Sternentstehung - Star Formation

Winter term 2022/2023

Henrik Beuther, Thomas Henning & Jonathan Henshaw

18.10 Today: Introduction & Overview (Beuther)
25.10 Physical processes I (Beuther)
08.11 Physcial processes II (Beuther)
15.11 Molecular clouds as birth places of stars (Henshaw)
22.11 Molecular clouds (cont.), Jeans Analysis (Henshaw)
29.11 Collapse models I (Beuther)
06.12 Collapse models II (Henning)
13.12 Protostellar evolution (Beuther)
20.12 Pre-main sequence evolution & outflows/jets (Beuther)
10.01 Accretion disks I (Henning)
17.01 Accretion disks II (Henning)
24.01 High-mass star formation, clusters and the IMF (Henshaw)
31.01 Extragalactic star formation (Henning)
07.02 Planetarium@HdA, outlook, questions (Beuther)
13.02 Examination week, no star formation lecture

Book: Stahler & Palla: The Formation of Stars, Wileys

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws2223.html

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Last week

- Virial theorem and applications to cloud (in)stability

- Cloud lifetimes

- Jeans analysis and applications to fragmentation

Topics today

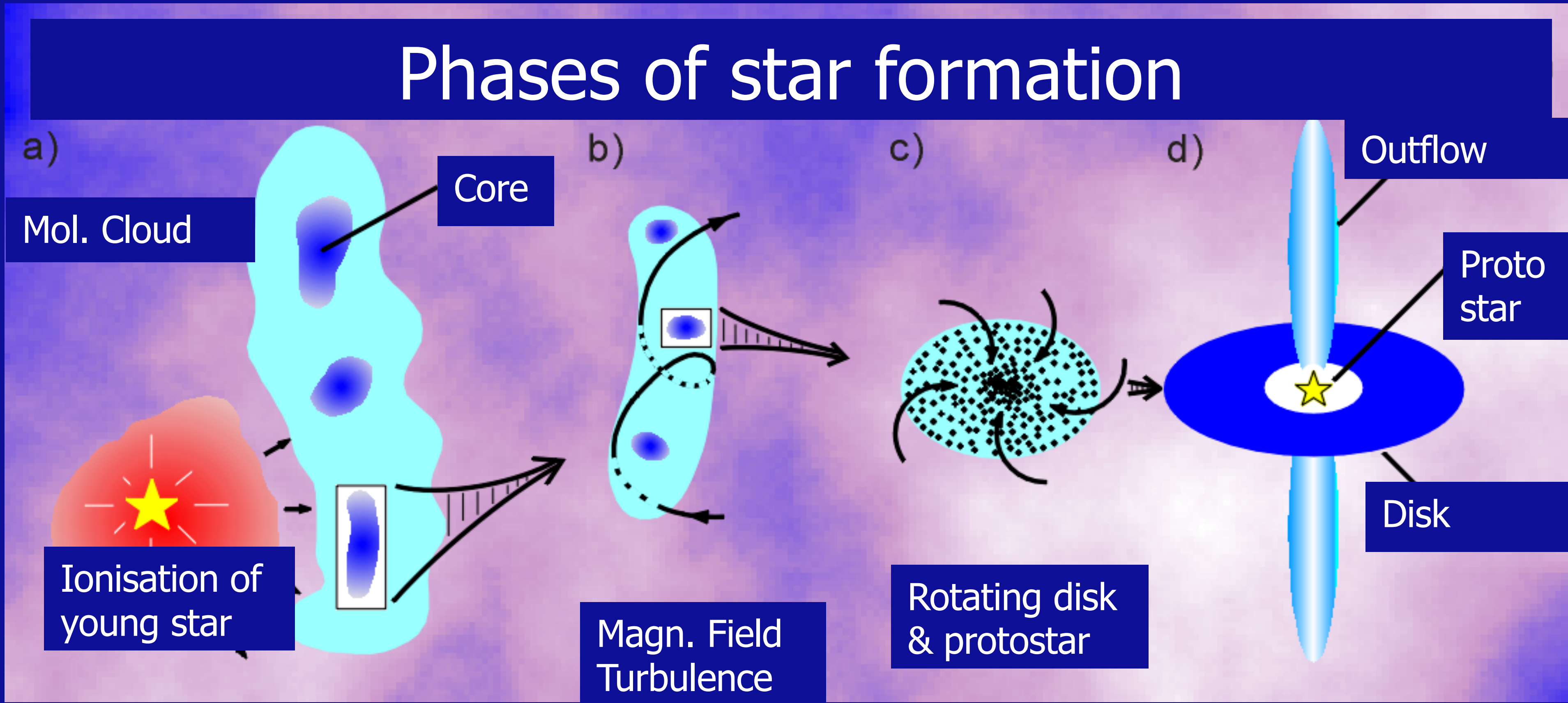
- Isothermal sphere, hydrostatic equilibrium, grav. stability, Bonnor-Ebert spheres

- Rotational support

- Magnetic support and ambipolar diffusion

- Infall signatures

Star formation paradigm



https://www.mpifr-bonn.mpg.de/473576/starform

Isothermal Sphere I

Three equations governing the equilibrium are:

Hydrostatic equilibrium

$$-\frac{1}{\rho}\nabla P - \nabla\Phi_g = 0 \qquad (1)$$

Ideal isothermal gas

$$P = \rho a_t^2 \qquad (2)$$

where the Φ_g obeys Poisson equation

$$\nabla^2\Phi_g = 4\pi G\rho \qquad (3)$$

Substituting equation 2 in 1 and after integration

$$ln\rho + \Phi_g/a^2 = const. \qquad (4)$$

In the spherical case, this is

$$\rho(r) = \rho_c exp(-\Phi_g/a^2) \qquad (5)$$

P: Pressure
ρ: density
Φ_g: grav. Potential
a_t: sound speed

Isothermal Sphere II

With ρ_c the density at the center and $\Phi_g(r=0)=0$,
the Poisson eq. becomes

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\Phi_g}{dr}\right) = 4\pi G\rho \qquad (1)$$

$$= 4\pi G\rho_c exp(-\Phi_g/a^2) \qquad (2)$$

Often, this equations is used in dimensionless form
with the dimensionless potential:

$$\phi = \Phi_g/a^2$$

and the dimensionless length ξ

$$\xi = \sqrt{\frac{4\pi G\rho_c}{a^2}}r$$

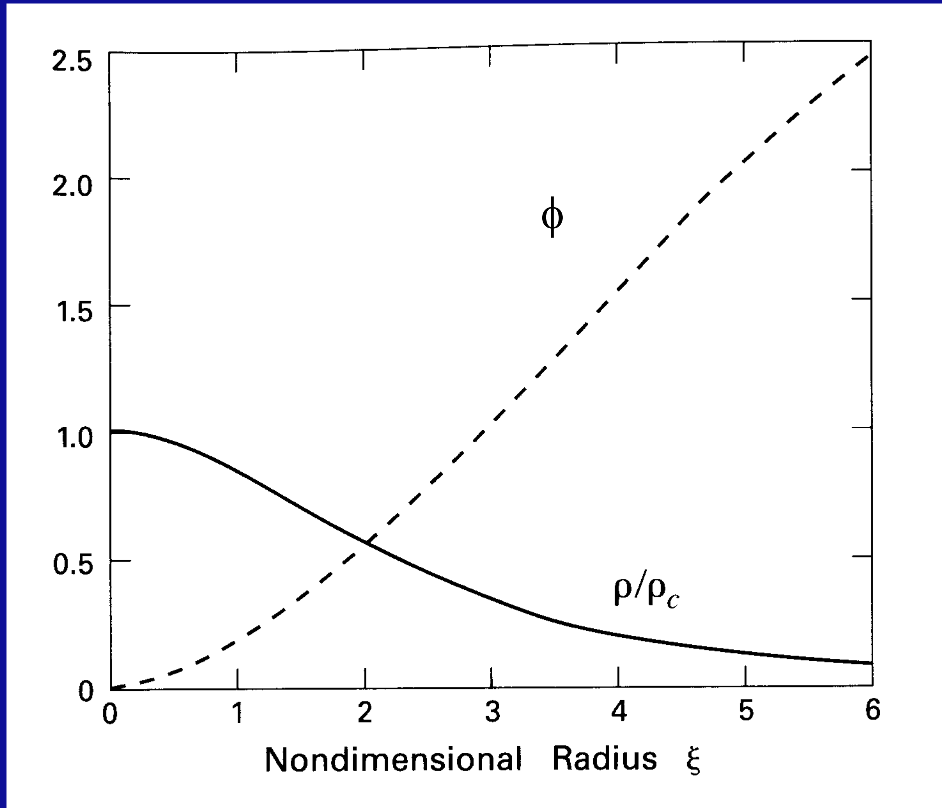
Then the Poisson eq. turns into the Lane-Emden eq.

$$\frac{1}{\xi^2}\frac{1}{d\xi}\left(\xi^2\frac{d\phi}{d\xi}\right) = exp(-\phi) \qquad (3)$$

Boundary conditions:
$\phi(0) = 0$
$\phi'(0) = 0$
Gravitational potential and force are 0 at the center.

