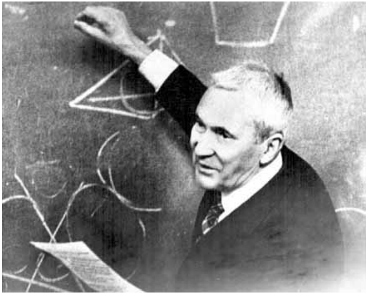
$$\begin{aligned} 3 &= 2a - b \\ -2 &= -3a \end{aligned}$$

- Solution $a = 2/3$ and $b = -5/3$

⇒ Very famous result of turbulence theory $E(k) \sim \epsilon^{2/3} k^{-5/3}$

Kolmogorov scale

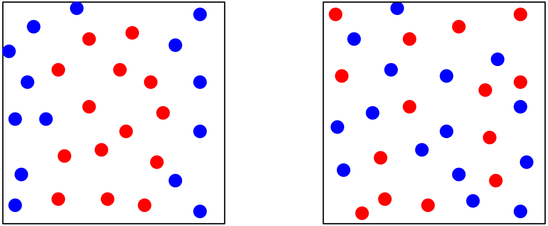




- Energy injected at large scales
- Cascades at constant rate through inertial range
- Molecular viscosity dissipates energy to heat below the Kolmogorov scale
- Assuming that Kolmogorov scale η only depends on energy dissipation rate ϵ and molecular viscosity ν we get $\eta = \left(\frac{\nu^3}{\epsilon}\right)^{1/4}$

Turbulent mixing

- Take a box with equally many red and blue balls
- Separate the red balls from the blue balls
- Let all balls random walk $N \gg 1$ steps



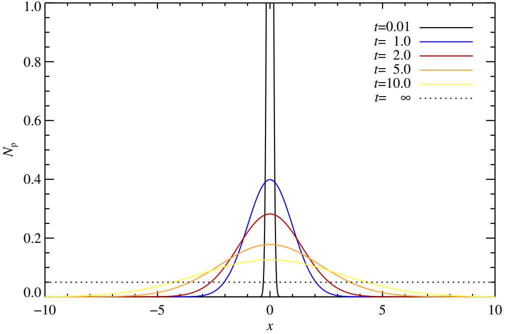
$\Rightarrow$ The two colours mix completely

$\Rightarrow$ Turbulence evens out concentrations (*turbulent diffusion*)

$\Rightarrow$ Turbulence evens out velocity differences (*turbulent viscosity*)

Random walk

- Start many particles at $x = 0$ and subject to random walk with step-size δx and time-step δt



- The mean distance from the axis is maintained ($\langle x \rangle = 0$ for all t)
- The mean squared distance from the axis goes as $\langle x \rangle^2 \sim Dt$ with the diffusion coefficient $D = (\delta x)^2/(\delta t) = v_\mathrm{t} \delta x$

Viscosity

Fluid elements in a Keplerian differential rotation profile $\Omega_{\mathrm{K}}(r) \propto r^{-3/2}$ rub against each other

- Inner ring slows down, while outer ring speeds up (?)

$\Rightarrow$ Donkey effect: inner ring falls to lower orbit and speeds up, outer ring raised to higher orbit and slows down

$\Rightarrow$ Transport of mass and angular momentum

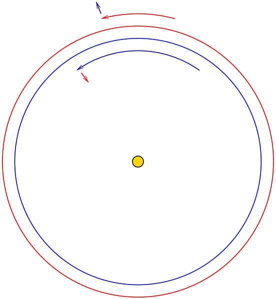
$\Rightarrow$ Energy release heats the disc

Protoplanetary discs accrete on to the star on the viscous time-scale

$$t_{\mathrm{visc}} = \frac{R^2}{\nu}$$

where ν is the viscosity, since the displacement in a random walk with diffusion coefficient D follows

$$\sigma \sim \sqrt{Dt}$$

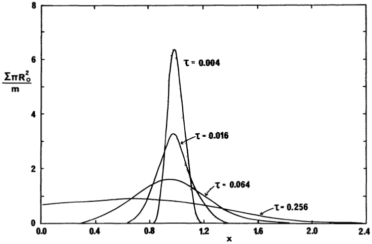


Spreading ring of material

- Time evolution of column density $\Sigma(R,t)$: [Pringle 1981]

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[R^{1/2}\frac{\partial}{\partial R}\left(\nu \Sigma R^{1/2}\right)\right]$$

- Evolution of narrow ring of material with constant ν:



Equilibrium mass flux: $\dot{M} = 3\pi\Sigma\nu$

Turbulent viscosity

Major problem: viscous time-scale is much longer than a Hubble time

$$t_{\rm visc} = \frac{R^2}{\nu}$$

von Weizsäcker 1948:
Replace molecular viscosity ν by turbulent viscosity $\nu_{\rm t}$

Shakura & Sunyaev 1973:
Assume that typical eddies have scale $\ell \sim \sqrt{\alpha} H$ and velocity $v_{\rm t} \sim \sqrt{\alpha} c_{\rm s}$

Famous α prescription of Shakura Sunyav 1973:

$$\nu_{\rm t} \sim \ell \times v_{\rm t} \sim \alpha H c_{\rm s}$$

Viscous time-scale revisited

Viscous time-scale:

$$t_{\rm visc} = \frac{R^2}{\nu}$$

For protoplanetary discs of scale $R \sim 10\,\mathrm{AU}$ and sound speed $c_{\rm s} \sim 500$ m/s we have

- $\nu_{\rm mol} \sim c_{\rm s}\lambda \quad \sim 10^3\,\mathrm{m}^2\,\mathrm{s}^{-1}, \; t_{\rm visc} \sim 10^{14}\,\mathrm{yr}$
- $\nu_{\rm t} \quad \sim \alpha H c_{\rm s} \sim 10^{12}\,\mathrm{m}^2\,\mathrm{s}^{-1}, \; t_{\rm visc} \sim 10^{5}\,\mathrm{yr}$

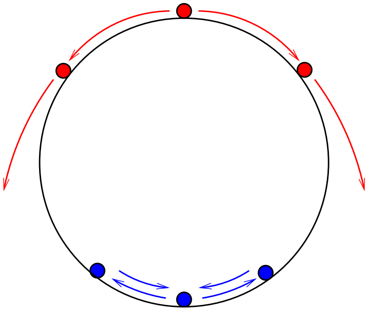
- Used here $\alpha = 0.01$

⇒ But what is α really?

