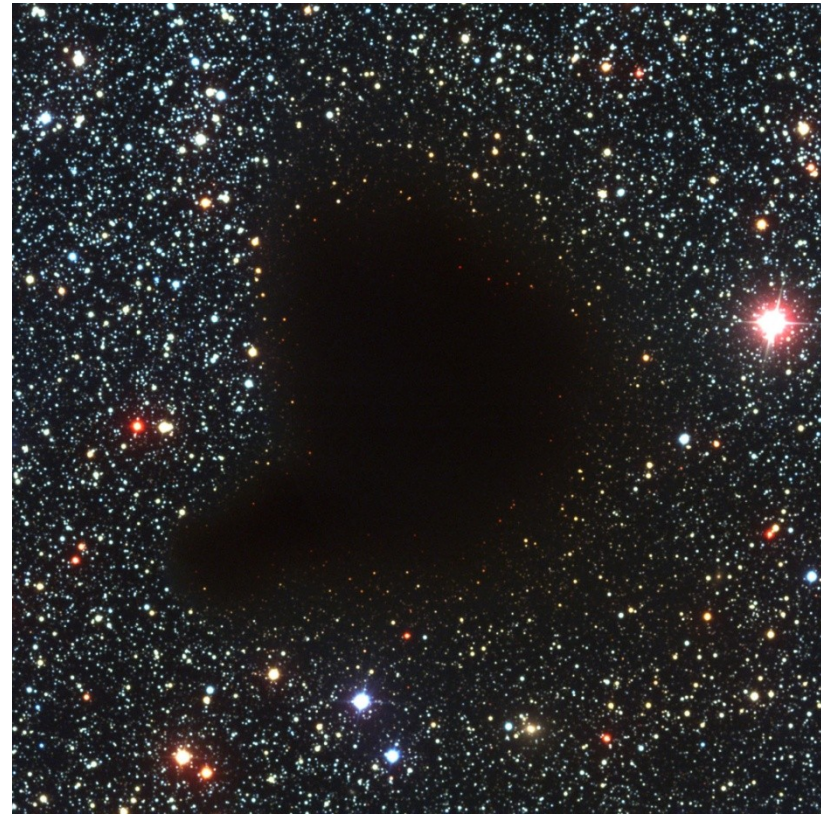


Star Formation

- Gravitational collapse
- Accretion discs
- Outflows

Gravitational collapse

- stars form due to the gravitational collapse of interstellar gas clouds
- coldest, densest clouds are those most likely to collapse
- these are the molecular clouds



Virial Theorem

- For a self-gravitating system (bound system) in equilibrium the virial theorem states that

$$2U + \Omega = 0 \quad \text{or} \quad U = -\frac{1}{2}\Omega$$

where U is the total thermal (kinetic) energy of the cloud and Ω is the total gravitational potential energy

(see notes on board for case of a simple circular orbit)

Jeans Mass

- In order for contraction of the cloud to occur we require the gravitational term to overcome the pressure term i.e.

$$- \Omega > 2U$$

For contraction to continue have to keep radiating half the PE lost !

(consequence of the Virial Theorem)

Jeans Mass

- For constant density cloud this gives

$$M_c > \left(\frac{5kT}{G\mu m_H} \right)^{\frac{3}{2}} \left(\frac{3}{4\pi\rho_c} \right)^{\frac{1}{2}}$$

- Critical mass known as the Jeans Mass

*See additional notes “Virial Theorem.docx” and
“How do stars form.pdf”*

VIRIAL THEOREM $\langle PE \rangle = - \langle KE \rangle$

- Simplest case is just circular orbit and is easy to show...but the Virial Theorem is very generally true when take time averages of statistically random motions in a BOUND system.
- Wide generality in physics e.g. Dark Matter was found because more galaxies had more KE than can be contained by PE associated with mass in light-emitting stars.
- **For a gas cloud: Jeans Mass Criterion**
 - KE of the particles (atoms) = $N \cdot 3kT/2$ (1/2 kT per degree of freedom)
 - PE for a spherical cloud $U = -3GM^2/5R$ (just quoted – get by stripping off shells)
 - ➔ Virial Theorem becomes:
 - $N \cdot 3kT/2 = - [3GM^2/5R]/2$
 - $3NkT = - 3GM^2/5R$
 - $N = \text{number of particles} = \text{Mass of cloud}/\text{average mass of particles} = M/m$
 - $M = 4\pi R^3 \rho / 3 \rightarrow R = [3M/4\pi\rho]^{1/3}$
 - ➔ Condition for collapse becomes:
 - $M > [5kT/Gm]^{3/2} [3/4\pi\rho]^{1/2}$ (NB in Melvin's notes $m = \mu m_H$)
- This is the Jeans mass condition for collapse of a cloud under gravity

Fragmentation

- Initially when a cloud collapses its temperature remains cold so that the Jeans mass drops as the density increases
- Hence, smaller mass fragments can become unstable to collapse – leads to star clusters
- Eventually fragments heat up and a hydrostatic core will form

Cloud Rotation

- If initial cloud of radius R has a uniform rotation rate Ω then conservation of specific angular momentum along the equator means

