Protoplanetary gas disks –
Accretion disks II

Protoplanetary Disks - Accretion Disks II

No solid body rotation, but a shear flow ->

Viscous forces

-> Mass transport inward, angular momentum transport outward

Solar System: Sun has 99% of mass, but less than 2% in angular momentum

-> Heating (very inner disk)

Original Idea: v. Weizsäcker (1943, 1948) ->

Solution of angular momentum problem related to formation of solar system

1943 "Rotation kosmischer Gasmassen"

general solution of equations by R. Lüst on the occasion of the 50th birthday of W. Heisenberg

Rediscovery

Cataclysmic variables (Lynden-Bell & Pringle 1974)

Quasars (Lynden-Bell 1969)

For a thin accretion disk the equations of mass conservation and angular momentum result in diffusion equation for Σ.

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

$\nu = \alpha \cdot c_s \cdot H$ (Shakura & Sunyaev 1973)

What is the reason for α ?

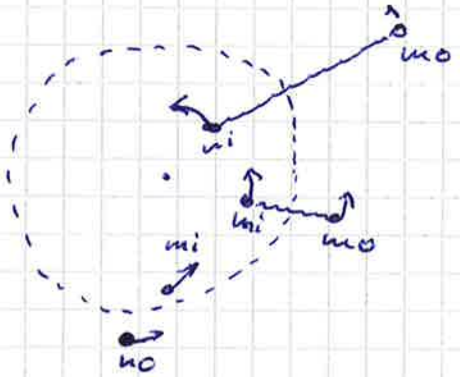
a) Molecular viscosity much too small

b) α represents viscosity of a "turbulent" flow

But what is the origin of "turbulence" in the flow (no hydrodynamic instability found in isothermal disk with Keplerian flow)

Solution: Fully ionized medium -> magnetic field acts on fluid → Magnetorotational instability

Magnetic fields bind fluid elements as they were connected by a spring.



Inner element orbit faster than outer element, but angular momentum of lower orbit is smaller than that of higher orbit -> "Spring" -> will pull back on mi and drag mo forward;

mi loses angular momentum -> gets faster

mo gains angular momentum -> gets slower

In ideal MHD simulations: $\alpha \sim 10^{-3} \dots 10^{-2}$

However, limited ionization degree and non-ideal effects (e.g. ambipolar diffusion)

Steady-state thin accretion disk

- Pressure of gas not important → motion in disk plane
- $\dot{M} = 2\pi R \Sigma \cdot (-v_R) = \text{const.}$

Simple considerations

(1) Centrifugal force = gravitational force (mom. equ.)

Cylindrical polar coordinates (R, ϕ, z)

Central point mass M_* should dominate

$$v_\phi^2 / R = G M_* / R^2$$

$$\omega = (G M_* / R^3)^{1/2}$$

Keplerian disk; $d\omega / dR \neq 0$ (shear flow)

(2) Number of accreting objects decays with time; Very similar to dust evolution

(3) $\dot{M} \sim M_*^2$ (diff. to understand just from accretion theory)

Special disks

Transition disks (gaps)

Photoevap. / Opacity gaps / Planets / stellar companions

Energy consideration

Energy dissipated from potential energy when $\dot{M}$ flows through ΔR

$$\dot{E} \sim \dot{M} \frac{G M_*}{2R} \frac{\Delta R}{R}$$

In thin disk radiation will be locally emitted:

$$\dot{E} \sim 4\pi R \Delta R \, \sigma T_e^4$$

(Area: $A = \pi R^2$; diff. $2\pi R \Delta R$; to 2 sides)

[opt. thick case of geometrically thin disk]

$$\Rightarrow \quad T_e^4 \sim G M_* \dot{M} R^{-3}$$

$$T_e \sim R^{-3/4}$$

(Note: Passively heated flat disk $T \sim R^{-3/4}$)
If $L_* > G M_* \dot{M} / R_*$ → Disk irrad. dominates T; $T_d \sim R^{-1/2}$

Complete calculation (Pringle 1981, ARAA 19, 137)

$$T_e^4 \simeq \frac{3 G M_* \dot{M}}{8 \pi \sigma R^3} \Big[1 - \underset{\uparrow}{(R_* / R)^{1/2}} \Big]$$

Selection of correct boundary conditions
R_* – Inner disk radius

Full luminosity of disk:

$$L_D = \int_{R_*}^{\infty} \sigma T_e^4 \, 4\pi R \, dR = \frac{G M_* \dot{M}}{2 R_*}$$

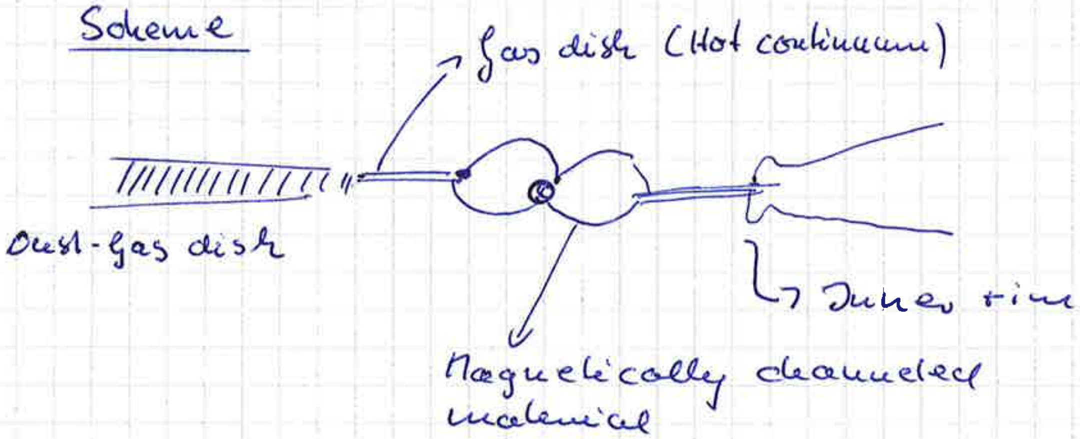
→ Only half of the potential energy will be emitted from disk

→ Disk is only half of the story; the same amount of energy will come from the boundary layer where the disk material comes to rest

Energy will be emitted in thin hot boundary layer (much hotter than disk!

T ~ 7000 - 10 000 K ⇒ UV radiation

Scheme



How to trace gas

- In "dusty" part → H_2 would only trace surface layer

  CO (but freeze-out, photodestruction)

- NIR and MIR lines of vibrationally excited CO traces gas > 1000 K

Disks around massive young stellar objects

1) Radiation pressure problem during formation of stars ->

Disks should be important ingredient of circum-stellar environment of massive YSOs.

2) Observational challenges

a) Still deeply embedded, large distances, clustered environment -> Confusion

b) (Sub)mm or NIR interferometry important to disentangle the spatial confusion

c) Right spectral line tracers still difficult to identify; Discrimination between disk and envelope emission

-> Often large rotating structures found in molecular line tracers

-> Disks around B-type stars (AFGL 490, IRAS 20126+4104)

-> Best example for disk around massive star: AFGL 4176 ($10^5 L_\odot$)

CH_3CN $J=13-12$ K-line (ind. of Keplerian rotation)

1.2 mm cont. emission: Mass ~ $8 M_\odot$