- Use numerical simulations to constrain α

Stability of hydrodynamical flows

1. Find equilibrium flow solution (e.g. Keplerian flow, simple shear flow, etc.)
2. Find out if flow is stable or unstable to small perturbations (analytical stability analysis or numerical simulation)
3. If unstable: measure strength of turbulent viscosity in non-linear turbulent state (numerical simulation)

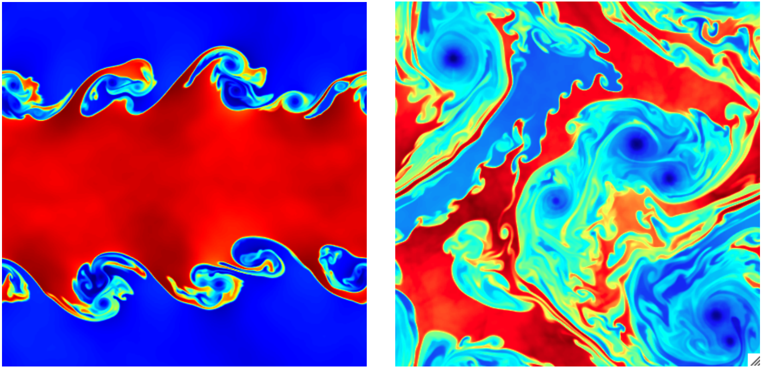


- Example of stability (blue ball) and instability (red ball)

Kelvin-Helmholtz instability

⇒ A very famous instability is the Kelvin-Helmholtz instability

- $v_x = -0.5$ in box centre, $v_x = +0.5$ at box edge

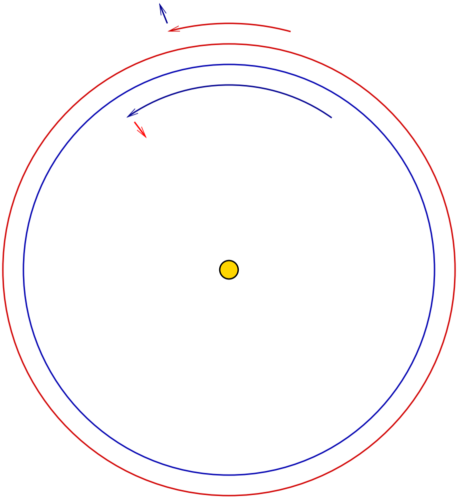


(Movie by Jim Stone)

⇒ *Turbulence thrives on energy differences*

Keplerian shear flows

- Unfortunately Keplerian shear flows are linearly stable
- This has been confirmed both analytically, in the laboratory, and using numerical simulations



Magnetorotational instability

Balbus & Hawley (1991):

A weak vertical magnetic field renders Keplerian shear flows *linearly* unstable to the *magnetorotational instability*

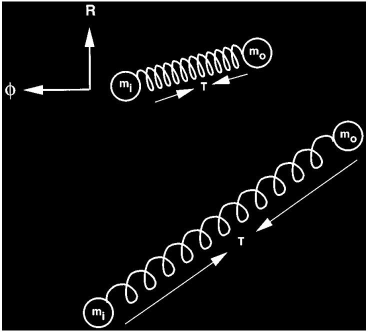
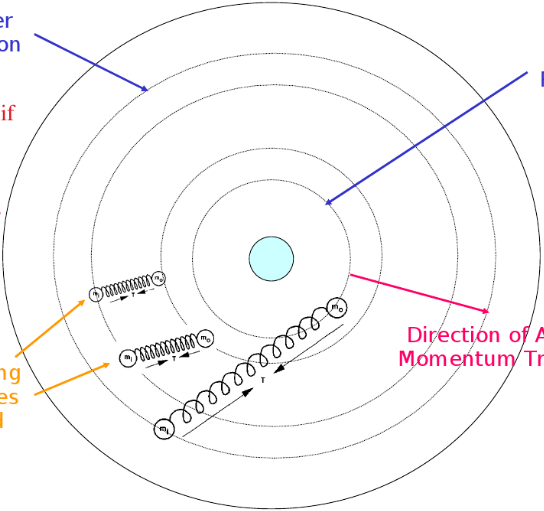


Figure from Balbus & Hawley (1998)

- MRI works if degree of ionisation high enough

Two masses on a spring



Slower
Rotation

Faster
Rotation

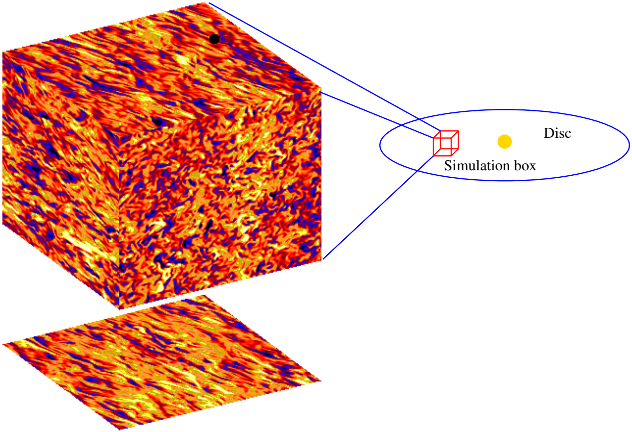
Unstable if
angular
velocity
decreases
outward