$$\omega r^2 = \Omega R^2 = \text{constant}$$

- Therefore the centrifugal force for a mass m

$$F_c = m\omega^2 r \propto r^{-3}$$

- Since gravity $F_G = \frac{GMm}{r^2}$ the

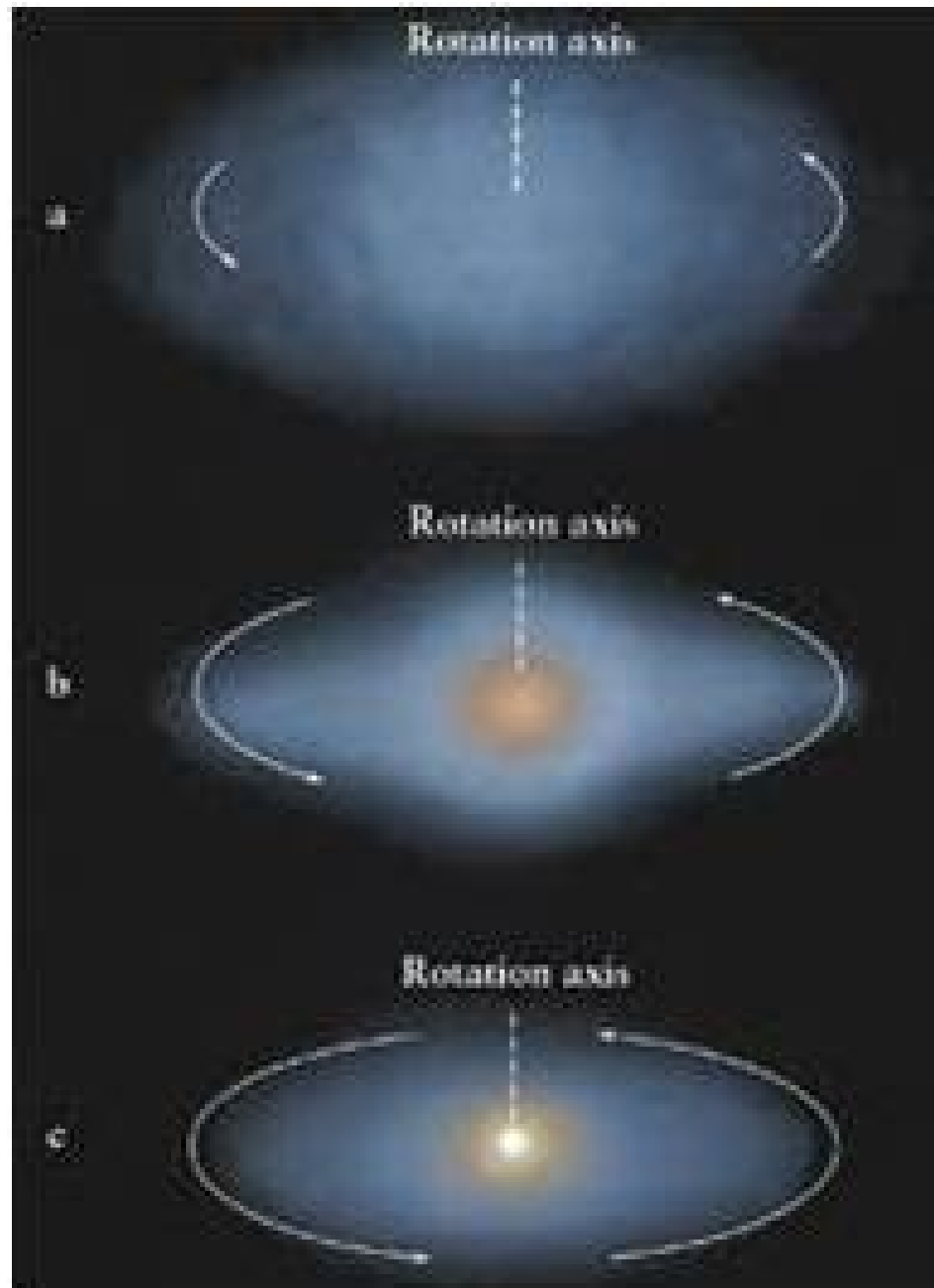
centrifugal force will eventually win out.

Centrifugal Radius

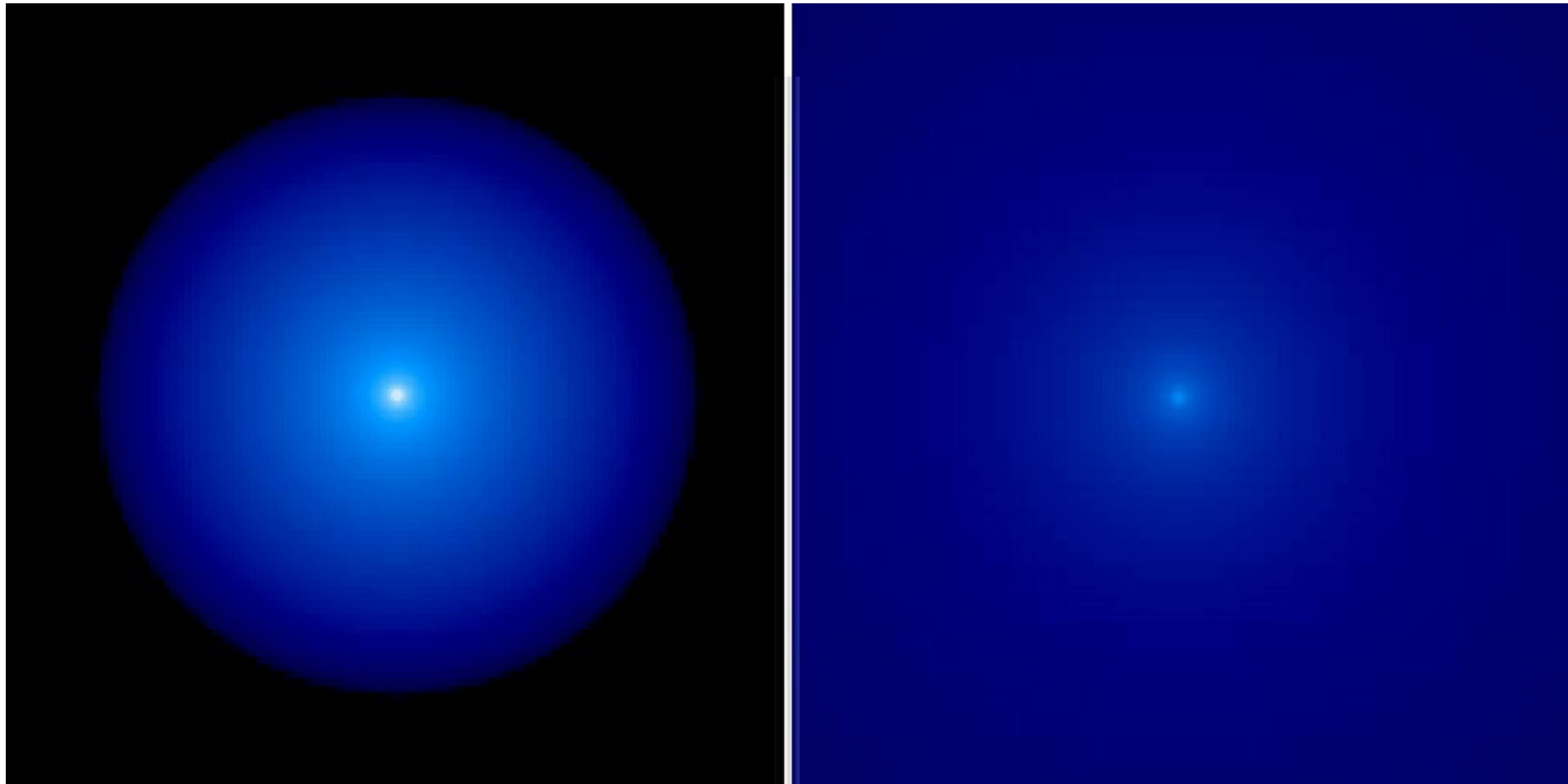
- Radius where $F_c = F_g$ is called the centrifugal radius

$$R_c = \frac{\Omega^2 R^4}{GM}$$

- Cloud can still contract parallel to rotation axis
- This leads to flattened rotating structures
 - accretion discs
- But need to lose a lot of angular momentum