→ Numerical integration: gravitational potential versus radius … then density

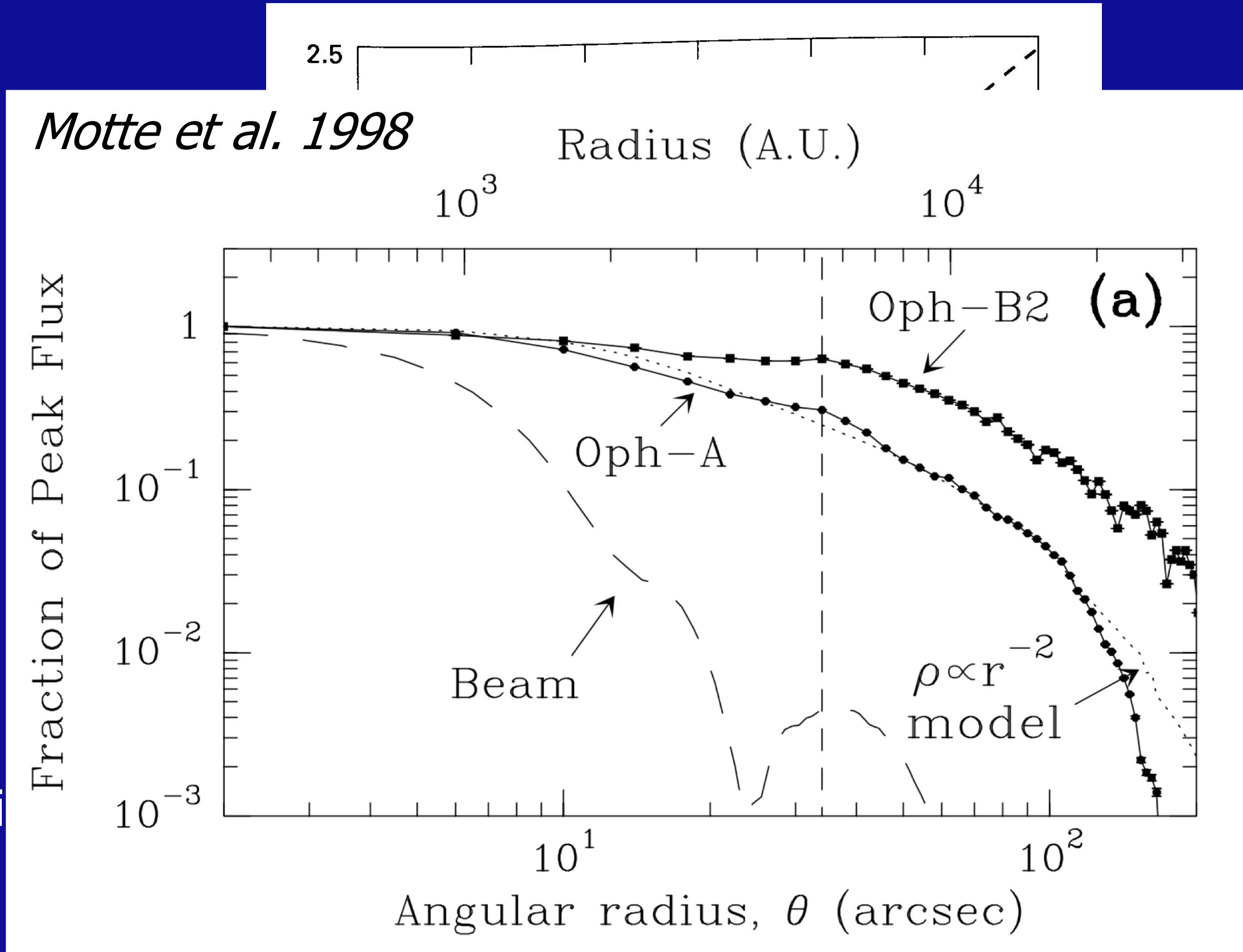
Isothermal Sphere III



- Density and pressure ($P=\rho a^2$) drop monotonically away from the center.
  → important to offset inward pull from gravity for grav. collapse.
- After numerical integration of the Lane-Emden equation
  → density ρ/ρ_c approaches asymtotically $2/\xi^2$.
- Hence the dimensional density profile of the isothermal sphere is:

$$\rho(r) = a^2/(2\pi G r^2) \sim 1/r^2.$$

Isothermal Sphere III



- Densi… …he center.
…. collapse.

- After…

→ density ρ/ρ_c approaches asymtotically $2/\xi^2$.

- Hence the dimensional density profile of the isothermal sphere is:

$\rho(r) = a^2/(2\pi G r^2) \sim 1/r^2$.

Isothermal Sphere IV

The dimensional mass is

$$
\begin{aligned}
M &= 4\pi \int_0^{r_0} \rho r^2 dr &(1)\\
&= 4\pi\rho_c \left(\frac{a_t^2}{4\pi G\rho_c}\right)^{3/2} \int_0^{\xi_0} e^{-\phi}\xi^2 d\xi &(2)
\end{aligned}
$$

Using the Lane-Emden eq. and the boundary condition $\phi'(0) = 0$

$$
\rightarrow M = 4\pi\rho_c \left(\frac{a_t^2}{4\pi G\rho_c}\right)^{3/2} \left(\xi^2 \frac{d\phi}{d\xi}\right)_{\xi_0} \quad (3)
$$

Defining furthermore a dimensionless mass m

$$
m = \frac{P_0^{1/2} G^{3/2} M}{a_t^4}, \text{ with } \mathrm{P}_0 = \rho_0 \mathrm{a}_\mathrm{t}^2 \quad (4)
$$

the dimensionless mass equals

$$
m = \left(4\pi\frac{\rho_c}{\rho_0}\right)^{-1/2} \left(\xi^2 \frac{d\phi}{d\xi}\right)_{\xi_0} \quad (5)
$$

Since ξ_0 is known for each ρ_c/ρ_0, and $\left(\xi^2\frac{d\phi}{d\xi}\right)_{\xi_0}$ can be read from the previous figure, one can evaluate m.

With:
$r = \sqrt{(a_t^2/(4\pi G\rho_c))}*\xi$
$\rho = \rho_c \exp(-\phi)$
Subscript 0 at cloud edge

Isothermal Sphere IV

The dimensional mass is

$$M = 4\pi \int_0^{r_0} \rho r^2 dr \quad (1)$$

$$= 4\pi\rho_c \left(\frac{a_t^2}{4\pi G\rho_c}\right)^{3/2} \int_0^{\xi_0} e^{-\phi}\xi^2 d\xi \quad (2)$$

Using the Lane-Emden eq. and the boundary condition $\phi'(0) = 0$

$$\rightarrow M = 4\pi\rho_c \left(\frac{a_t^2}{4\pi G\rho_c}\right)^{3/2} \left(\xi^2 \frac{d\phi}{d\xi}\right)_{\xi_0}$$