Direction of Angular
Momentum Transport

Stretching
Amplifies
B-field

Magnetorotational turbulence

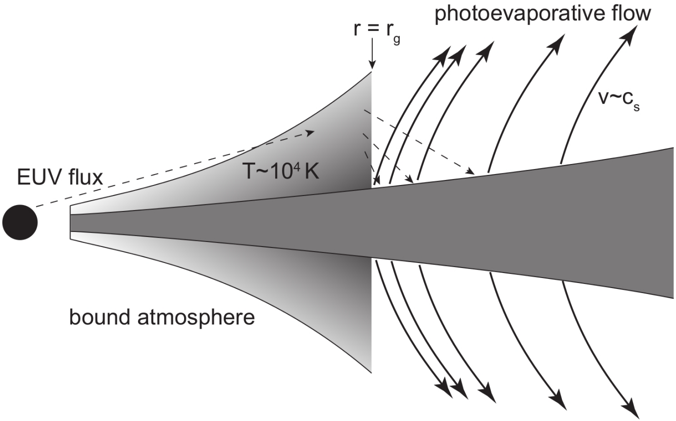
- To model the non-linear evolution of the MRI, we need to solve the full set of dynamical equations numerically in 3-D



- Measured viscosity strength $\alpha \sim 10^{-4}$-10^{-1}

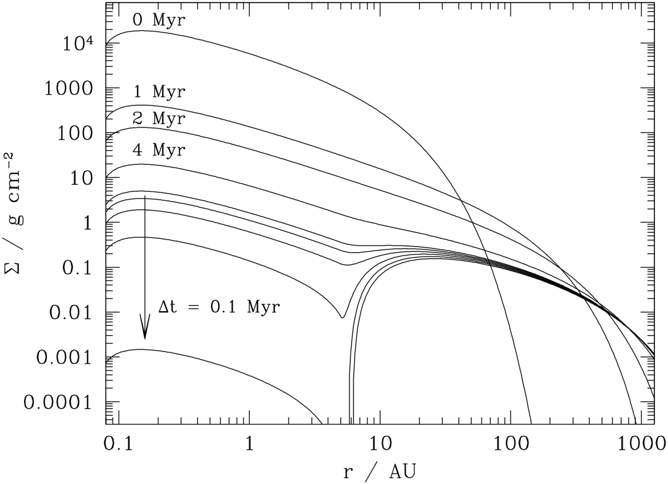
$\Rightarrow$ Turbulence caused by MRI can explain accretion onto young stars

Disc dispersal



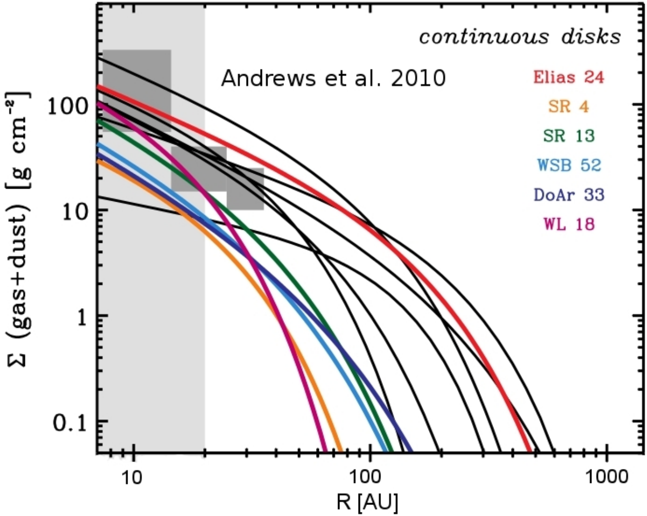
- Stellar EUV radiation ionizes and heats the surface layers of the disc
- Where the thermal energy of the surface layer remains small compared to the binding energy, the hot gas forms a bound atmosphere
- At larger radii, where the gas is more weakly bound, the hot gas flows away in a thermally driven wind

Disc evolution with photoevaporation



- $\dot{M}_{\rm photo}$ acts at all time, but in the beginning $\dot{M}_{\rm acc} > \dot{M}_{\rm photo}$
- Only when $\dot{M}_{\rm acc} \sim \dot{M}_{\rm photo}$, photoevaporation starts to clear the disc

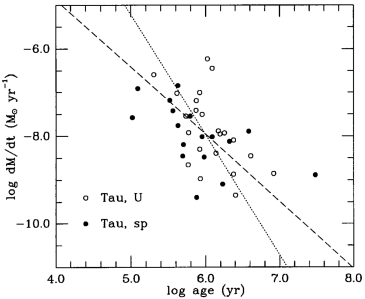
Constraints from Observations

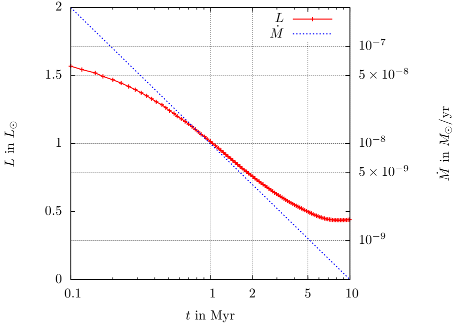


$$\Sigma \propto r^{-\alpha_\Sigma} \quad \text{with} \quad \alpha_\Sigma = 0.4 - 1.1$$

Evolution of the star and the disc

- Accretion rate $\dot{M}$ ($\propto \Sigma_{\mathrm{g}}$) changes with time (Hartmann et al., 1998)
  $\Rightarrow$ Accretion rate changes by a factor of 100 in 5 Myr!
- Star changes luminosity in time (Baraffe et al., 1998)
  $\Rightarrow$ Stellar luminosity changes by a factor of 3 in 5 Myr!





$\Rightarrow$ The disc is subject to massive changes in its lifetime!

