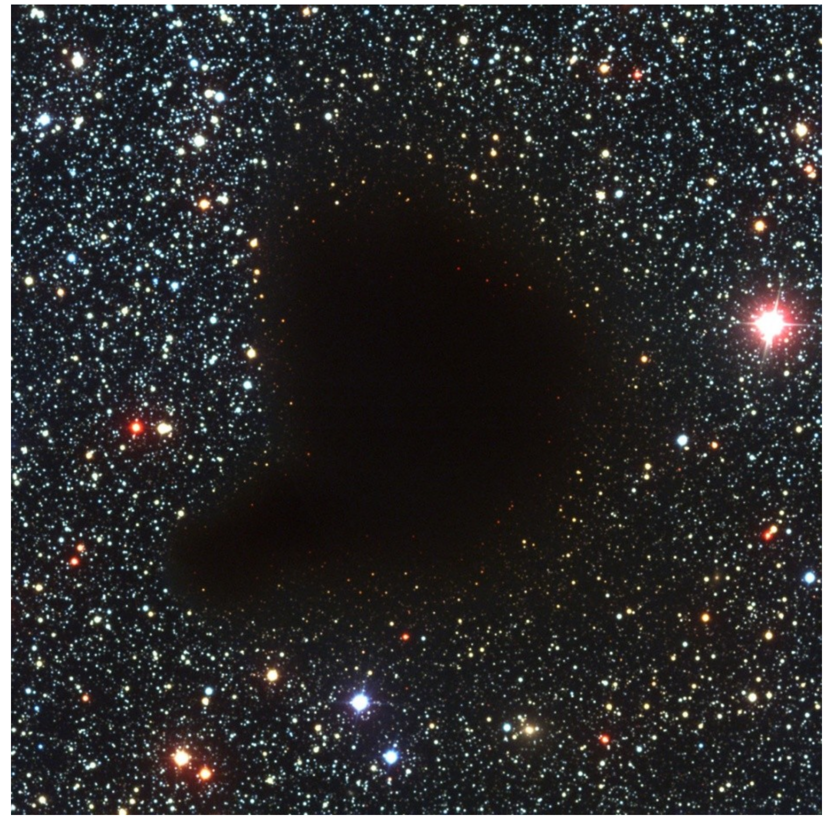
Star Formation

- 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

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

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 <PE>= - <KE/2>

- 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. 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:
  - $N.\ 3kT/2 = -[3GM^2/5R]/2$
  - $3NkT = -3GM^2/5R$
  - N= number of particles = Mass of cloud/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 $F_G = \dfrac{GMm}{r^2}$ the centrifugal force will eventually win out.