Numerical simulation



Krumholz et al. (2007)

Magnetic field during collapse

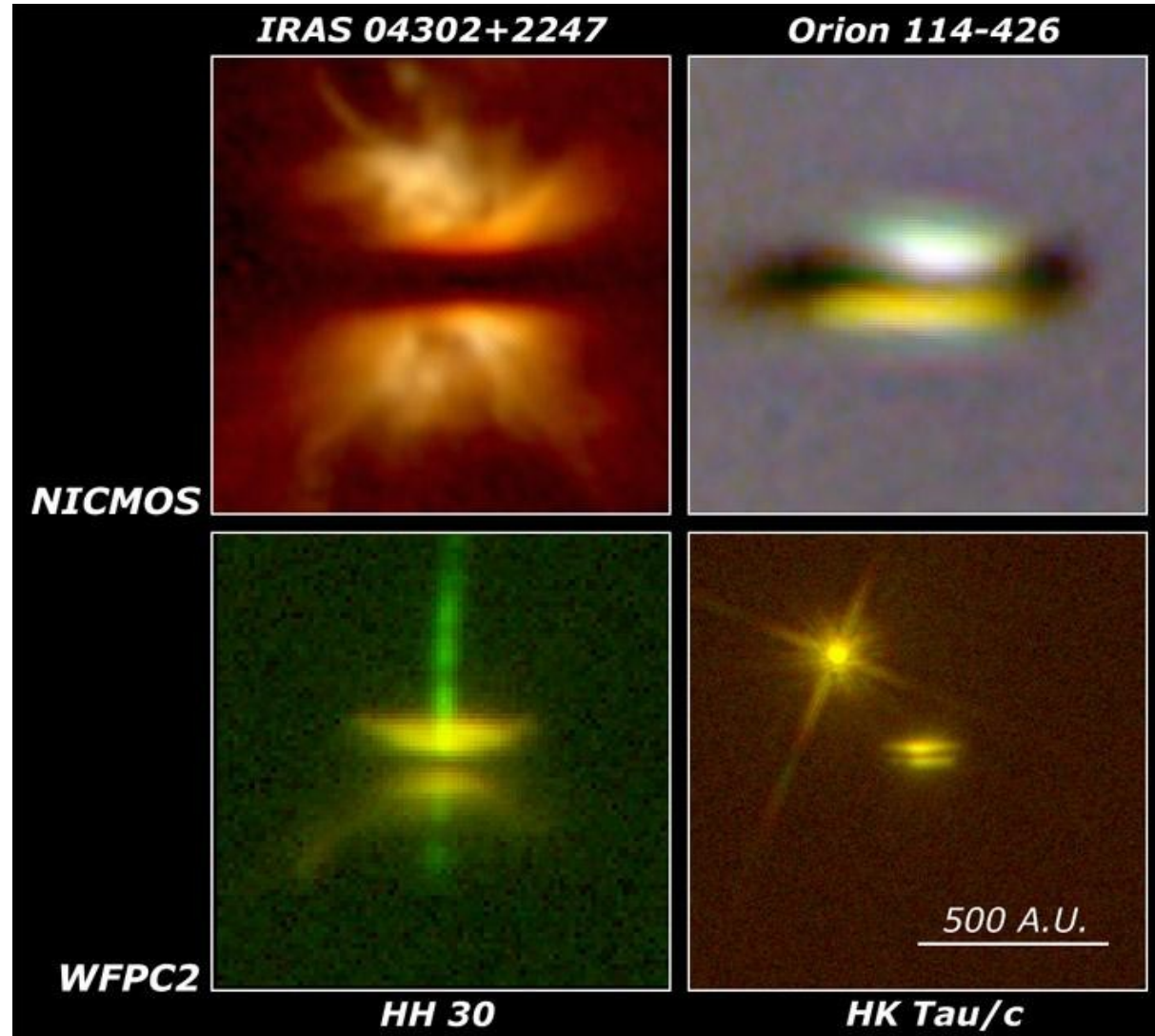
- Molecular clouds always have some level of ionization due to passage of energetic particles – cosmic rays
- Hence the initial magnetic field in the cloud will get dragged in during the collapse
- Need to lose a lot of magnetic flux too

Accretion Discs

- Infalling, rotating material forms a disc around the proto-star
- Viscous forces allow mass to accrete inwards whilst transferring angular momentum outwards (*as in AGN – see later*)
- Material heats up and radiates with luminosity