Composition of the disc

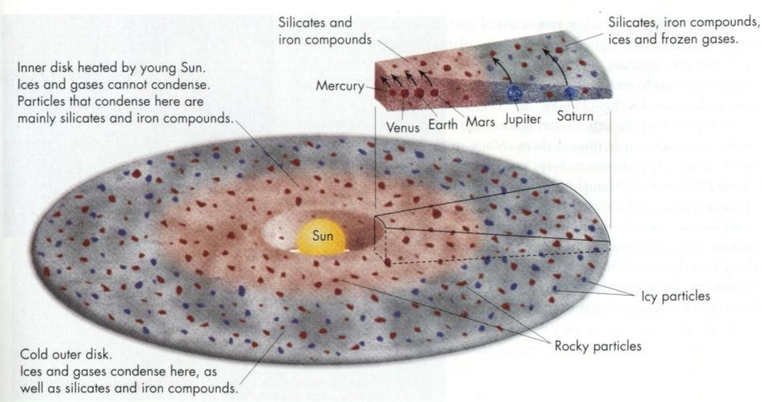


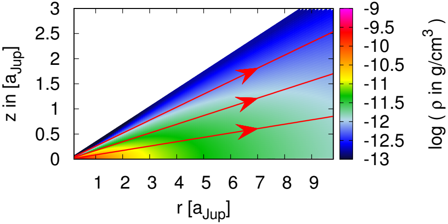
FIGURE OV4.6

Heat from the young Sun prevented ice from condensing in the inner parts of the Solar Nebula. The planetesimals—and ultimately the planets—that formed there are therefore composed mainly of rock and iron.

- The inner regions of the disc are hotter than the outer regions: $\Rightarrow$ Icy particles only in the outer parts of the disc!

Numerical simulations: Disc Model

- 2D hydrodynamical disc model with viscous heating, radiative cooling and stellar irradiation



- Mass flux through disc: $\dot{M}$ disc with α viscosity:

$$\dot{M} = 3\pi\nu\Sigma = 3\pi\alpha H^2\Omega_K\Sigma$$

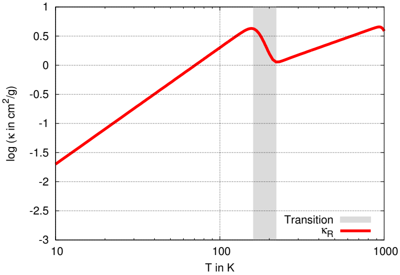
- Change of $\dot{M}$-rate by changing Σ

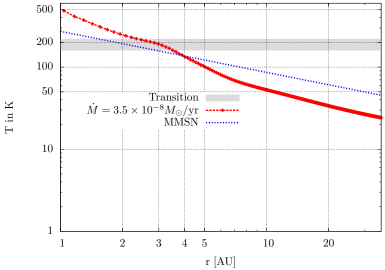
Disc structure: opacity transition at the water ice line

- Cooling of the disc:

$$\mathbf{F} = -\frac{\lambda c}{\rho \kappa_\mathrm{R}} \nabla E_\mathrm{R}$$

- Grey area marks transition in opacity at the ice line
- Change of opacity: $\Rightarrow$ change of cooling
- Change of cooling: $\Rightarrow$ change in $T(r)$





(*Bitsch et al., 2014, 2015a*)

Disc structure: $\dot{M}$ and viscosity

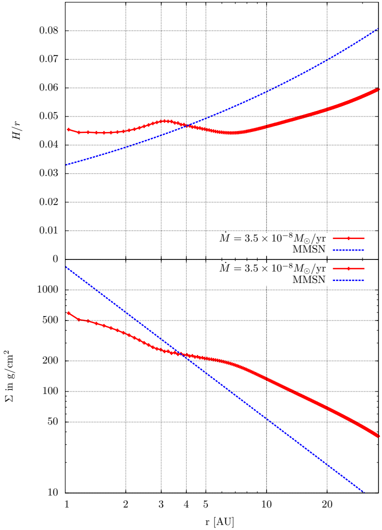
- Hydrostatic equilibrium:

$$T = \left(\frac{H}{r}\right)^2 \frac{GM_\star}{r} \frac{\mu}{\mathcal{R}}$$

- bump in T: bump in H/r
- $\dot{M}$ disc:

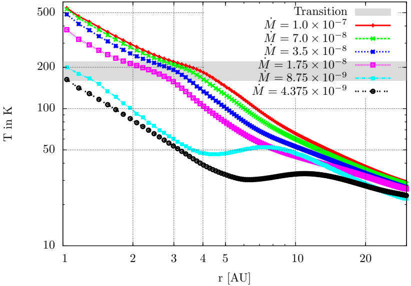
$$\dot{M} = 3\pi\nu\Sigma = 3\pi\alpha H^2 \Omega_\mathrm{K} \Sigma$$

- $\dot{M}$ constant at each r:
  $\Rightarrow$ dip in Σ



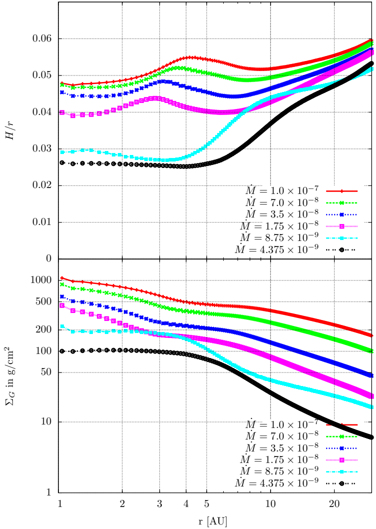
(*Bitsch et al., 2014, 2015a*)

Disc structure evolution



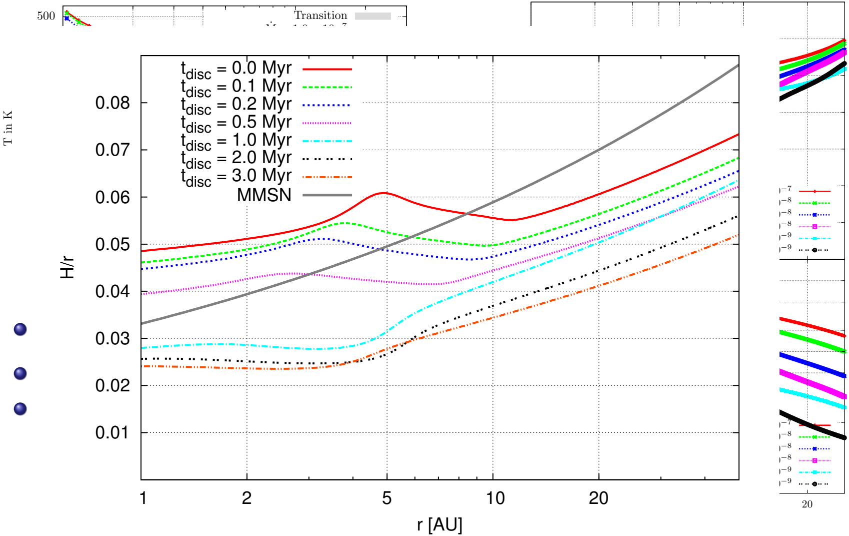
- $\dot{M}$ decreases with decreasing Σ
- $\dot{M} = 3\pi\nu\Sigma = 3\pi\alpha H^2\Omega_{\rm K}\Sigma$
- Evolution in time follows Hartmann et al. 1998 equation:

$$\log\left(\frac{\dot{M}}{M_\odot/\text{yr}}\right) = -8.00 - 1.40\log\left(\frac{t_{\rm disc} + 10^5\text{yr}}{10^6\text{yr}}\right) .$$