Centrifugal Radius

• Radius where $F_C = F_G$ is called the centrifugal radius

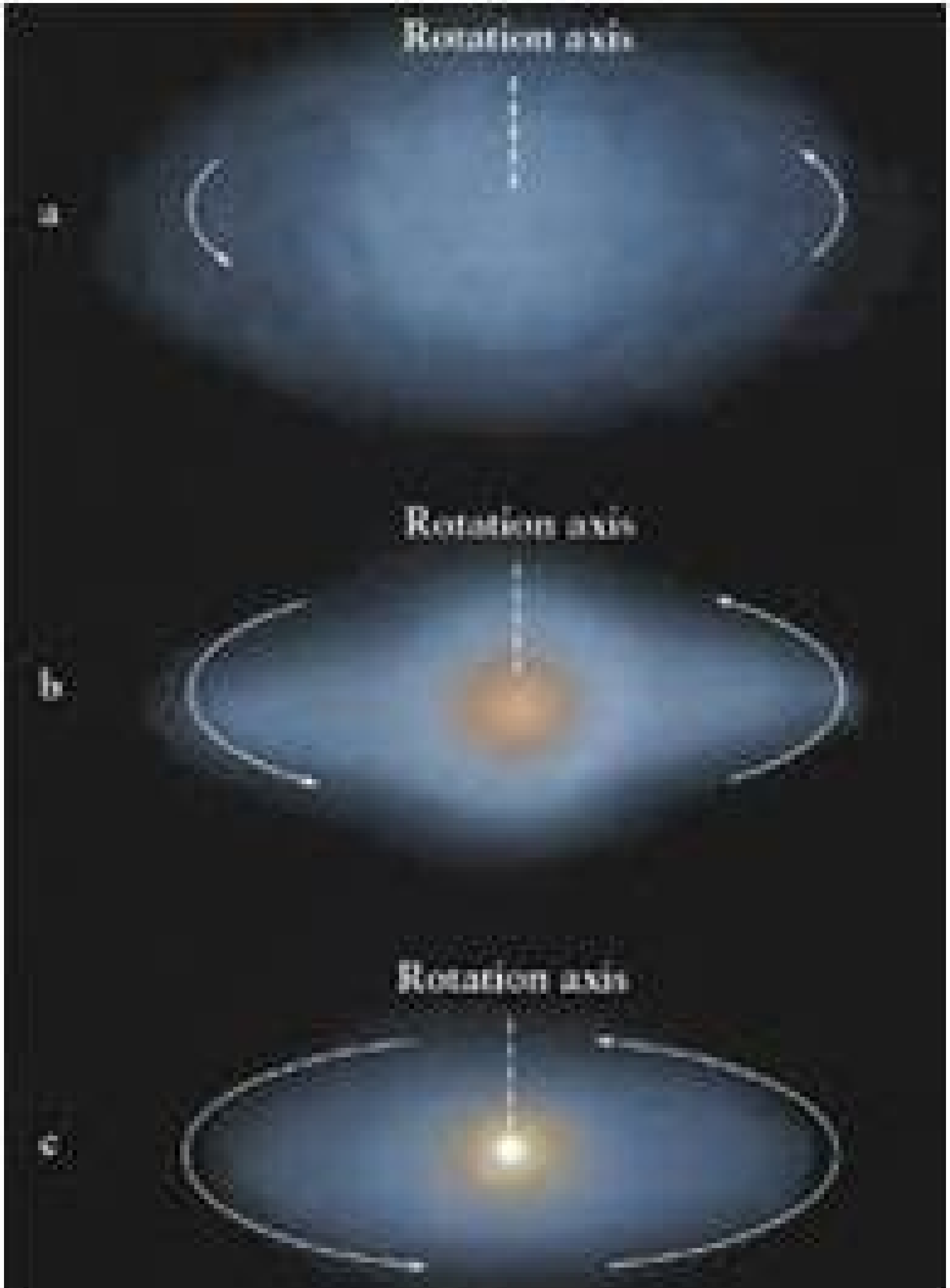
$$R_C = \frac{\Omega^2 R^4}{GM}$$

• Cloud can still contract parallel to rotation axis

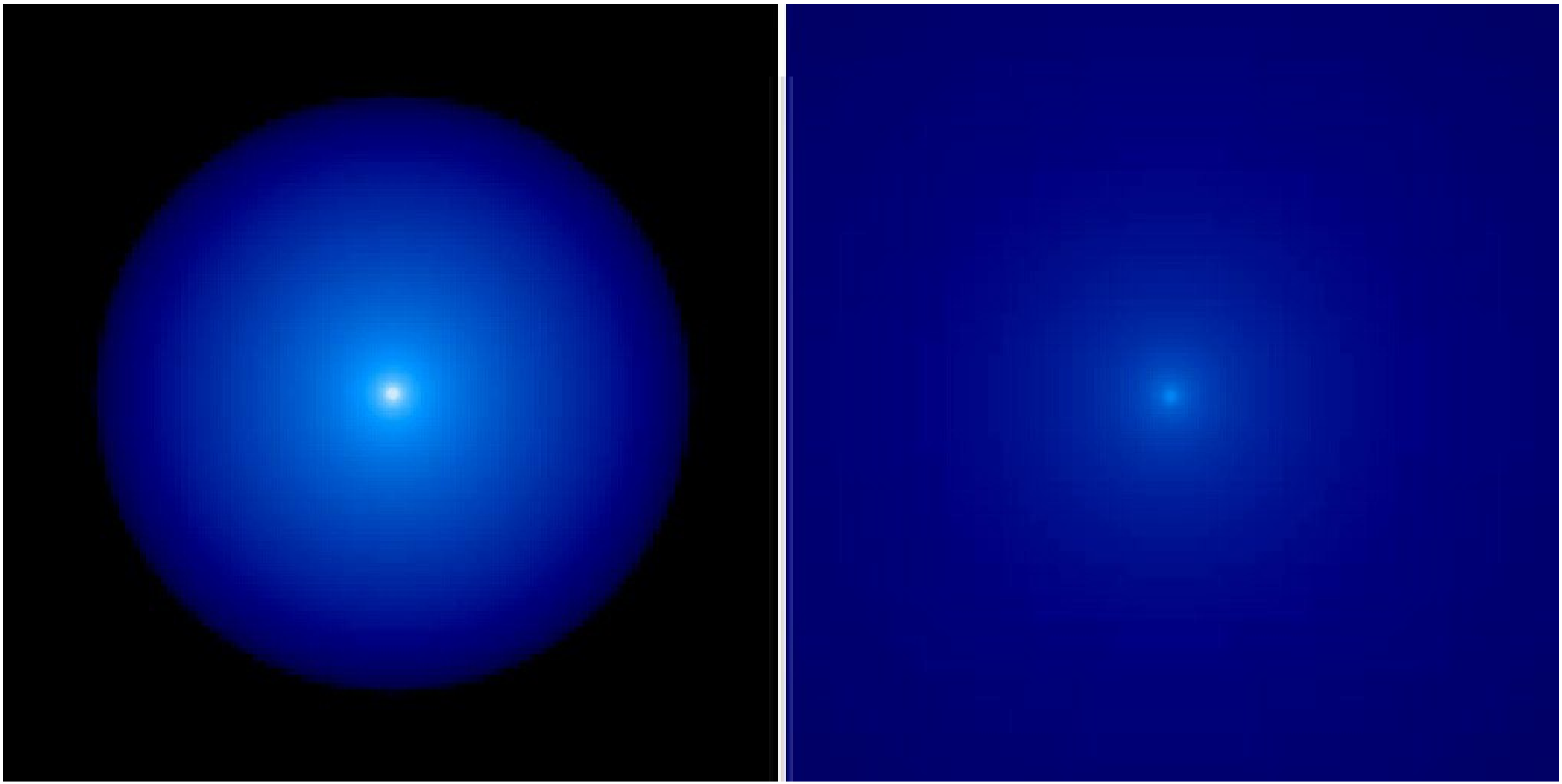
• This leads toflattened rotating structures

- accretion discs

• But need to lose a lot of angular momentum


Rotation axis
a
Rotation axis
b
Rotation axis
c

Numerical simulation



Krumholz et al. (2007)