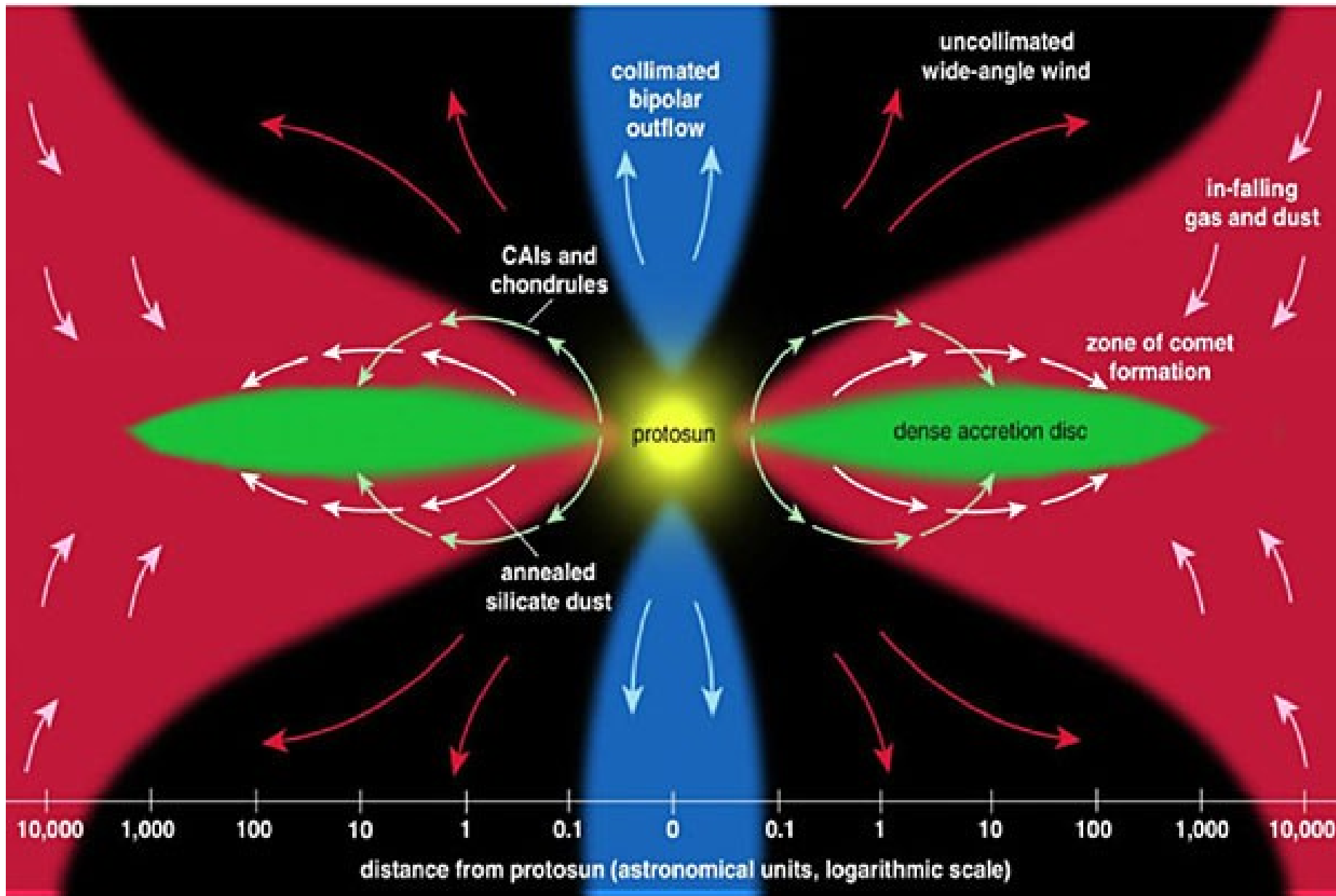
$$L_{\text{acc}} \sim \frac{GM \dot{M}}{R_s} \text{ See later lectures}$$

- Can see discs indirectly in absorption against nebulae or scattered light in the optical

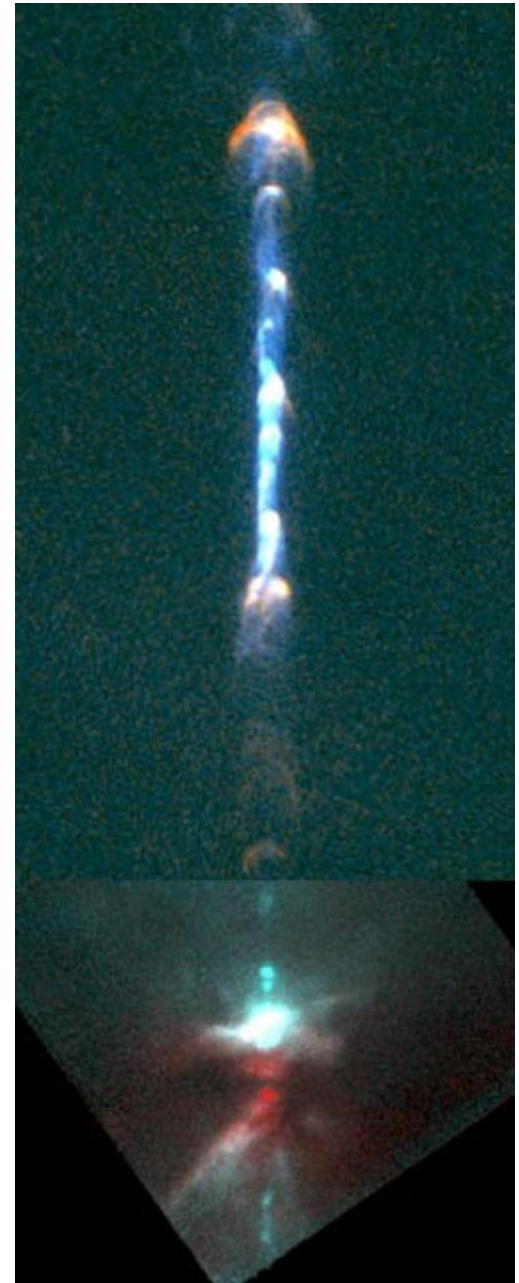
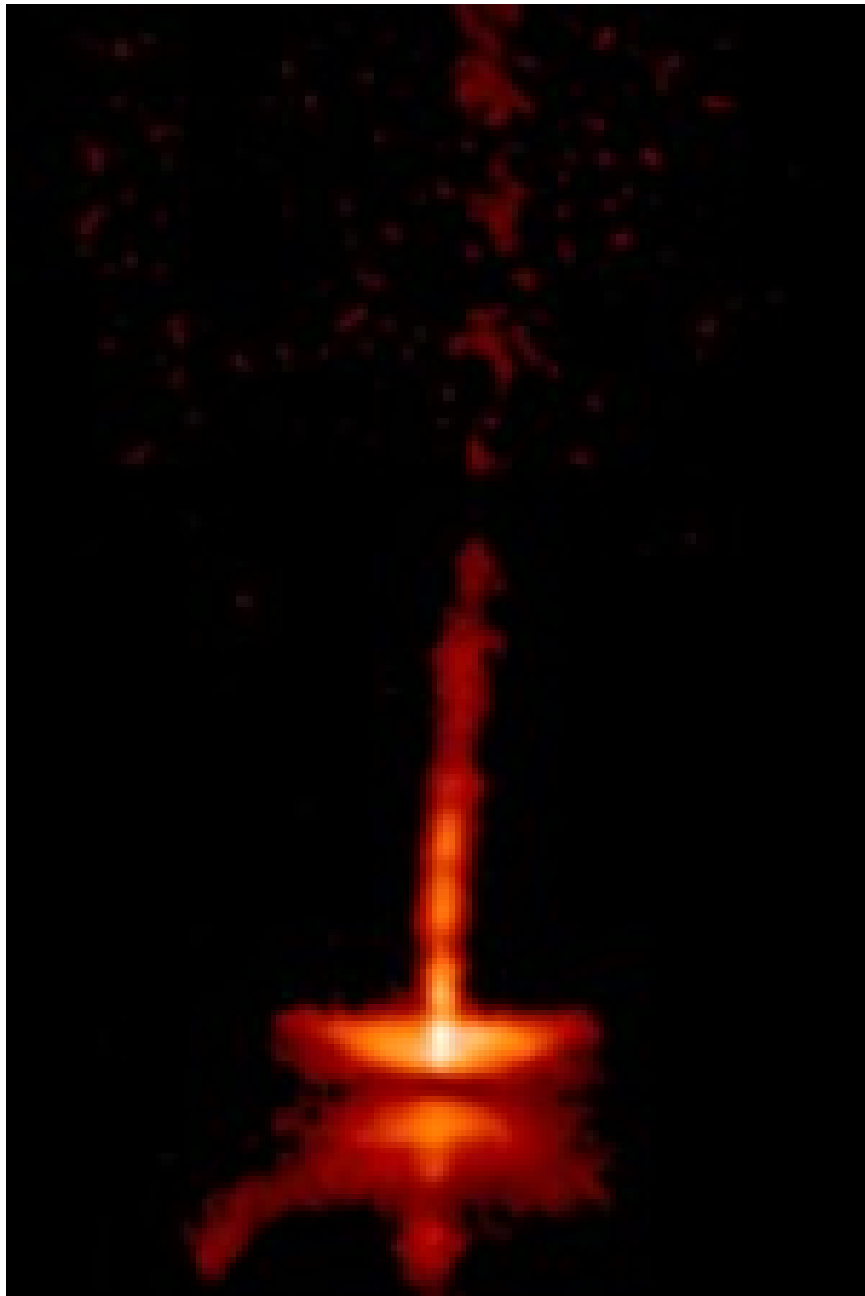