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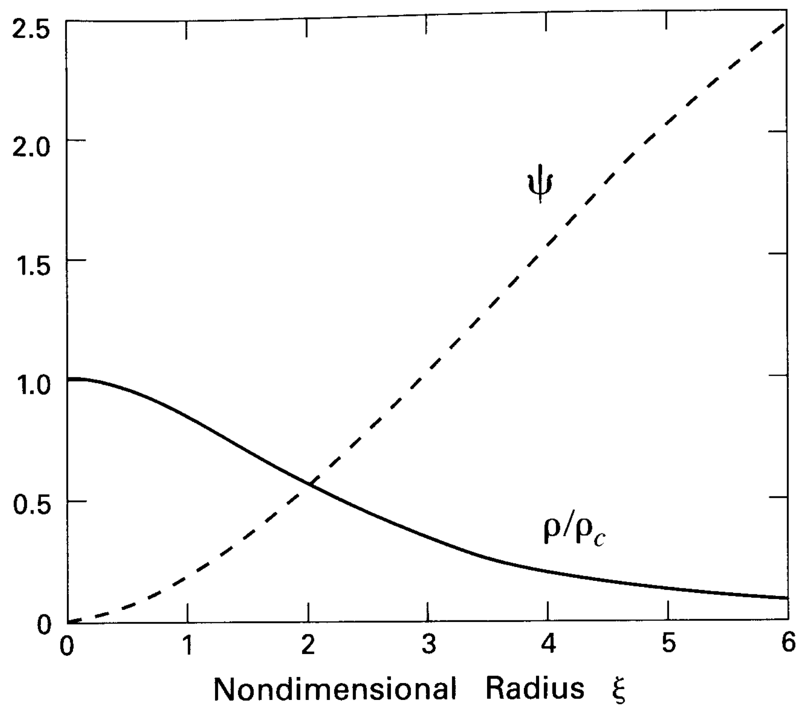
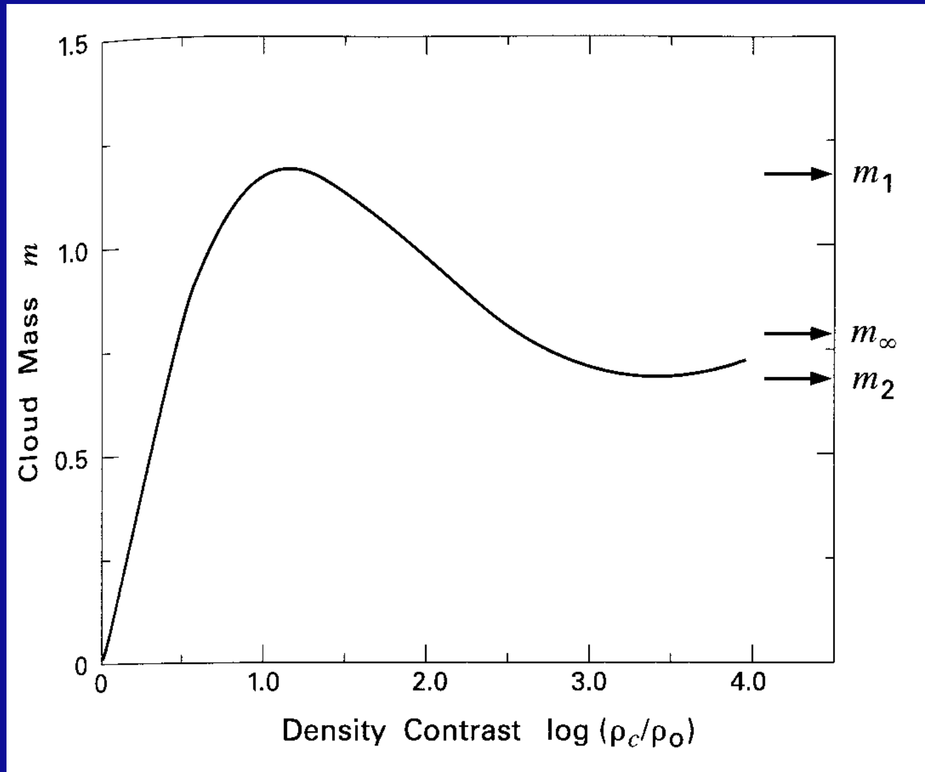
Since ξ_0 is known for each ρ_c/ρ_0, and $\left(\xi^2 \frac{d\phi}{d\xi}\right)_{\xi_0}$ can be read from the previous figure, one can evaluate m.

With:
$r = \sqrt{(a_t^2/(4\pi G\rho_c))} * \xi$
$\rho = \rho_c \exp(-\phi)$
Subscript 0 at cloud edge



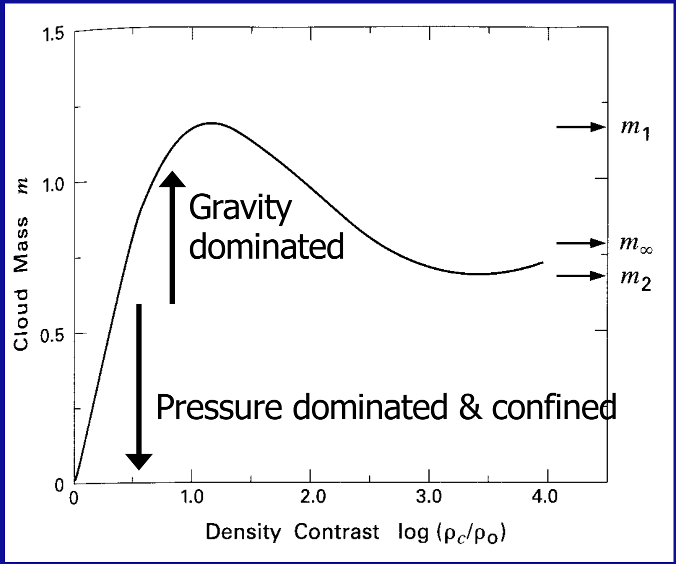
Isothermal Sphere V



The beginning is for a radius ξ_0=0, hence ρ_c/ρ_0=1 and m=0.

For increasing ρ_c/ρ_0, m (and Φ) increases until ρ_c/ρ_0=14.1, corresponding to the dimensionless radius ξ_0=6.5.

Gravitational stability



- Low density-contrast cloud: Increasing outer pressure P_0 → rise of m & ρ_c/ρ_0.
- With internal pressure $P=\rho a_t^2$ and $\rho \sim 1/r^2$ decreasing outward → inner P rises more strongly than P_0 → cloud remains stable.

- High-density contrast: following the Boyle-Mariotte law for an ideal gas:

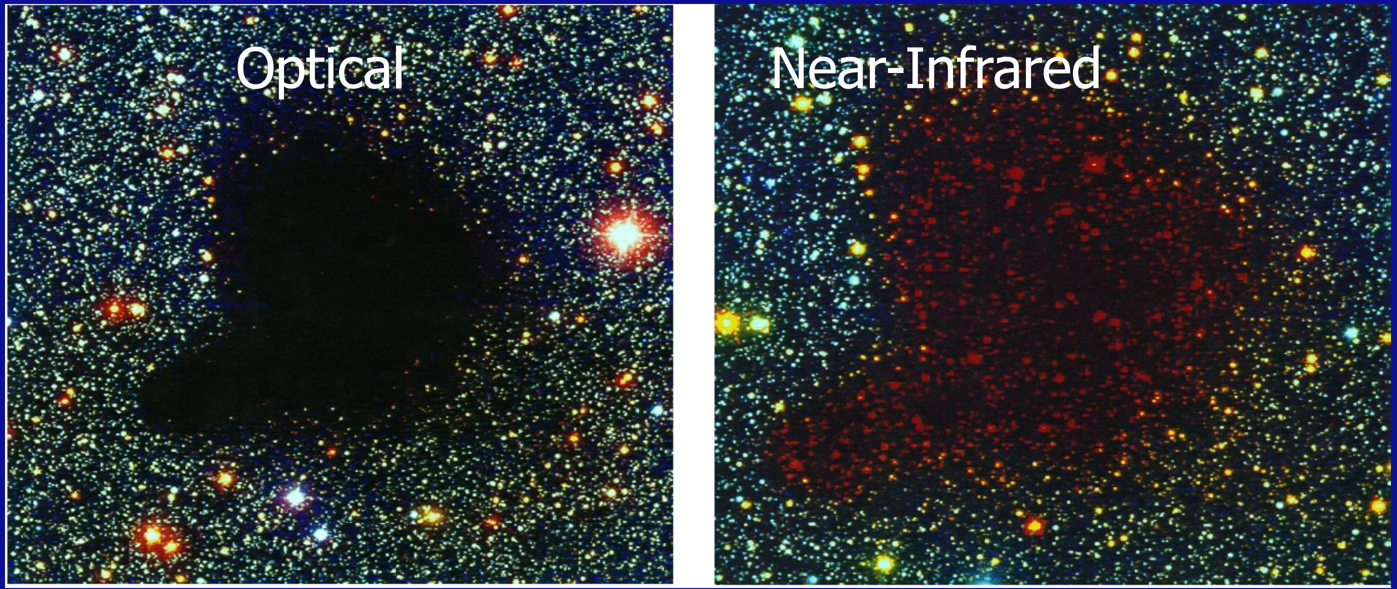
$$PV = \text{const} \rightarrow P*4/3\pi r^3 = \text{const}$$

→ core shrinks with increasing outer pressure P_0.