Magnetic field during collapse

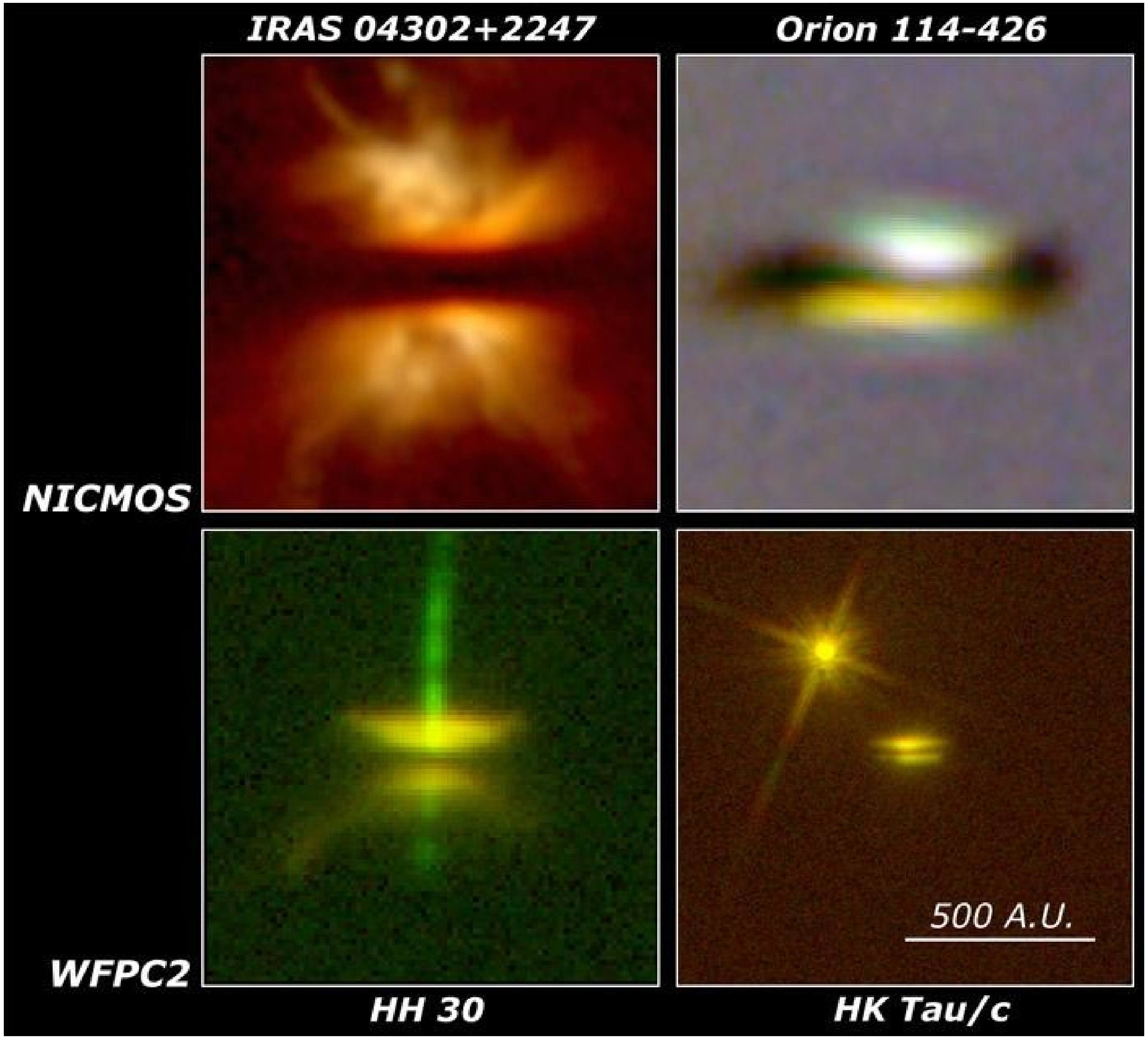
- Molecular clouds always have some level of ionization due to passage of energetic particles – cosmic rays
- Hence the initial magnetic field in the cloud will get dragged in during the collapse
- Need to lose alot of magnetic flux too

Accretion Discs

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

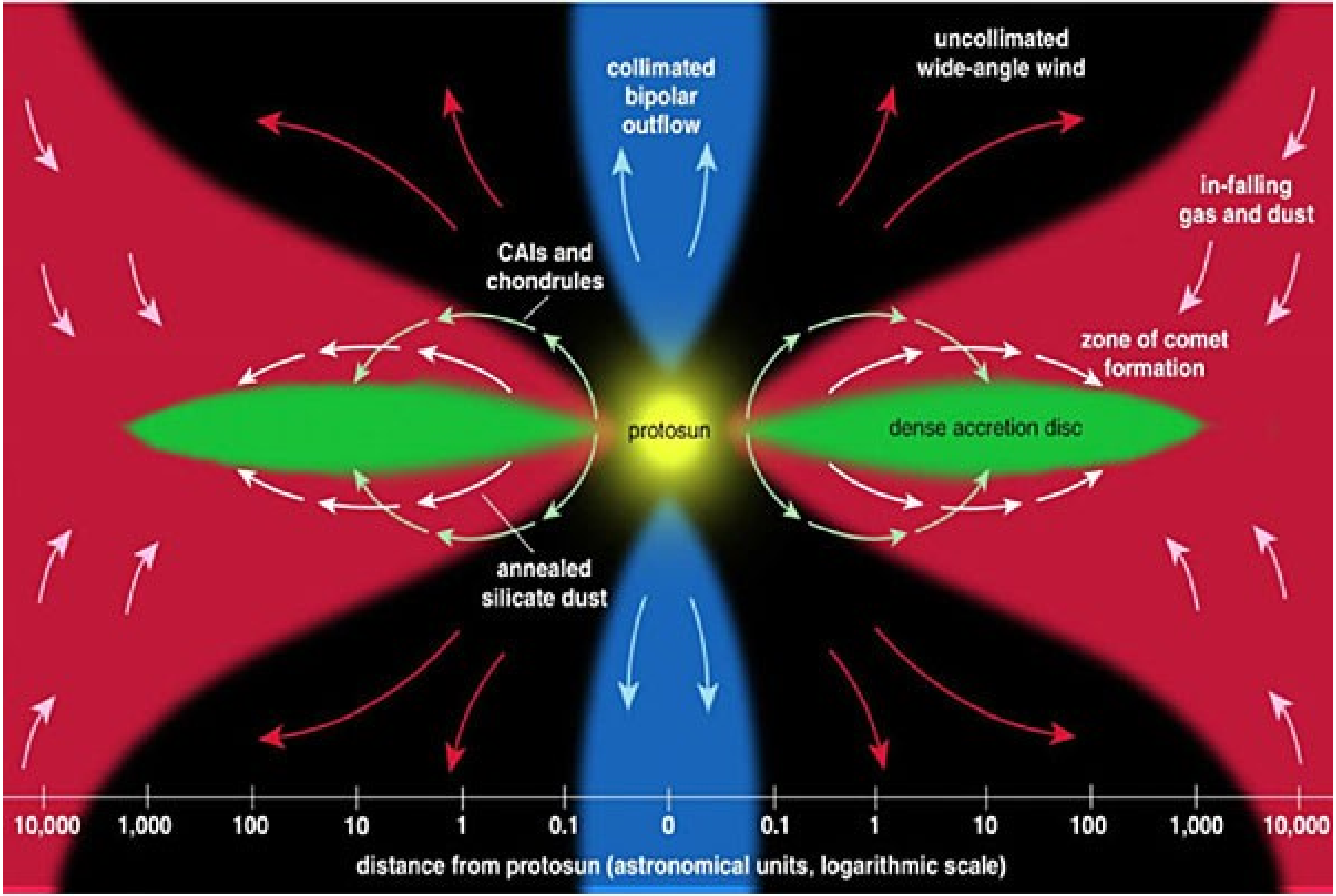
$$L_{acc} \sim \frac{GM\dot{M}}{R_S}$$ See later lectures