Jets and bipolar outflows

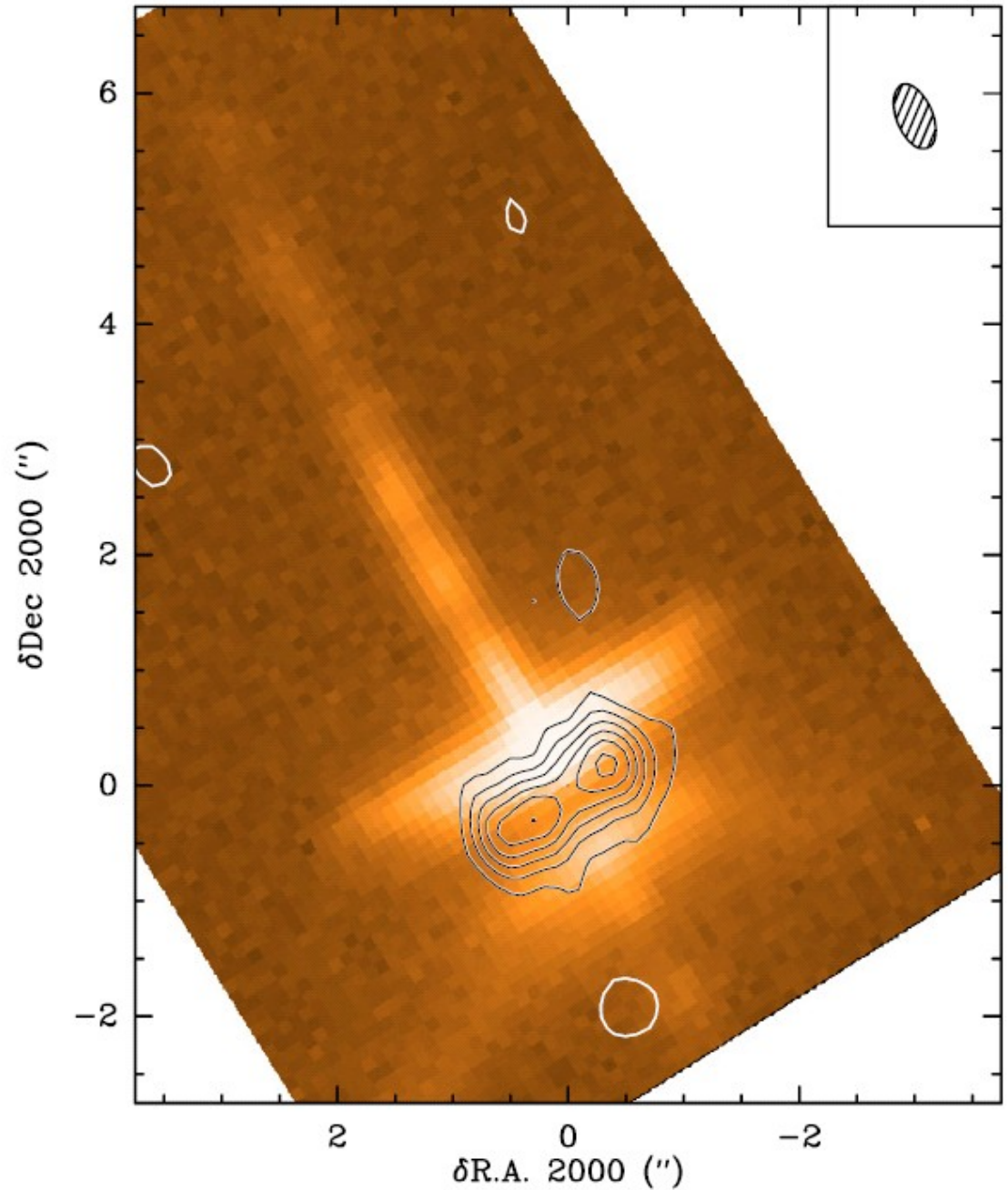
- Rotating magnetic fields in the star-disc system act to drive material out along the rotation axis
- Jets of ionized material are seen moving at several hundreds of km/s
- Bipolar molecular outflows moving at several tens of km/s that clear cavities



(from Nuth, J. A., 2001, *American Scientist*, v. 89, p.230.)