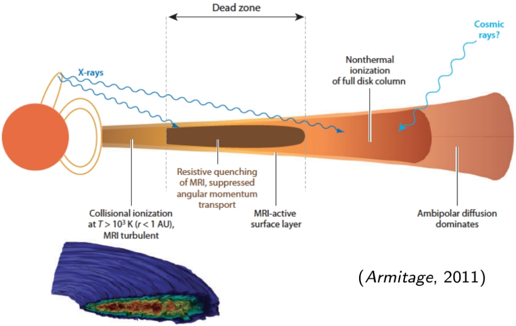
(*Bitsch et al., 2015a*)

Disc structure evolution

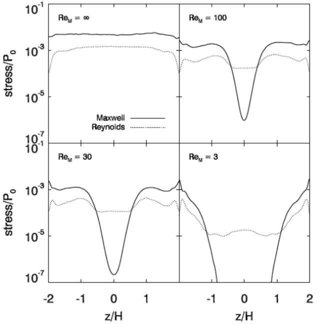


(*Bitsch et al., 2015a*)

Dead zone and layered accretion



(*Armitage*, 2011)



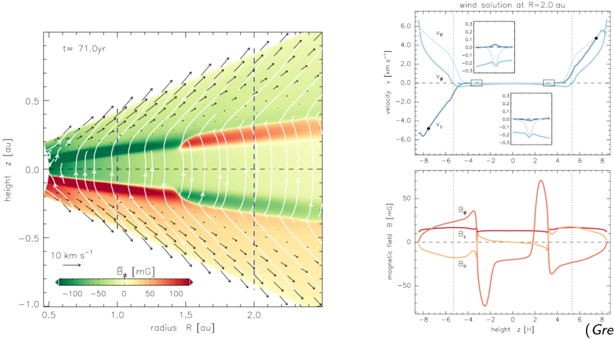
(*Gammie*, 1996; *Fleming & Stone*, 2003; *Oishi et al.*, 2007)

- Cosmic rays do not penetrate to the mid-plane of the disc, so the ionisation fraction in the mid-plane is too low to sustain MRI

⇒ Accretion in active surface layers or by disc winds
(*Blandford & Payne, 1982; Fromang et al., 2012; Bai & Stone, 2013*)

⇒ Weak turbulence and low collision speeds in the dead zone

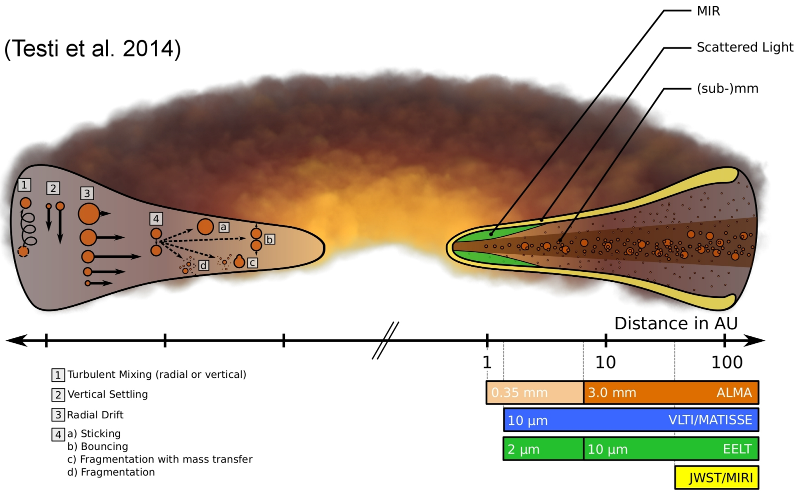
Disc wind model



(*Gressel et al.*, 2015)

- Mid-plane is decoupled from the magnetic field by ohmic diffusion and surfacelayers by ambipolar diffusion (*Bai & Stone, 2013*)
- Threading magnetic field enters a wind configuration (*Blandford & Payne, 1982*)
- Angular momentum transported vertically away from the mid-plane
- Thin but rapid accretion flow where azimuthal magnetic field changes sign about 3 *H* from the mid-plane (*Gressel et al., 2015*)
- Mid-plane is completely laminar with no turbulent motion

Observations of protoplanetary discs



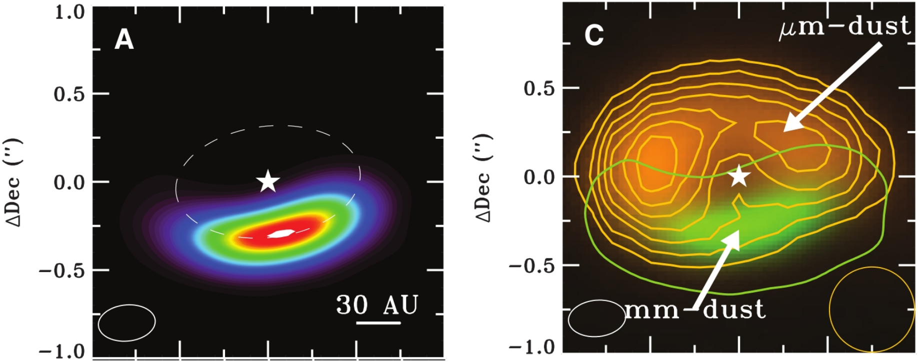
(Testi et al. 2014)

⇒ More about grain growth in the next lectures!