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

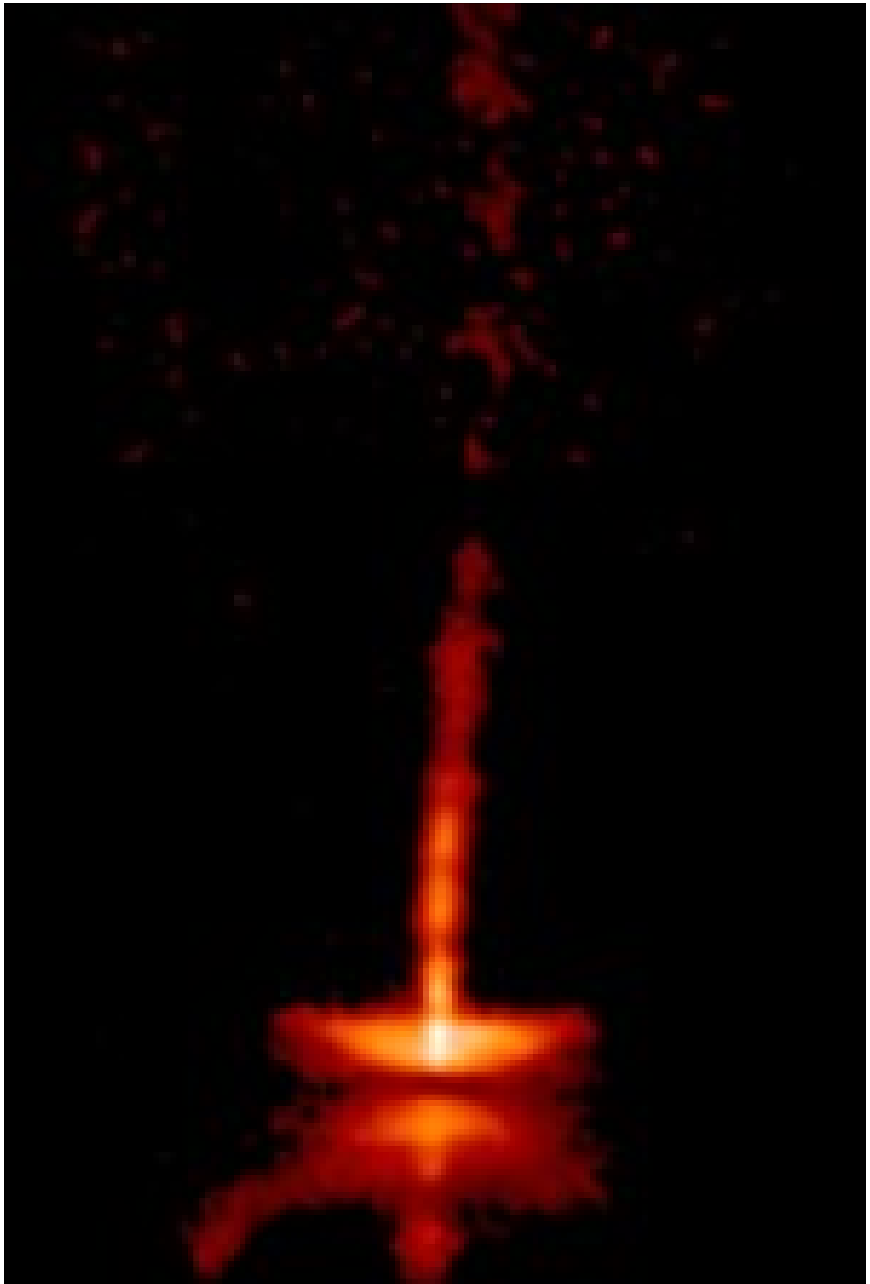


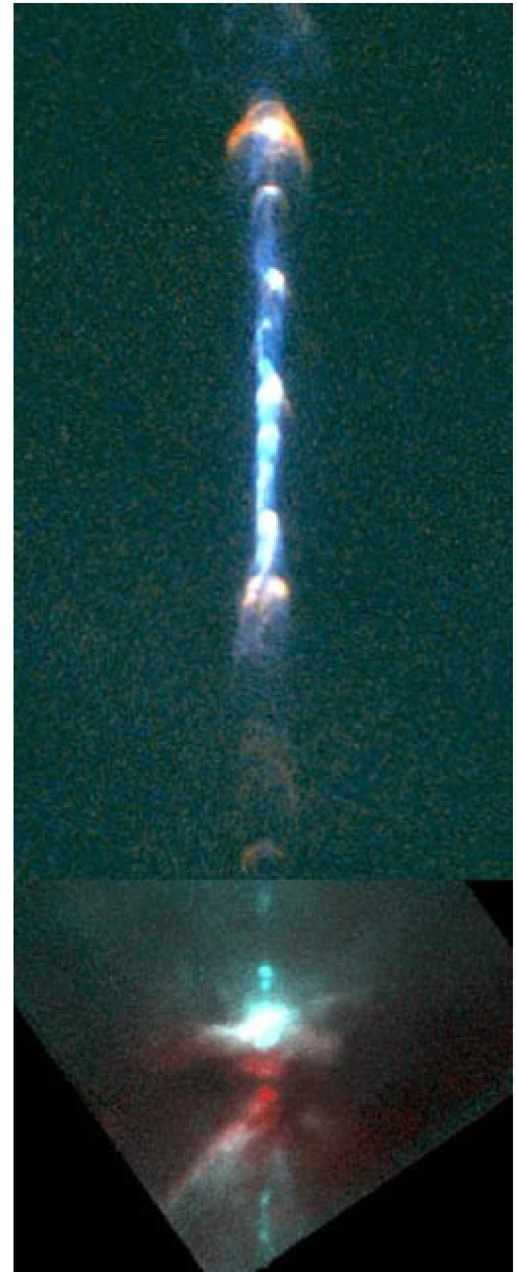
Jets and bipolar outflows