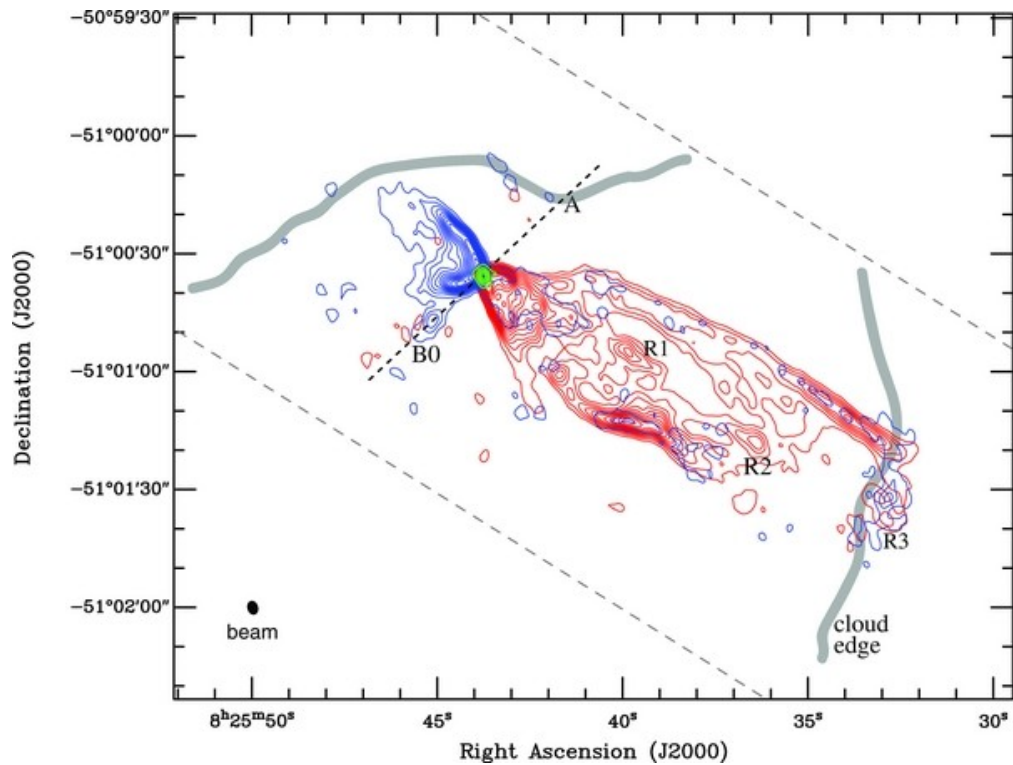


- Can see disc directly in molecular gas (CO)





Optical picture showing jet



Mm-wave picture showing molecular outflow (ALMA telescope)

Summary

- Stars form in cold, dense cores of molecular clouds
- Angular momentum leads to formation of accretion discs
- Magnetic fields drive outflows perpendicular to the discs

Masers

- A combination of dense molecular gas and either
 - strong IR radiation field
 - or collisions in outflows
- Leads to pumping of excited levels and a population inversion in certain molecules such as OH, H₂O, CH₃OH
- This leads to maser emission