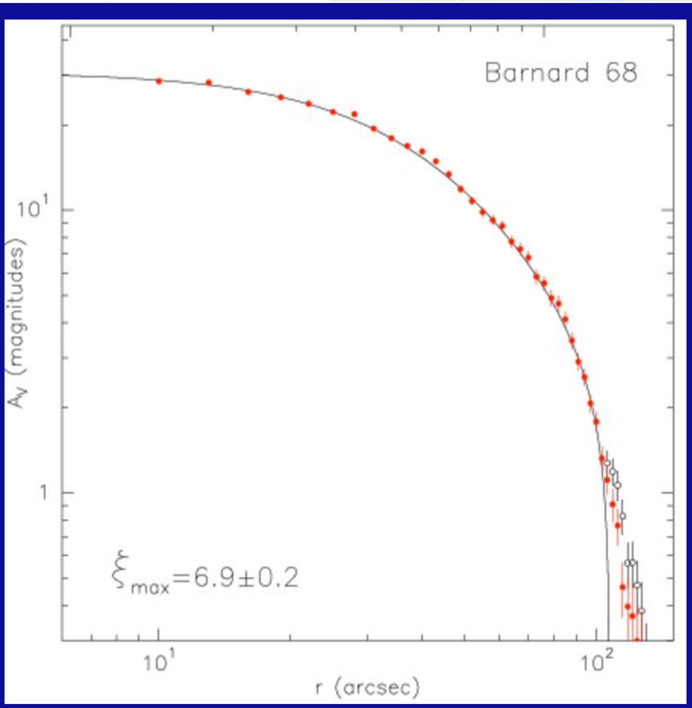
- All clouds with $\rho_c/\rho_0 > 14.1$ ($\xi_0=6.5$) are gravitationally unstable, the critical mass is the Bonnor-Ebert mass (eq. 4, 2 slides ago, Ebert 1955, Bonnor 1956)

$$M_{BE} = (m_1 a_t^4)/(P_0^{1/2} G^{3/2})$$

Gravitational stability: The case of B68



ξ_0=6.9 is only marginally about the critical value 6.5
→ gravitational stable or at the verge of collapse



Topics today

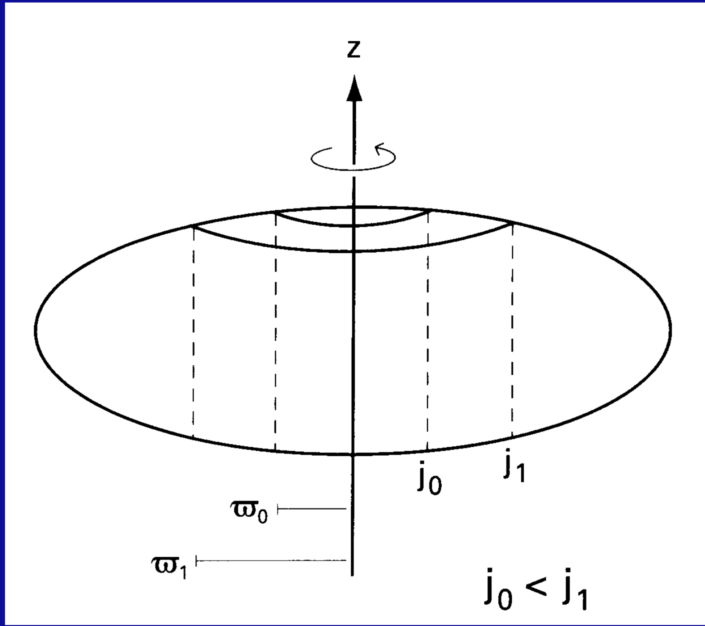
- Isothermal sphere, hydrostatic equilibrium,
  grav. stability, Bonnor-Ebert spheres

- Rotational support

- Magnetic support and ambipolar diffusion

- Infall signatures

Basic rotational configurations I



Adding a centrifugal potential Φ_{cen}, the hydrodynamic equation reads

$$-1/\rho \ \text{grad}(P) - \text{grad}(\Phi_g) - \text{grad}(\Phi_{cen}) = 0$$

With Φ_{cen} defined as

$$\Phi_{cen} = - \int (j^2/\omega^3) \, d\omega$$

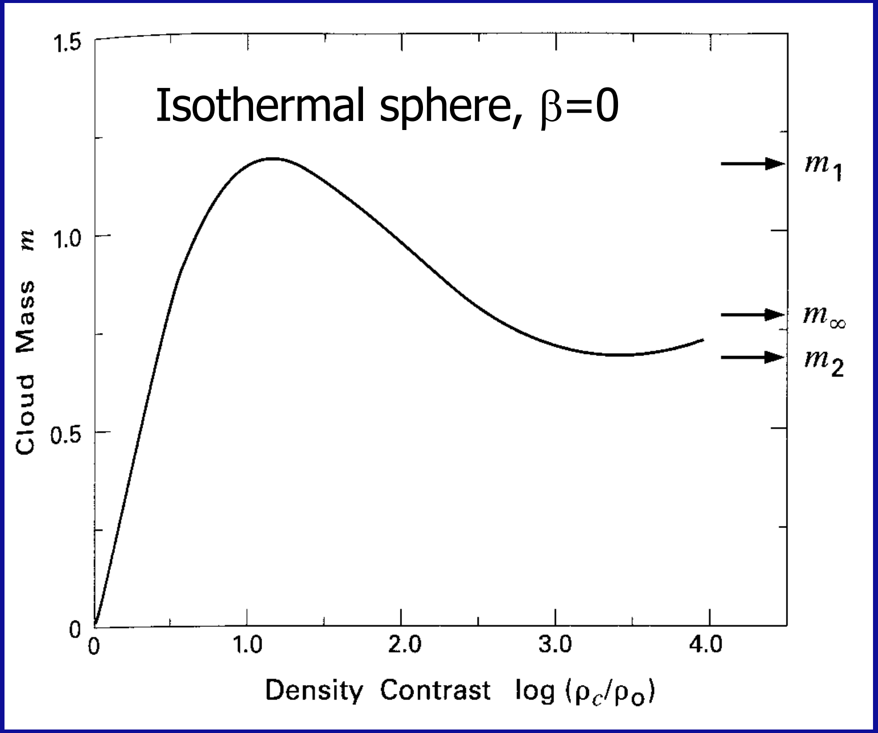
j: specific angular momentum

ω: cylindrical radius

and $j=\omega u$ with u the velocity around the rotation axis

Rotation flattens cores and may be additional support against collapse.

Basic rotational configurations II

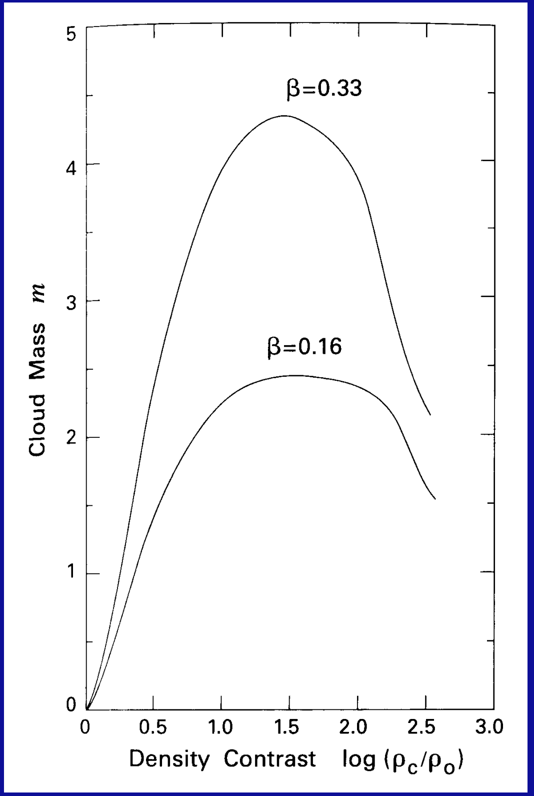


Compared to previous Bonnor-Ebert models, these rotational models have (in addition to the density contrast ρ_c/ρ_0) the parameter β quantifying the degree of rotation. β defined as ratio of rotational to gravitational energy:

$$\beta = T_{rot}/W$$

$\beta > 1/3$ corresponds to breakup speed of the cloud. So $0 < \beta < 1/3$

Basic rotational configurations III



In realistic clouds, for flattening to appear, the rotational energy has to be at least 10% of the gravitational energy. T_{rot}/W equals approximately β.