Atacama Large Millimeter Array

⇒ ALMA is the most powerful submm observatory

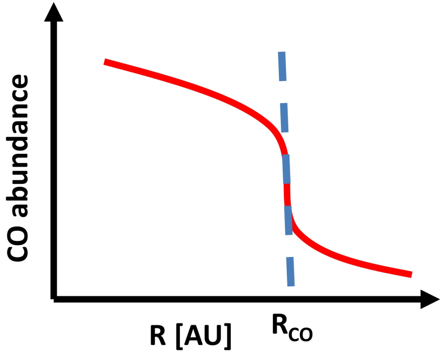
Dust concentrations around Oph IRS 48



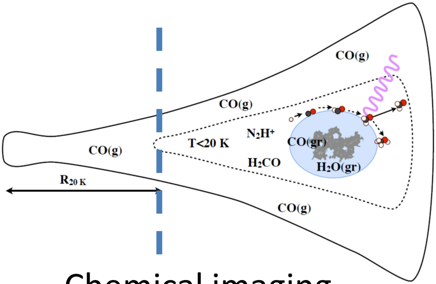
- first detection of dust concentration in disc
- Asymmetry for big/small grains ⇒ planet in the disc?

(*van der Marel et al. 2013*)

How to detect the CO snow line?



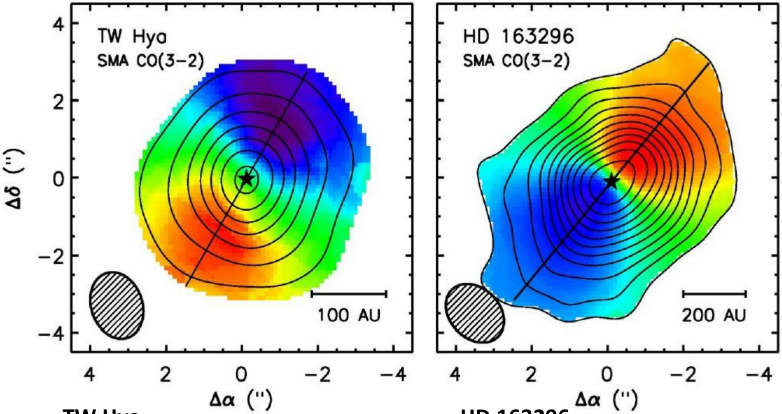
CO abundance drop



Chemical imaging

- Snow lines important for planet formation (⇒ see next talks)
- Water snow line too close to the star for observations

CO discs are huge



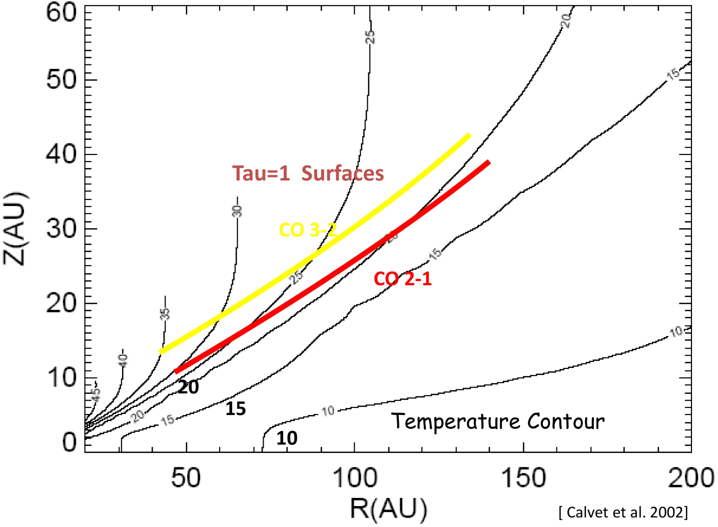
TW Hya

HD 163296

- Classical T Tauri star
- 8-12 Myr old
- Inclination 7°

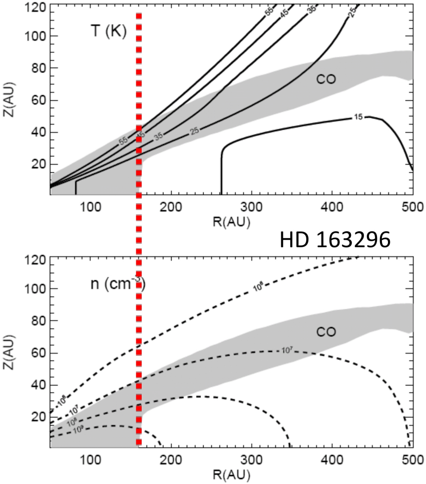
- Herbig Ae star
- 3-5 Myr old
- Inclination 44°

Radial and vertical disc structure



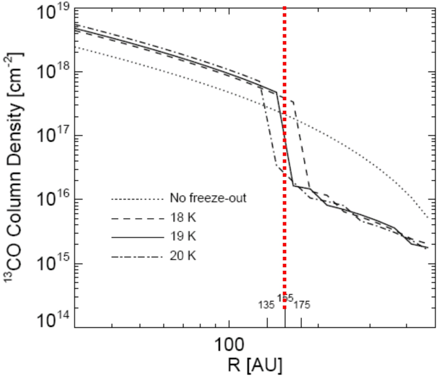
[Calvet et al. 2002]

Location of the CO snow line based on SMA observations



HD 163296

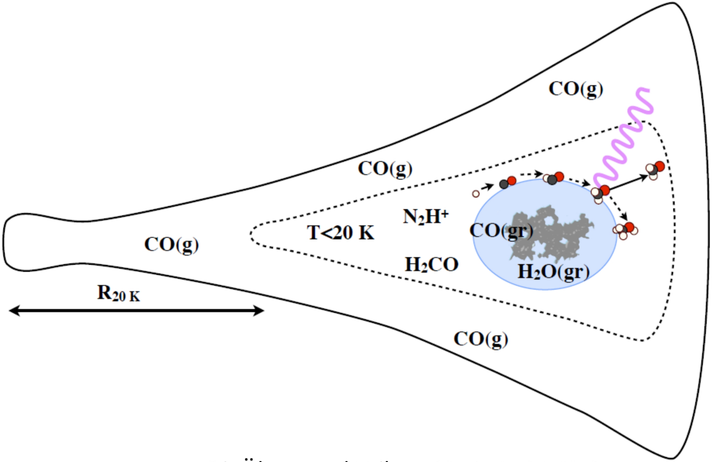
R_{CO} = 155 AU



[Qi, d'Alessio, Öberg et al. 2011]

⇒ Observations are very challenging!