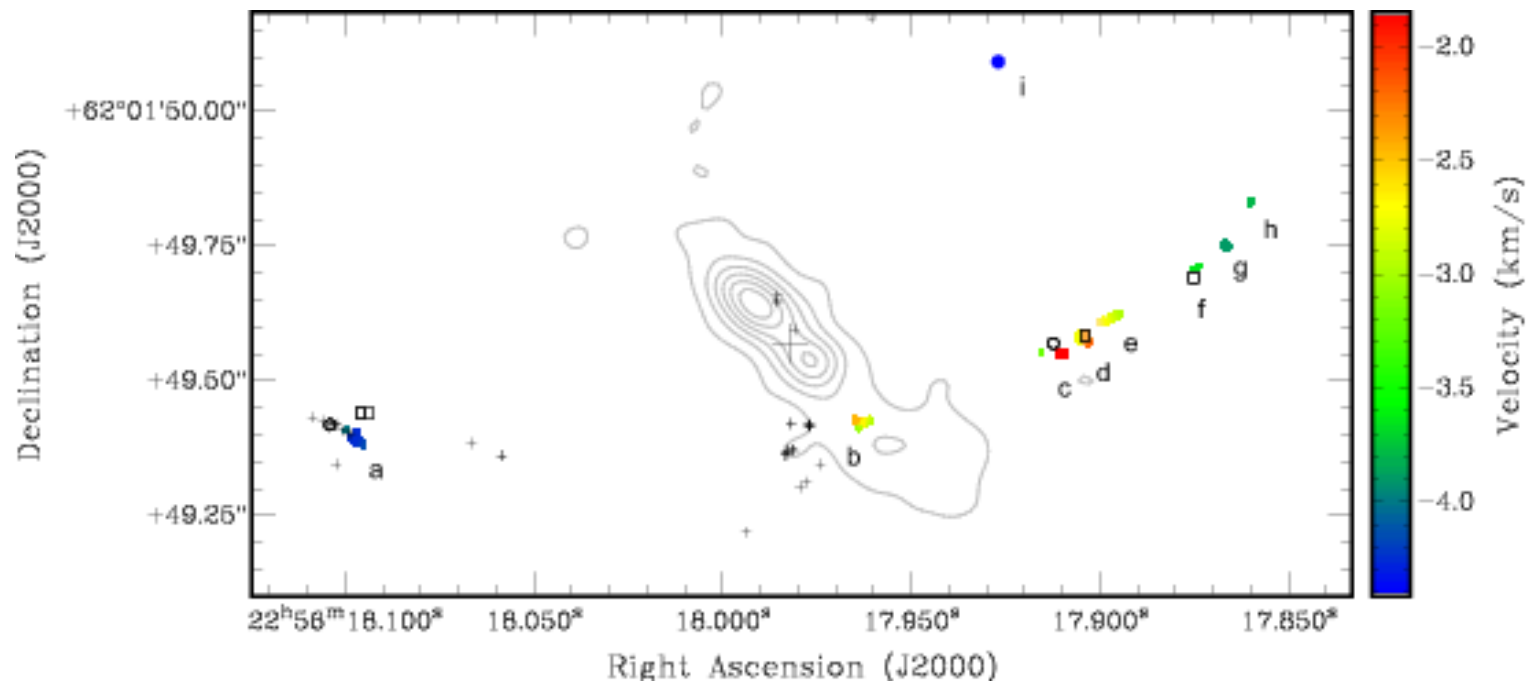
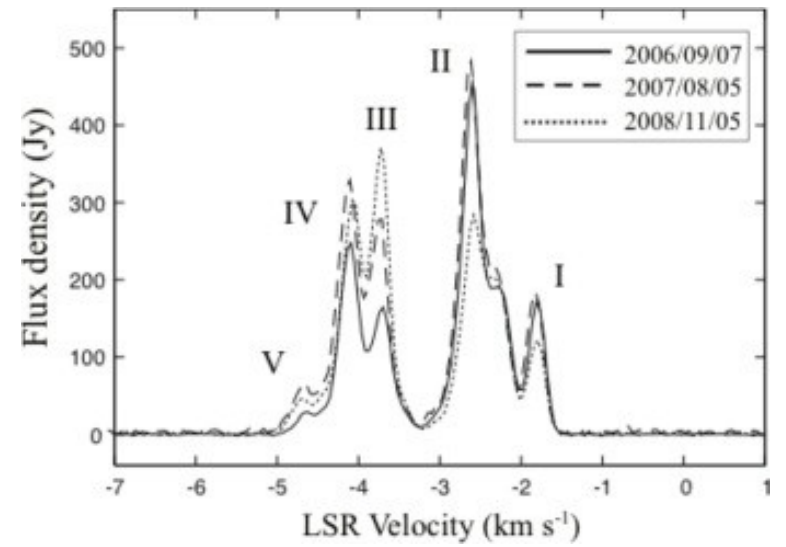
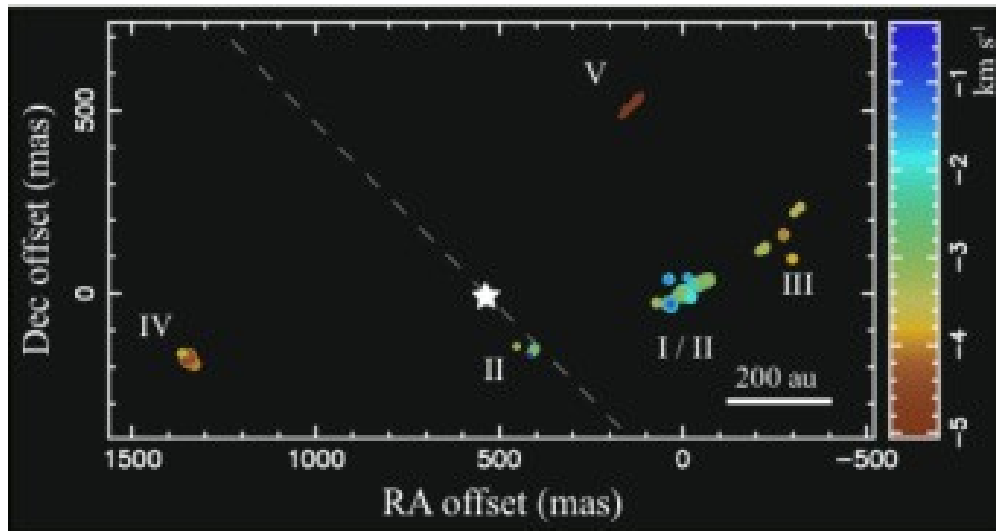
Stimulated Emission

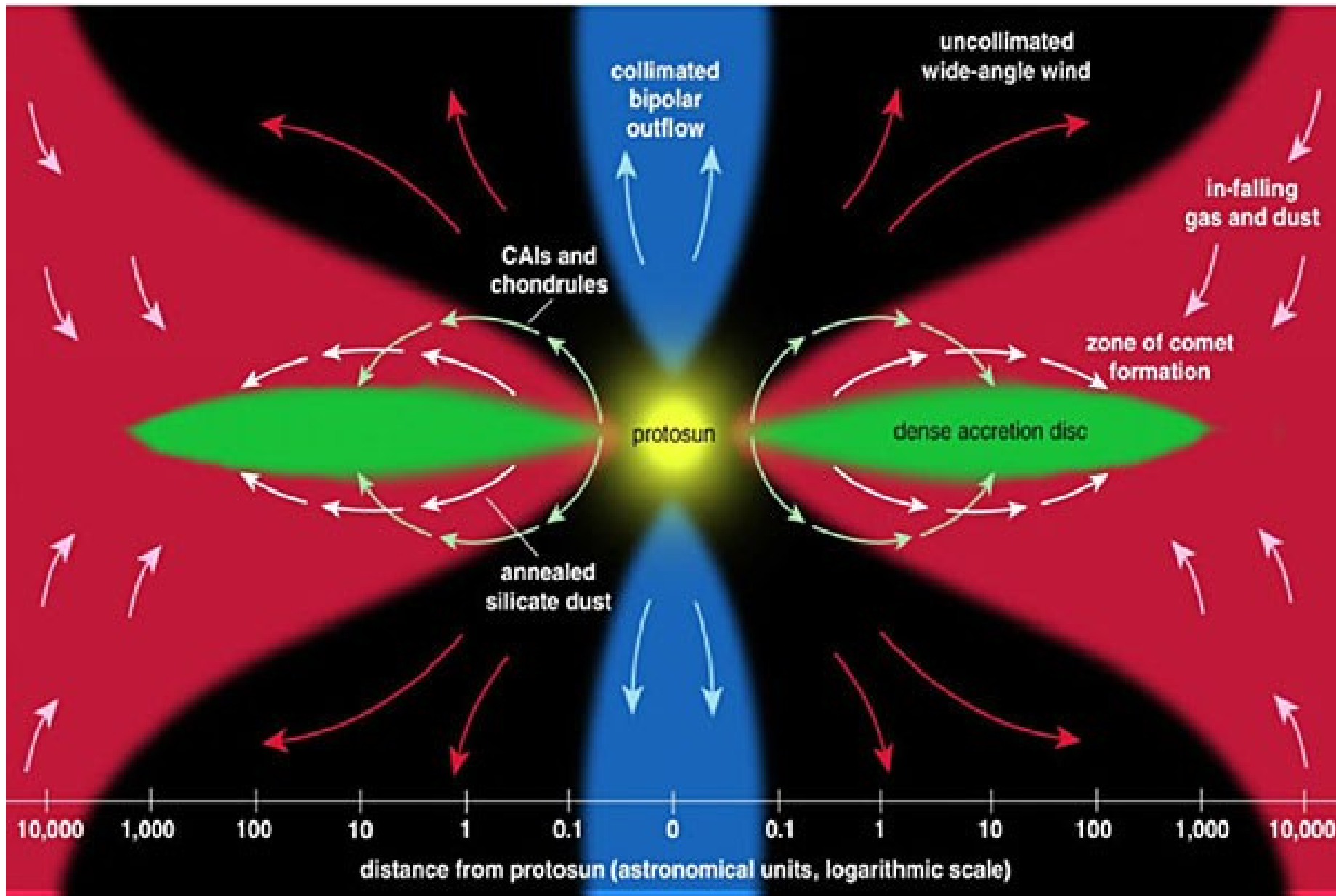
- passing photon with same frequency as the maser transition can stimulate a radiative de-excitation
- emitted photon has same direction as stimulating photon