<u>Examples:</u>

$T_{rot} \approx I\Omega^2 = mr^2\Omega^2$

(I: moment of inertia, Ω: rotational velocity)

$W \approx Gm^2/r$

→ $T_{rot}/W \approx 1\mathrm{x}10^{-3}\,(\Omega/(1\mathrm{km\ s^{-1}pc^{-1}}))^2\,(r/(0.1\mathrm{pc}))^3\,(m/(10M_{sun}))^{-1}$

GMCs: Velocity gradient of 0.05km/s representing solid body rotation, $200M_{sun}$ and 2pc size imply also $T_{rot}/W \sim 10^{-3}$ (similar values for dense cores)

→ Cloud elongations do not arise from rotation, and centrifugal force NOT sufficient for cloud stability!

Other stability factors are necessary --> Magnetic fields

Specific angular momentum

Specific angular momentum $j = J/M$ is reduced from molecular cloud to star.

	$J/M\,(cm^2/s)$
Molecular clump	10^{23}
Binary ($P \sim 10^4$yr)	$4 \times 10^{20} - 10^{21}$
Binary ($P \sim 10$yr)	$4 \times 10^{19} - 10^{20}$
Binary ($P \sim 3$d)	$4 \times 10^{18} - 10^{19}$
T Tauri star	10^{17}
Sun	10^{15}

→ Specific angular momentum needs to be reduced by 6 orders of magnitude from molecular cloud to T Tauri star scale.

Topics today

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- Rotational support

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- Infall signatures

Magnetic fields I

The equation for magneto-hydrodynamic equilibrium now:

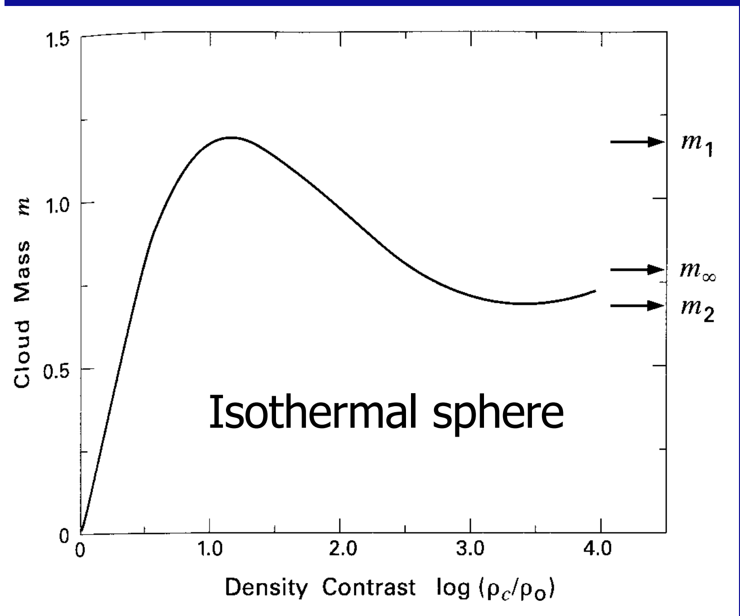
$$-1/\rho \; \mathrm{grad}(P) - \mathrm{grad}(\Phi_g) - 1/(\rho c)\, \mathbf{j} \times \mathbf{B} = 0$$

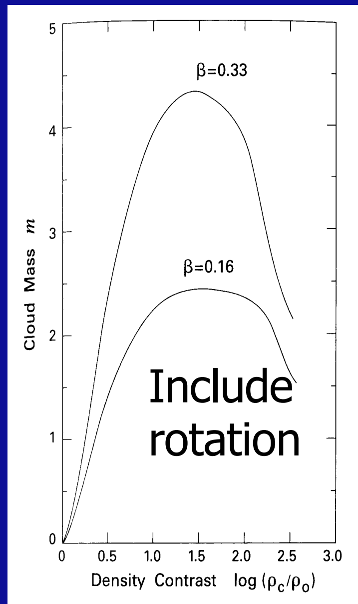
Numerical solving → solutions with 3 free parameters:
the density contrast ratio ρ_c/ρ_0,
the ratio α between magnetic to thermal pressure

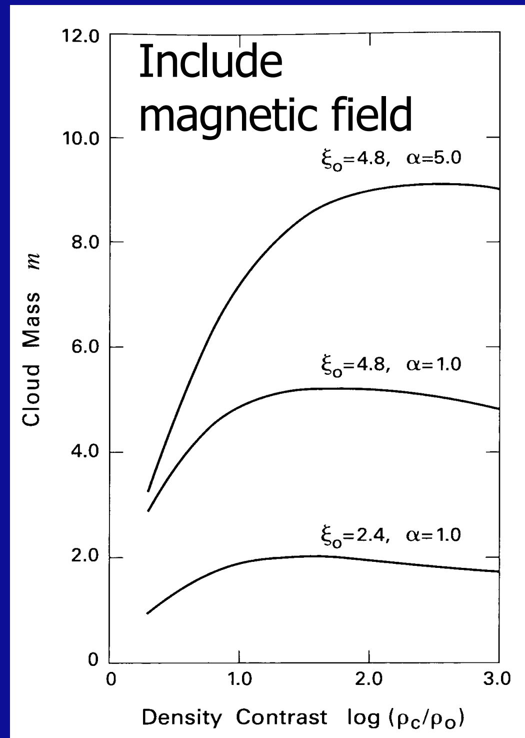
$$\alpha = B_0^2/(8\pi P_0)$$

and the dimensionless radius of the initial sphere

$$\xi_0 = (4\pi G \rho_0 / a_t^2)^{1/2} * R_0$$







Fit to numerical results: $m_{crit} = 1.2 + 0.15\, \alpha^{1/2}\, \xi_0^2$

Magnetic fields II

Conversion to dimensional form (multiply by $a_t^4/(P_0^{1/2}G^{3/2})$):
→ first term equals the Bonnor-Ebert Mass ($M_{BE} = m_1 a_t^4/(P_0^{1/2}G^{3/2})$)

$$M_{crit} = M_{BE} + M_{magn}$$

with $M_{magn} = 0.15\ \alpha^{1/2}\ \xi_0^2 a_t^4/(P_0^{1/2}G^{3/2})$
$= 0.15\ 2/\mathrm{sqrt}(2\pi)\ (B_0 \pi R_0^2/G^{1/2}) \propto B_0$

--> magnetic mass M_{magn} proportional to the B-field!

Qualitative difference between purely thermal clouds and magnetized clouds.
If increase of outer pressure P_0 around core of mass M
→ Bonnor-Ebert mass decreases until $M_{BE} < M$ → then cloud collapse

However, in magnetic case: if $M < M_{magn}$ → cloud remains stable
because M_{magn} is constant as long a flux-freezing applies.

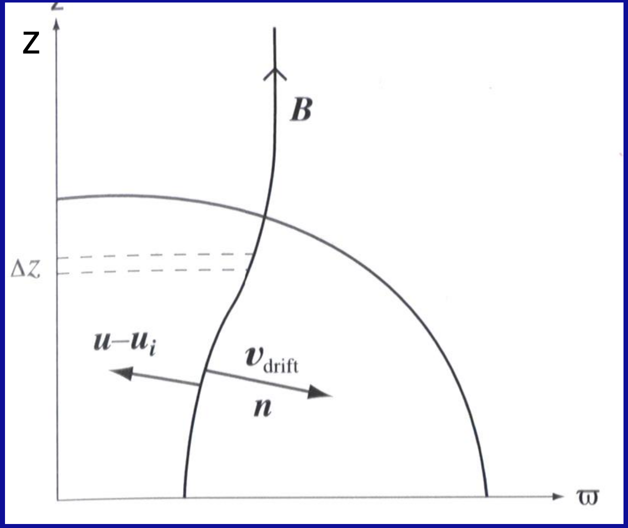
Ambipolar diffusion I

- Lower density GMCs, large ionization degree → ions & neutrals strongly collisionally coupled.
- Dense cores: lower ionization degree → neutrals & ions easier decouple.