- 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

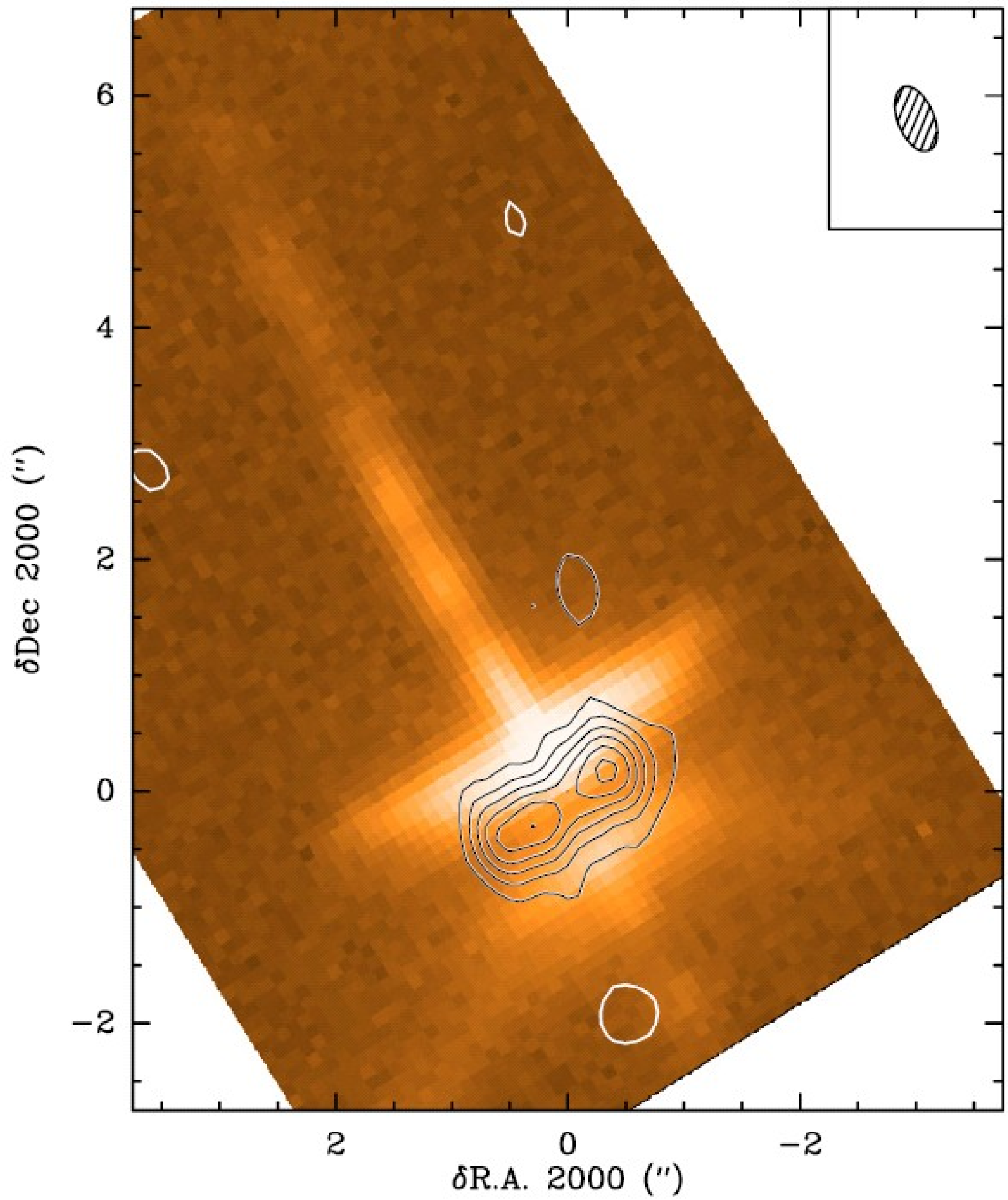


(from Nuth, J. A., 2001, *American Scientist*, v. 89, p.230.)