→beaming

Amplification

- photons can stimulate other molecules
→ cascade as in a laser
- can also view phenomena as a negative optical depth:
instead of attenuation $I_l \propto e^{-\tau}$
you get amplification $I_l \propto e^{\tau}$
- intense spots of maser emission

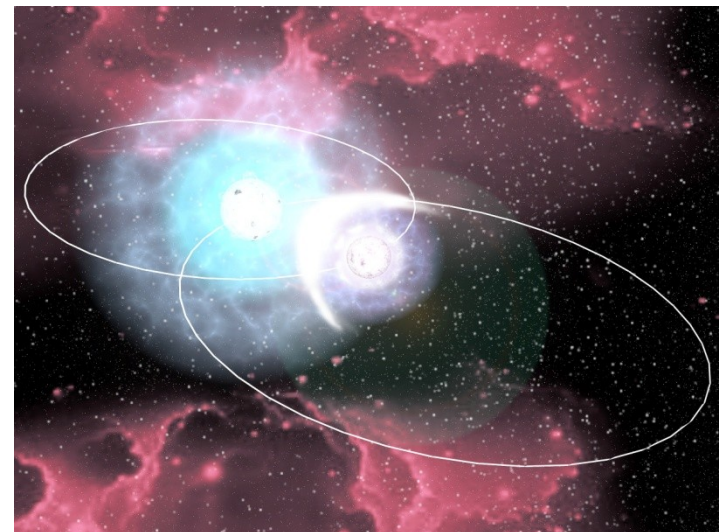
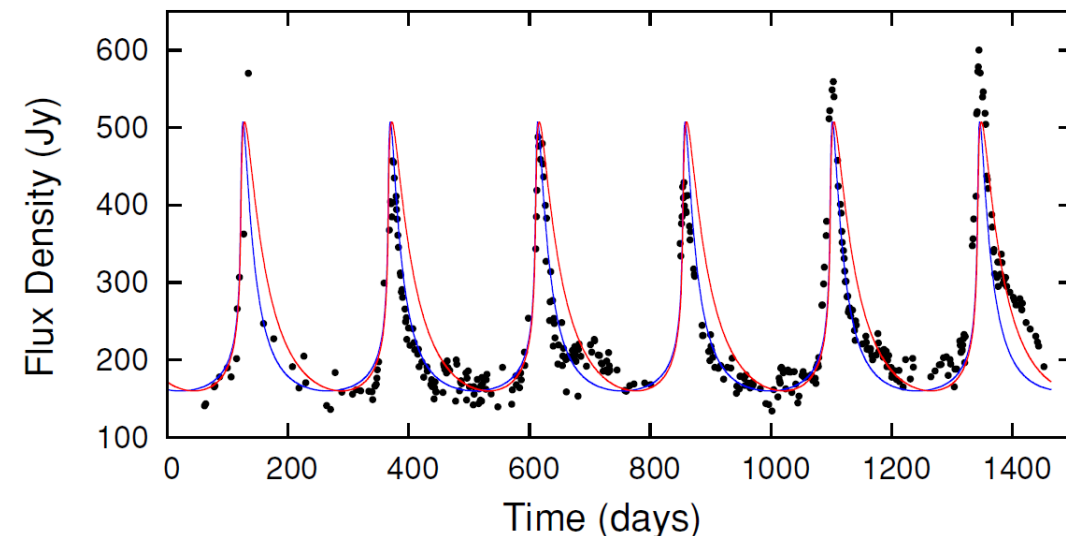




(from Nuth, J. A., 2001, *American Scientist*, v. 89, p.230.)

Periodic Methanol Masers

- Some methanol masers exhibit periodic flaring of the intensity of some components
- May be caused by colliding winds in an eccentric massive young binary system



END

Free-fall time

$$\frac{d^2 r}{dt^2} = -\frac{GM(r)}{r^2} = -\frac{4\pi GR_c^3 \rho_c}{3r^2}$$

since the $M(r)$ the mass internal to r will remain constant.

- Approximate solution can be obtained by assuming acceleration stays constant at the initial value ie.

$$\frac{d^2 r}{dt^2} = -\frac{4\pi GR_c^3 \rho_c}{3R_c^2} = -\frac{4\pi GR_c \rho_c}{3}$$

giving free - fall time $t_{ff} = \sqrt{\frac{3}{2\pi G \rho_c}}$

Infalling Cloud

- If assumed in free-fall – no pressure

$$\frac{1}{2} m v_{ff}^2 = \frac{GMm}{r}$$

$$v_{ff}(r) = \sqrt{\frac{2GM}{r}}$$

and \dot{M} is the mass infall rate where

$$\dot{M} = 4\pi r^2 \rho v$$

- So if constant \dot{M} then $\rho \propto r^{-\frac{3}{2}}$

Massive star formation

- Timescale for contraction of the protostellar hydrostatic core to the H burning main sequence is

$$\tau_{\text{K-H}} \sim \frac{GM^2}{R} / L$$

and for MS stars $L \propto M^{3.3}$ so $\tau_{\text{K-H}} \propto M^{-1.3}$

- For massive stars $\tau_{\text{K-H}} \ll \tau_{\text{ff}}$ and they arrive on the MS whilst still deeply embedded in their molecular cloud