Neutrals stream through ions accelerated by gravity.

→ drag force between ions & neutrals from collisions.

- Furthermore, Lorentz force acts on ions.



- Drift velocity between ions and neutrals: $v_{drift} = v_i - v_n$
- Drag force between ions and neutrals is: $F_{drag} = n_n \langle \sigma_{in} v_{drift} \rangle m_n v_{drift}$

(average number of collision per unit time $n_n \langle \sigma_{in} v_{drift} \rangle$ times the transferred momentum $m_n v_{drift}$)

→ equation of motion with drag & Lorentz force:

n_n: neutral density
n_i: number of ions
σ_{in}: ion-neutral cross section
m_n: mass of neutral

$$n_i F_{drag} = \mathbf{j} \times \mathbf{B}/c = 1/(4\pi)\,(\mathrm{rot}\,\mathbf{B}) \times \mathbf{B}$$

(with Ampere's law: rot $\mathbf{B} = 4\pi/c * \mathbf{j}$)

$$\rightarrow v_{drift} = (\mathrm{rot}\,\mathbf{B}) \times \mathbf{B} \,/\, (4\pi n_i n_n m_n \langle \sigma_{in} v_{drift} \rangle)$$

Ambipolar diffusion II

Dense core with size L → time-scale for ambipolar diffusion:

$$t_{ad} = L/|v_{drift}| = (4\pi n_i n_n m_n <\sigma_{in} v_{drift}>)L \,/\, (|(\mathrm{rot}\ \mathbf{B}) \times \mathbf{B}|)$$

Approximating (rot **B** = B/L): $|(\mathrm{rot}\ \mathbf{B}) \times \mathbf{B}| = B^2/L$

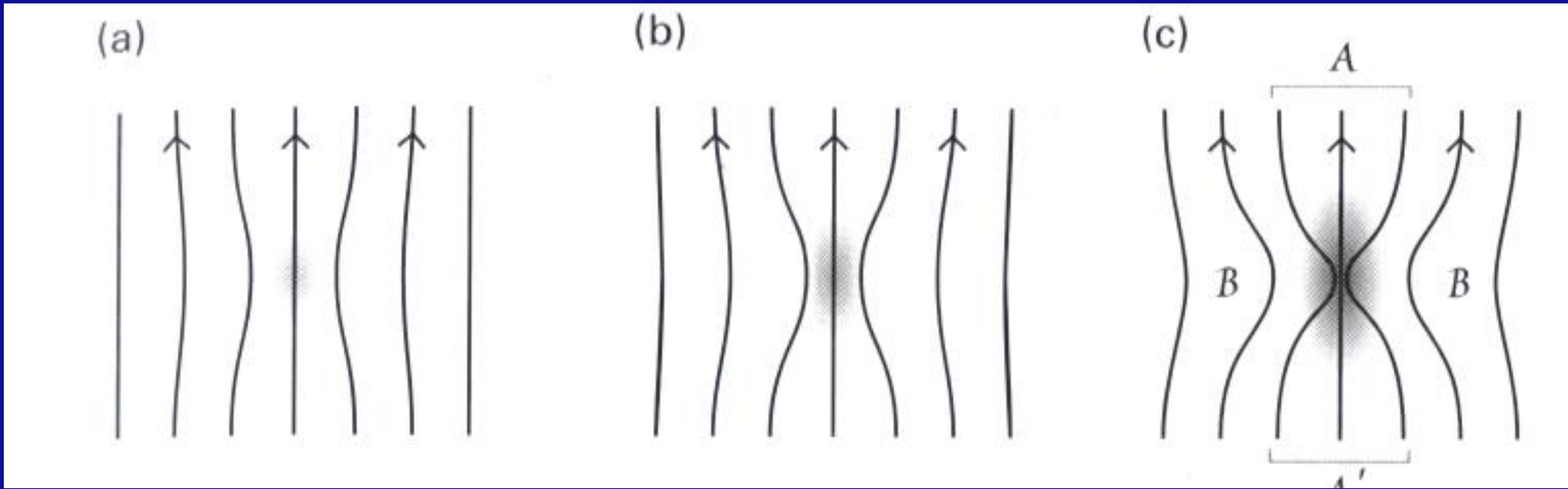
$$\rightarrow t_{ad} = (4\pi n_i n_n m_n <\sigma_{in} v_{drift}>)L^2 \,/\, B^2$$

→ ambipolar diffusion time-scale proportional to:
ionization degree, density & size of the cloud; inversely prop. to mag. field

$$\rightarrow t_{ad} \approx 3\mathrm{x}10^6\mathrm{yr}\ (n_{H2}/10^4\mathrm{cm}^{-3})^{3/2}\ (B/30\mu G)^{-2}\ (L/0.1\mathrm{pc})^2$$

Still under discussion whether this time-scale sets the star formation rate or whether it is too slow and other processes like turbulence are required.

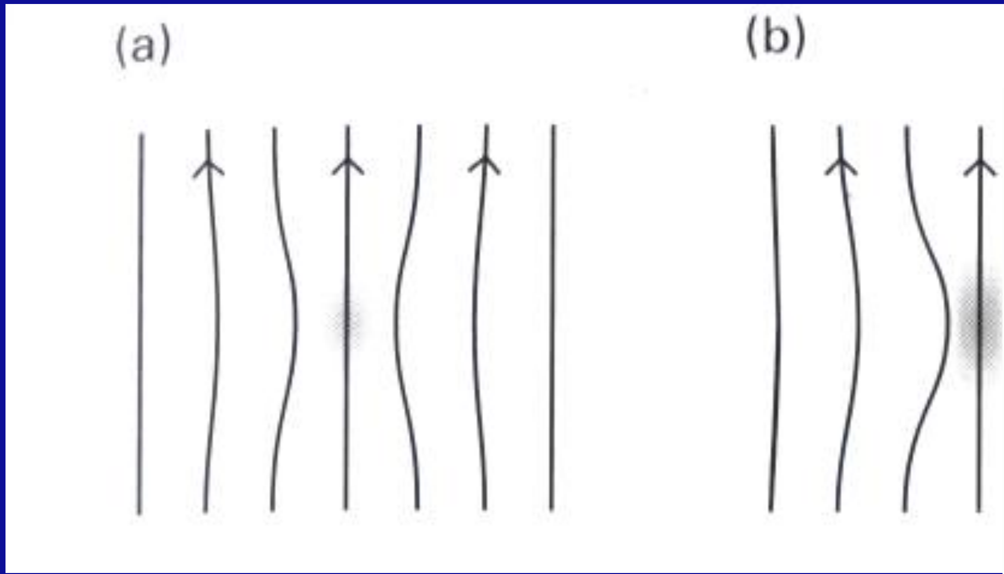
Ambipolar diffusion caveat



Star Formation timescale: Observations indicate rapid star formation on the order 1-2 million years. Ambipolar diffusion usually requires longer cloud life-times.