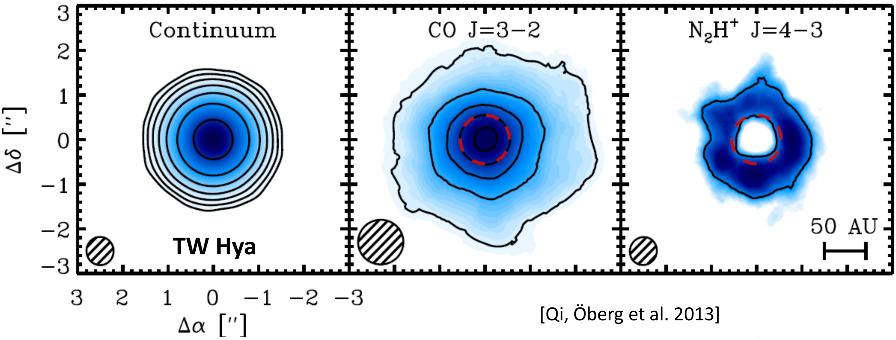
Chemistry at the CO snow line



Qi, Öberg and Wilner 2013, ApJ, 765,34

$N_2 + H_3^+ \rightarrow N_2H^+ + H_2$, but if CO is in gaseous form, the reaction $CO + H_3^+ \rightarrow COH^+ + H_2$ wins!

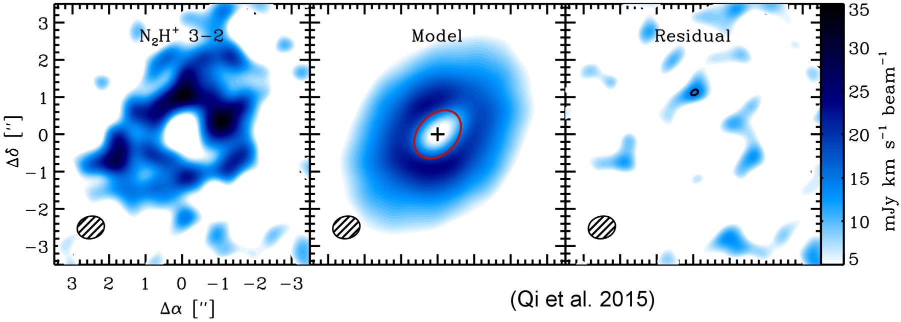
Chemical image of CO snow line in TW Hya



[Qi, Öberg et al. 2013]

- N_2H^+ is destroyed by the gas CO and enhanced by the freeze-out of CO gas

CO snow line in HD 163296

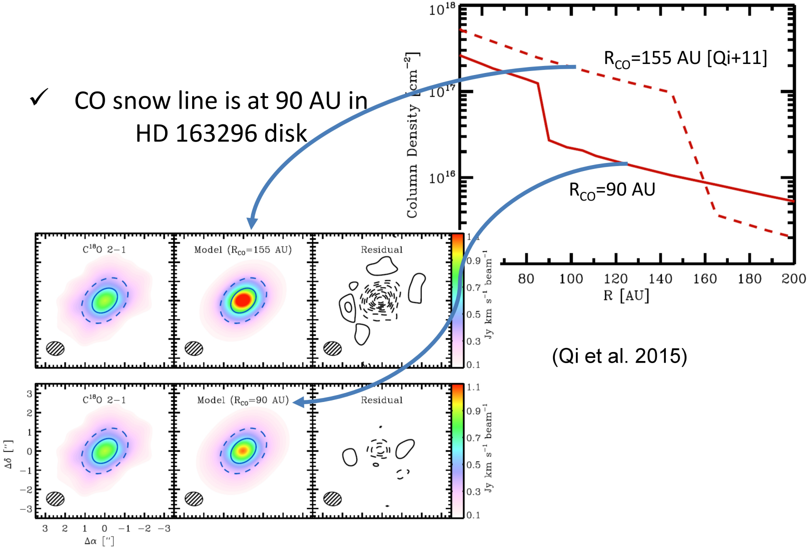


(Qi et al. 2015)

- Red line marks the best fit inner radius of N_2H^+ at 90 AU!
- Previous observations predicted the snowline to be at 155 AU!

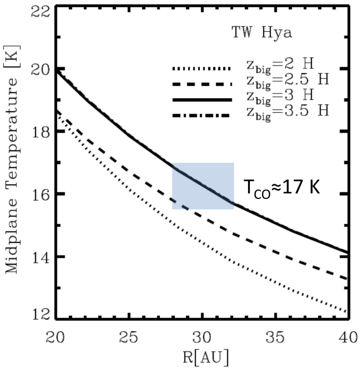
New CO measurements with ALMA

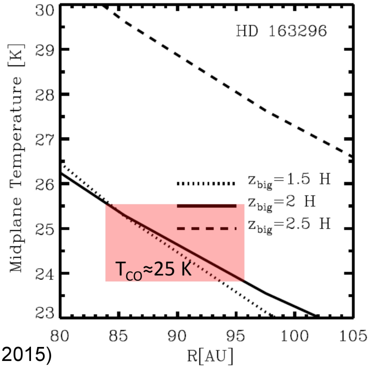
- ✓ CO snow line is at 90 AU in HD 163296 disk



(Qi et al. 2015)

Different CO snow lines?