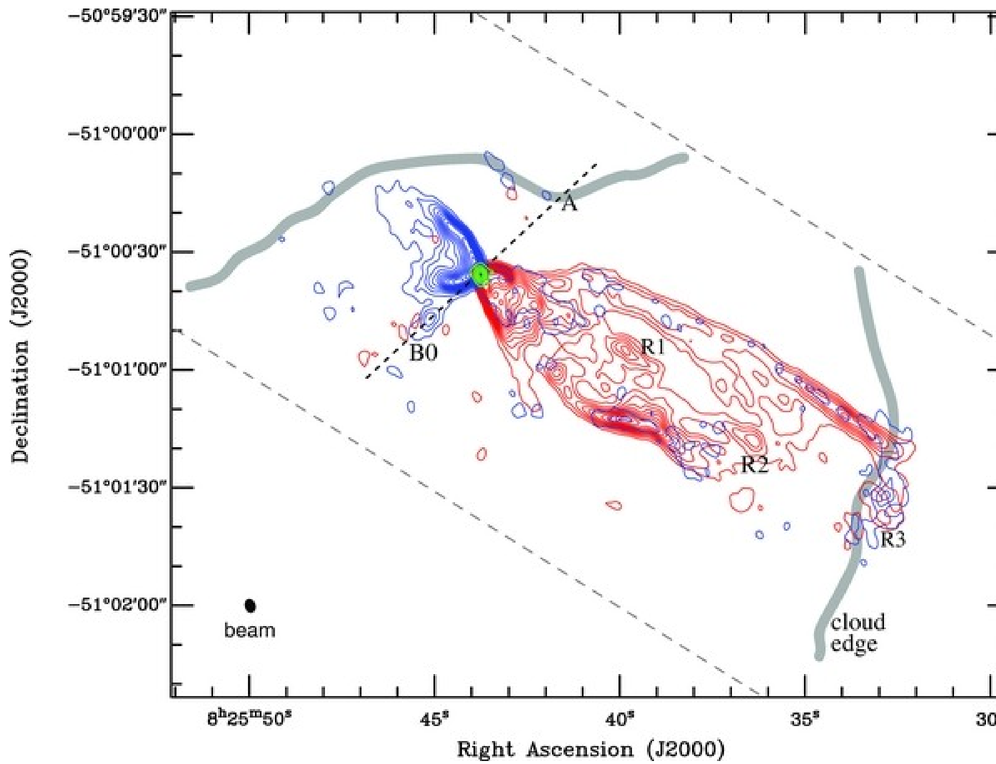




- Can see disc directly in molecular gas (CO)



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, H_2O, CH_3OH
- 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

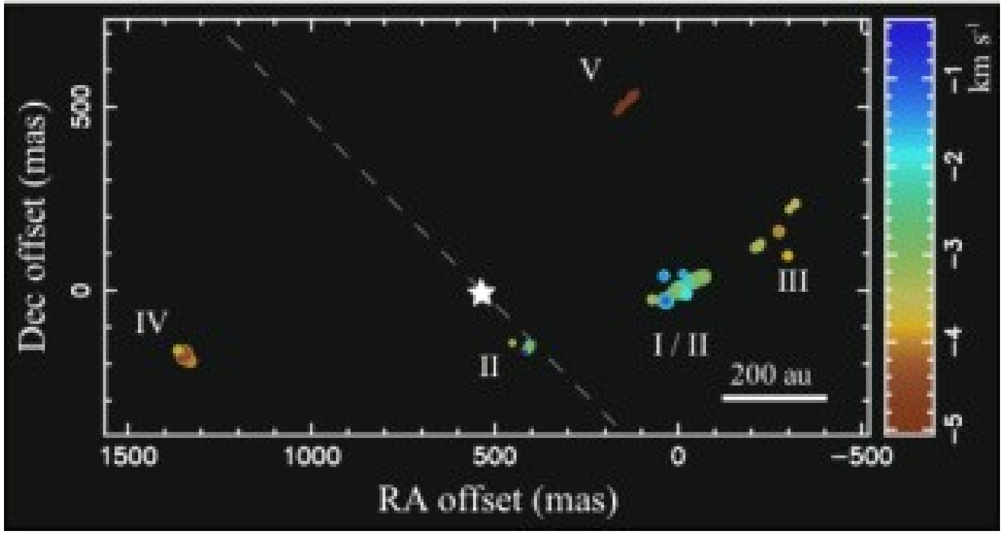
$\rightarrow$beaming

Amplification

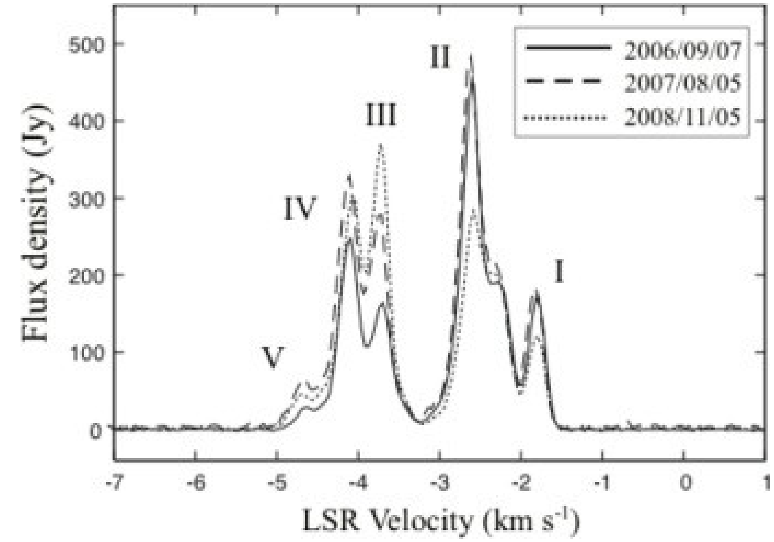
- photons can stimulate other molecules $\rightarrow$cascade as in a laser
- can also view phenomena as a negative optical depth:

  instead of attenuation $I_l \propto e^{-\tau}$

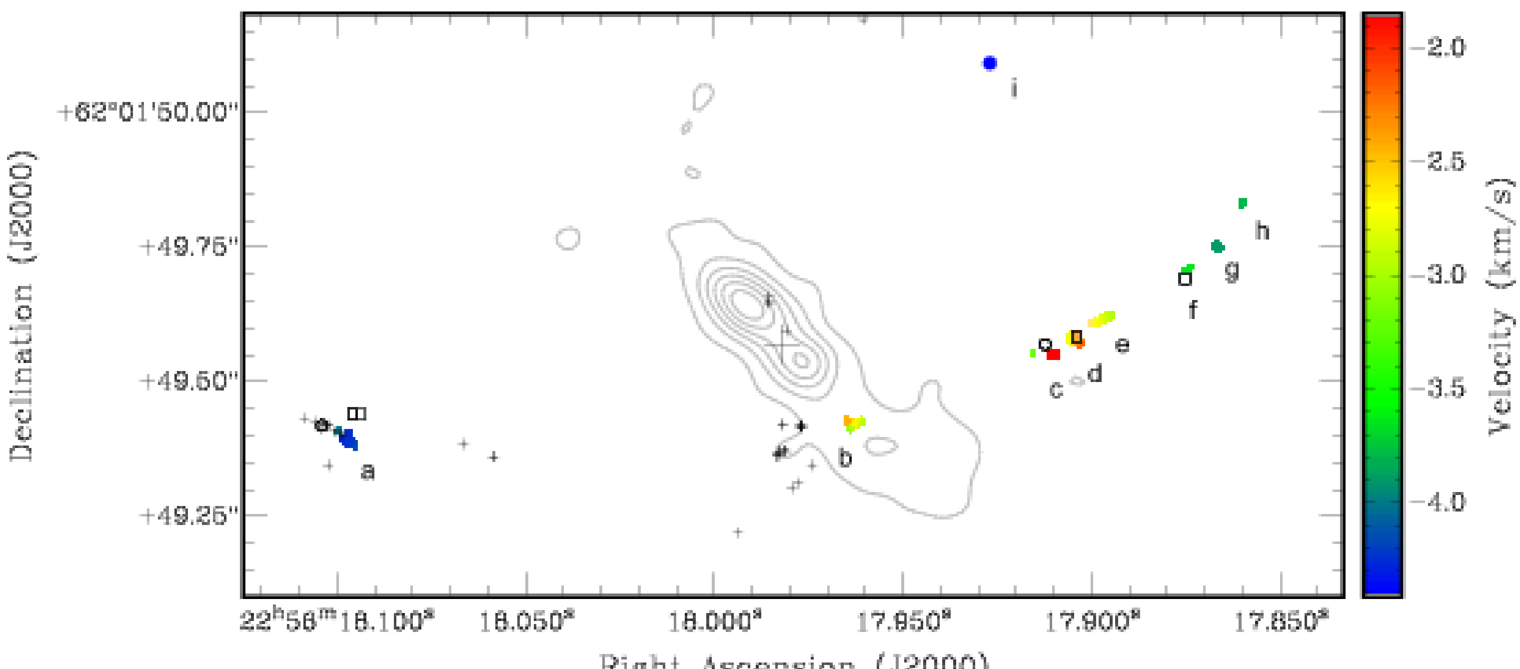
  you get amplification $I_l \propto e^{\tau}$
- intense spots of maser emission



V
III
I / II
II
IV
200 au
Dec offset (mas)
RA offset (mas)
1500
1000
500
0
−500
km s⁻¹
−1
−2
−3
−4
−5



2006/09/07
2007/08/05
2008/11/05
II
III
IV
V
I
Flux density (Jy)
LSR Velocity (km s⁻¹)