→ Maybe gravo-turbulent fragmentation necessary …

Ambipolar diffusion caveat



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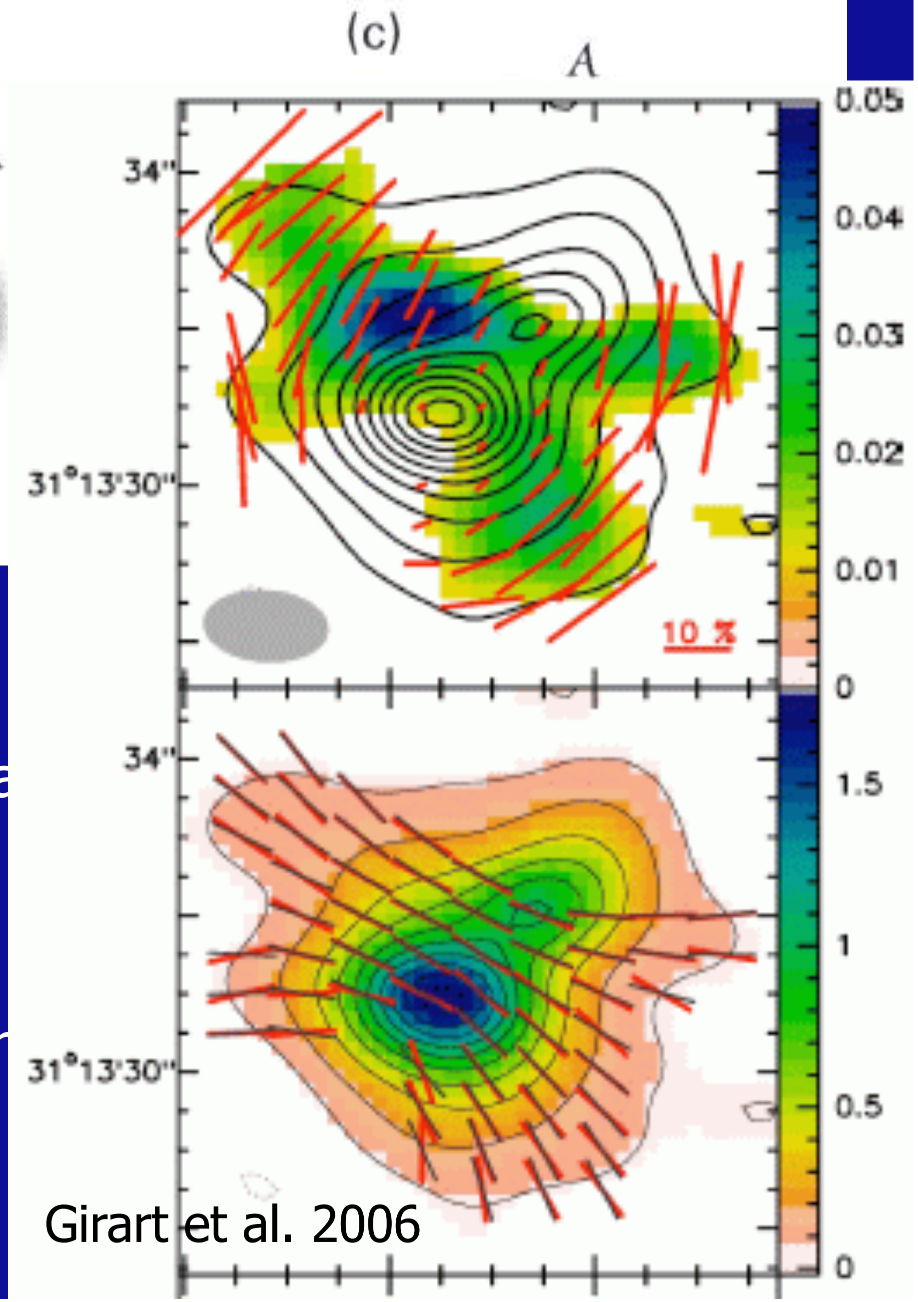
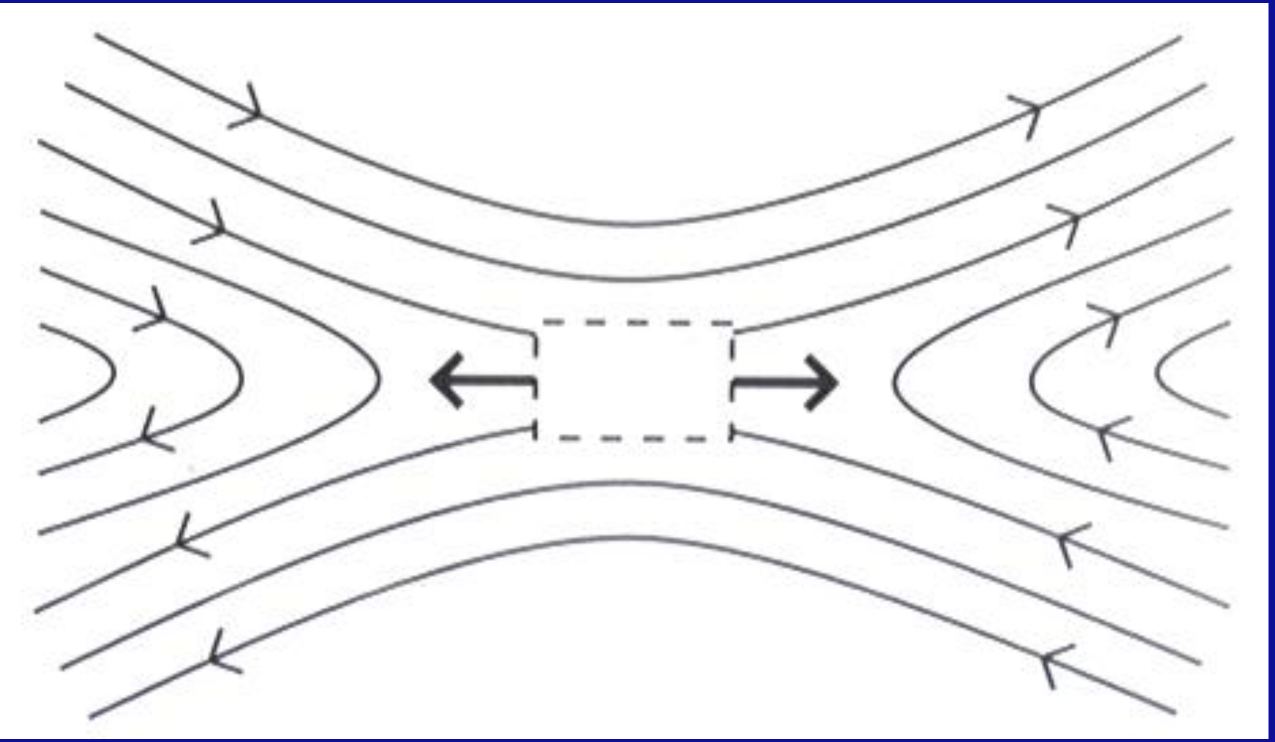


Girart et al. 2006

Magnetic reconnection



- Field lines of opposite direction are dragged together.
  → antiparallel B field lines annihilate and
  → magnetic energy dissipates as heat.
- This process was first invoked to explain large luminosities observed in solar flares.