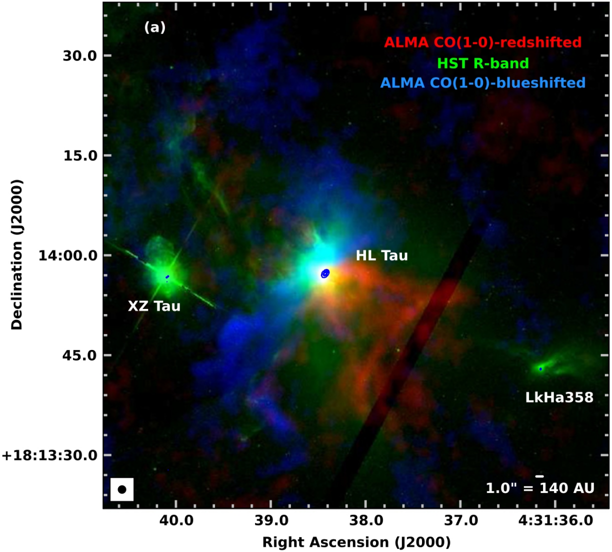




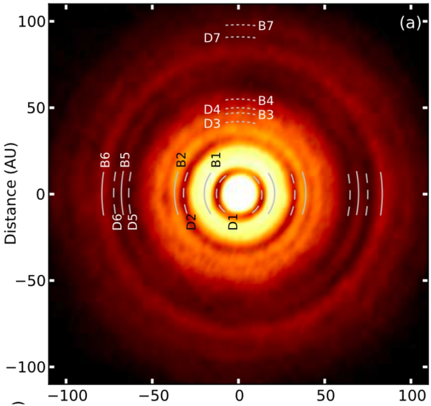
(Qi et al. 2015)

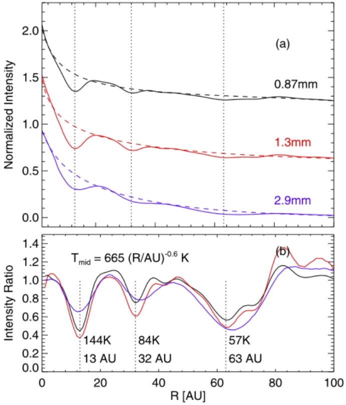
- CO snow line at different temperatures
  ⇒ different chemical compositions at different evolutionary stages?
- Important to measure CO snow line and not assume that T_{CO} is constant!

HL tau region



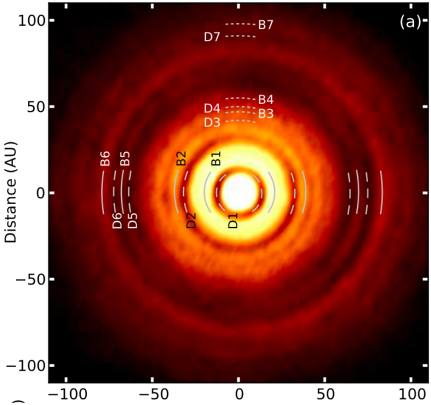
Pebbles in HL tau

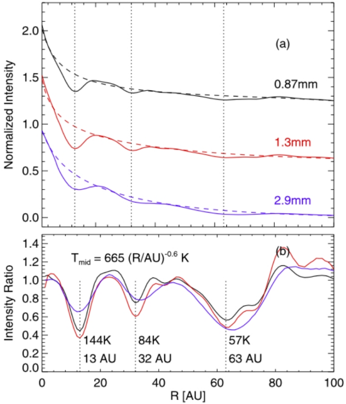




- This beautiful ALMA image of HL Tau was published in 2015 (*ALMA Partnership, 2015*)
- Emission at mm wavelengths comes mainly from mm-sized pebbles
- Dark rings have been interpreted as density depressions caused by the presence of planets (*Dipierro et al., 2015; Picogna & Kley, 2015*)

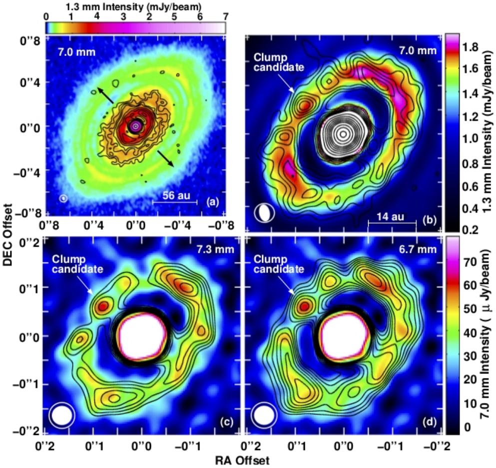
Dark rings and ice lines





- The dark rings have also been proposed to coincide with ice lines of major volatile species (H_2O, NH_3, CO) *(Zhang, Blake, & Bergin, 2015)*

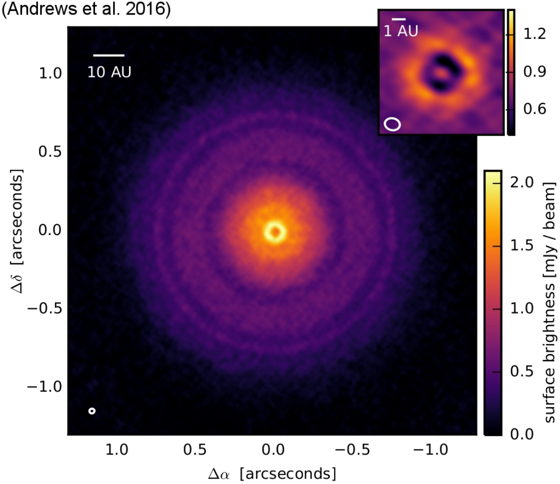
HL-Tau at larger wavelength



- VLA observations at mm-wavelength of HL-Tau: larger wavelength can penetrate the inner disc (*Carrasco-Gonzalez et al. 2016*)
- Planet formation in the inner parts of the disc?

New measurements from TW Hya

(Andrews et al. 2016)



⇒ Are symmetric structures common in discs?

Summary

- Protoplanetary discs evolve in time
- Disc models consider more and more physics
- Observations hold many surprises ⇒ see HL tau!
- Chemistry becomes more and more important
- The disc structure and evolution is important for planet formation