+62°01'50.00"
+49.75"
+49.50"
+49.25"
Declination (J2000)
22h58m18.100s
18.050s
18.000s
17.950s
17.900s
17.850s
Right Ascension (J2000)
Velocity (km/s)
-2.0
-2.5
-3.0
-3.5
-4.0
a
b
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e
f
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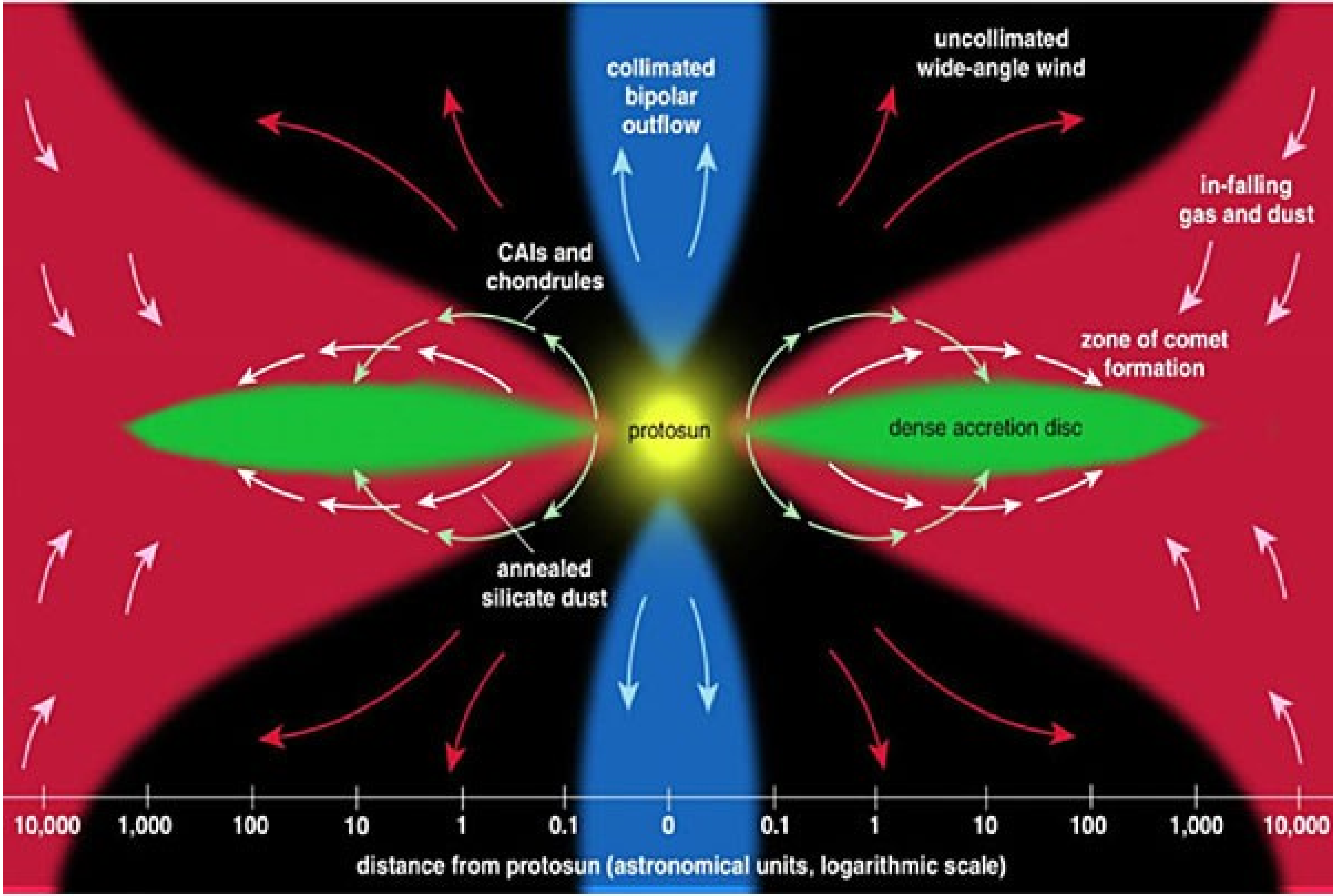
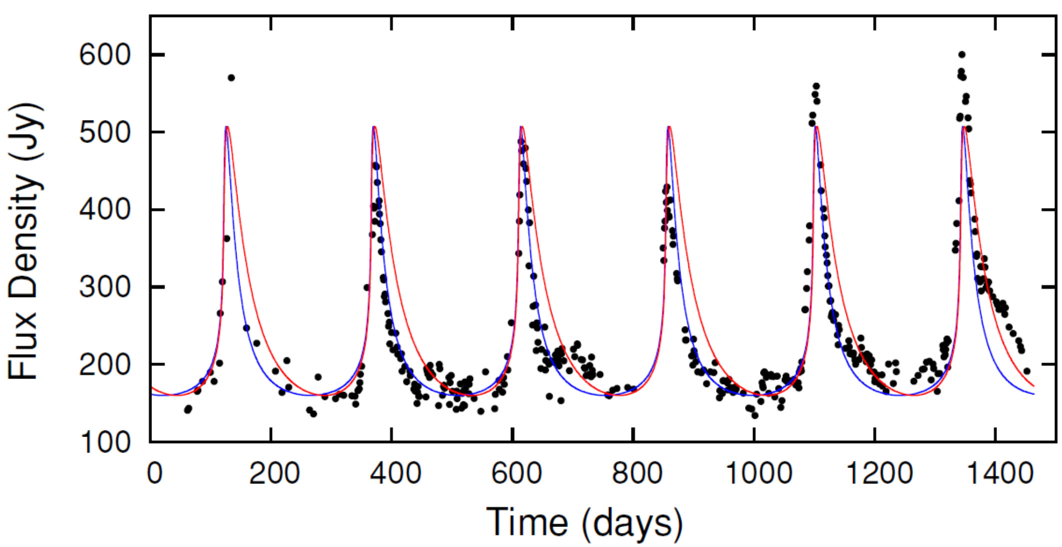
h
i

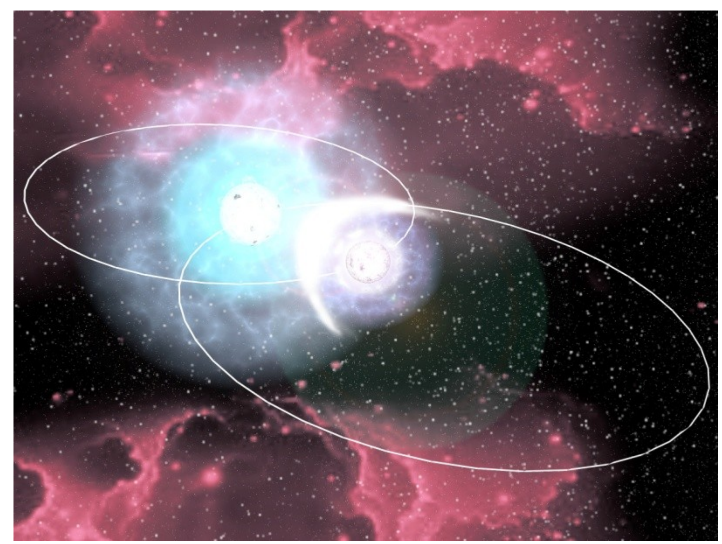


(from Nuth, J. A., 2001, *American Scientist*, v. 89, p.230.)

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

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

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.

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

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

Infalling Cloud

- If assumed in free-fall – no pressure

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

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

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