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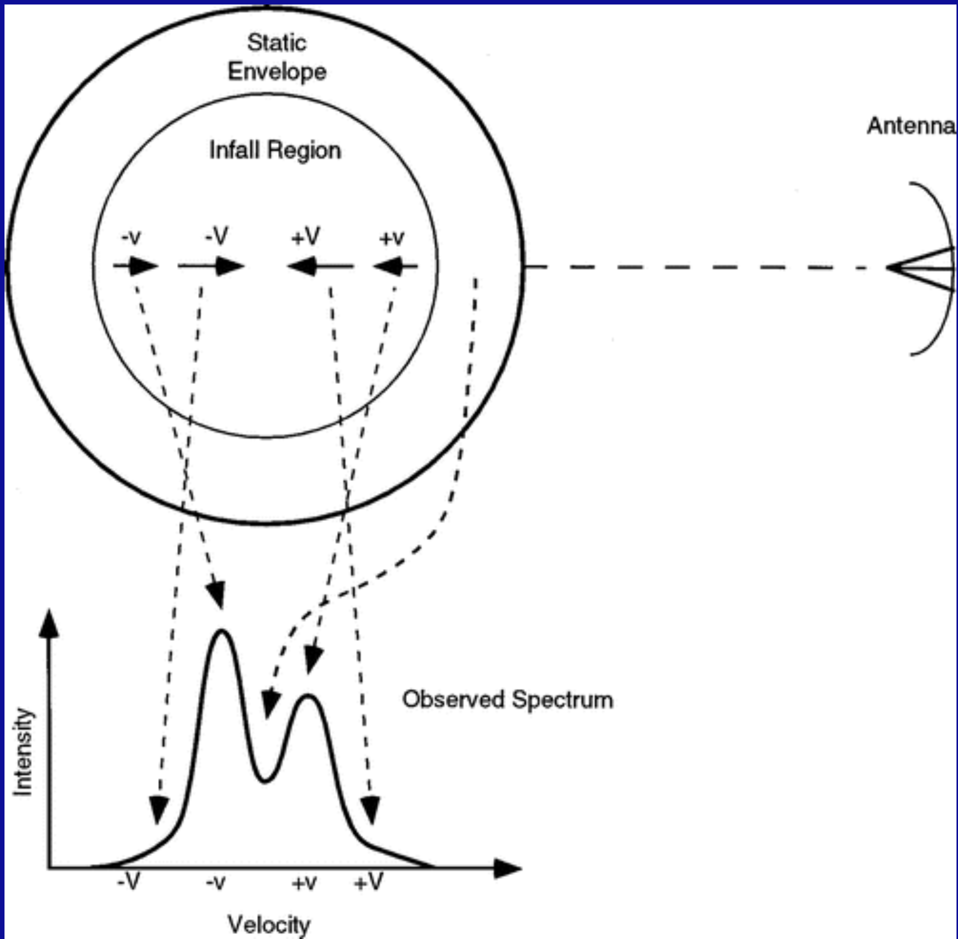
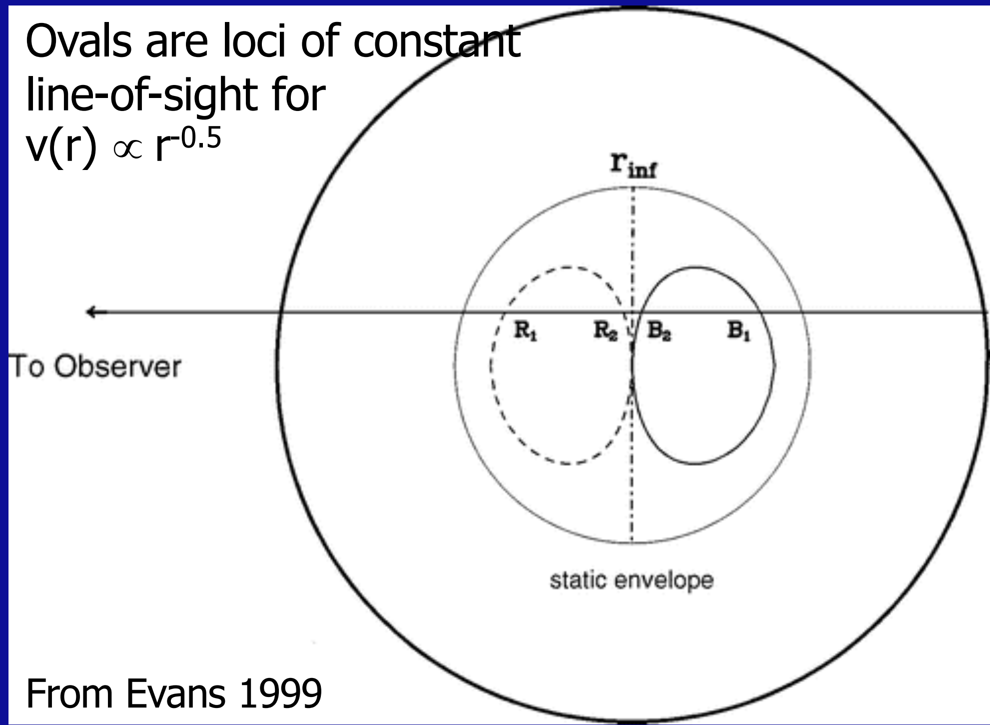
Infall signatures I

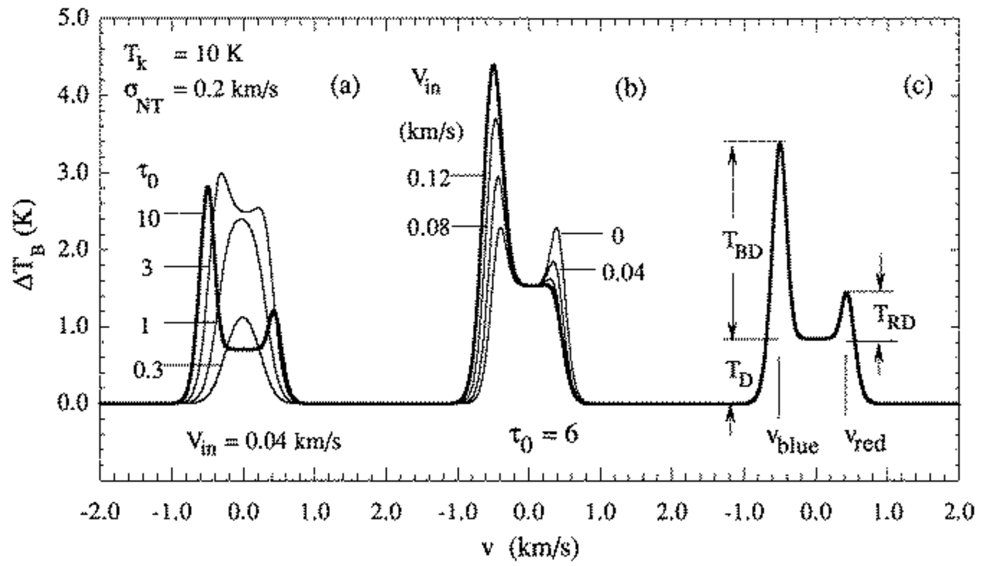




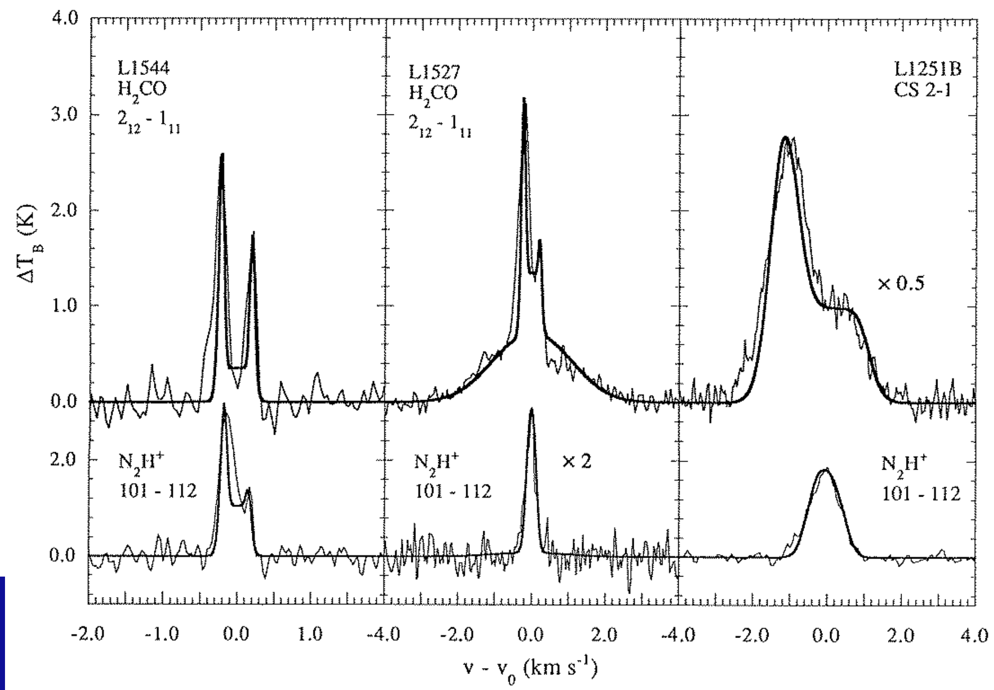
1. Rising T_{ex} along line of sight
2. Velocity gradient
3. Line optically thick
4. An additional optically thin line peaks at center

Infall signatures II

Models



Spectra and fits (Myers et al. 1996)



Model with two uniform regions along the line of sight with velocity dispersion σ and peak optical depth τ_0 → infall velocity v_{in}:

$$v_{in} \approx \sigma^2/(v_{red}-v_{blue}) * \ln((1+\exp(T_{BD}/T_D))/(1+\exp(T_{RD}/T_D)))$$

In low-mass regions v_{in} is usually of the order 0.1 km/s. In high-mass regions V_{in} can exceed 1km/s and hence be supersonic.

Summary

- Hydrostatic equilibrium between thermal pressure and gravitational force.
  → Bonner Ebert mass for gravitationally stable cores.

- Can rotation support cloud stability?

- Magnetic cloud support and ambipolar diffusion

- Observational signatures of infall motions

Sternentstehung - Star Formation

Winter term 2022/2023

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Heidelberg Joint Astronomical Colloquium

Winter Semester 2022 — Tuesday November 29th, 16:00

Main Lecture Theatre, Philosophenweg 12

Dylan Nelson (Institut für Theoretische Astrophysik)

The connection(s) between galaxies and their gaseous halos

Caption: Gas motion on Mpc scales around a halo

Those unable to attend the colloquium in person are invited to participate online through Zoom.

More information is given on HePhySTO: https://www.physik.uni-heidelberg.de/hephysto/