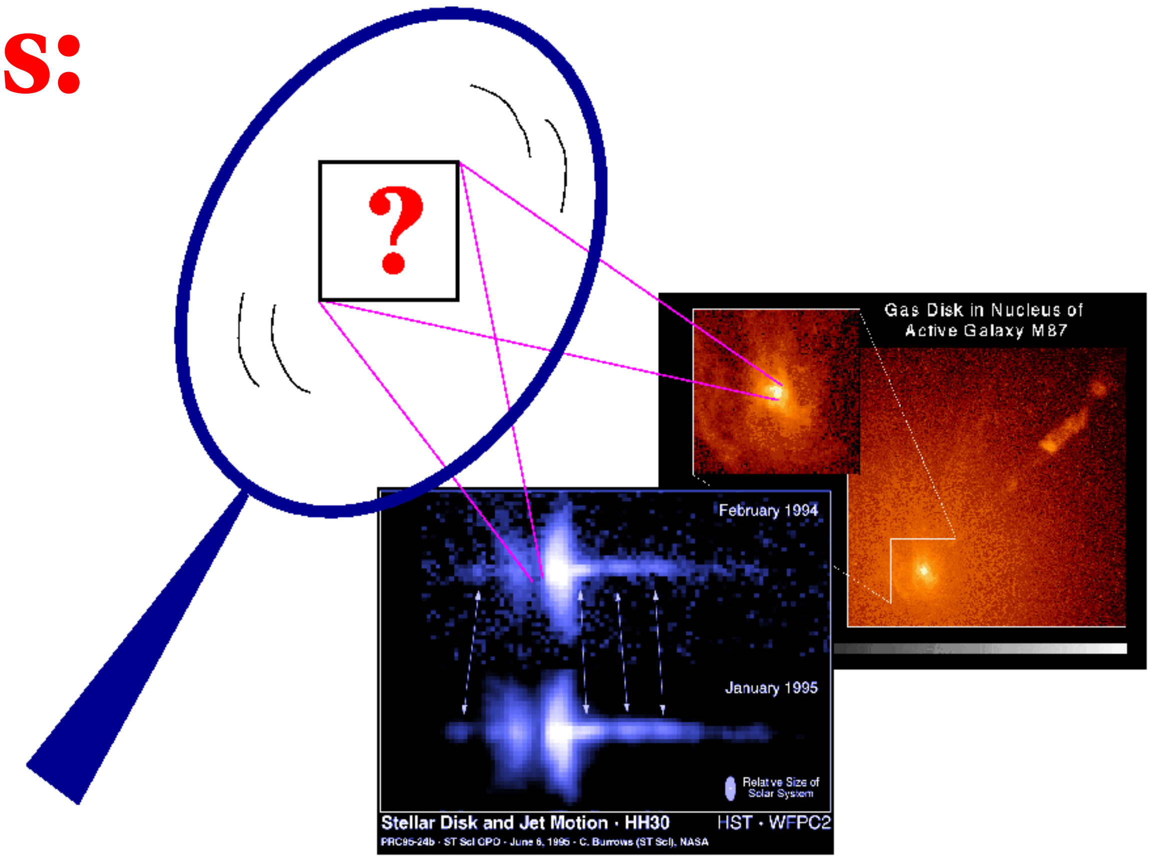
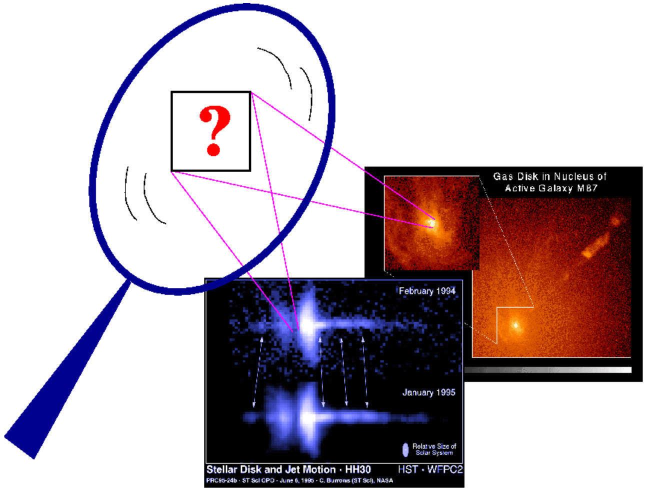
Outflows & Jets: Theory & Observations



Lecture winter term 2008/2009

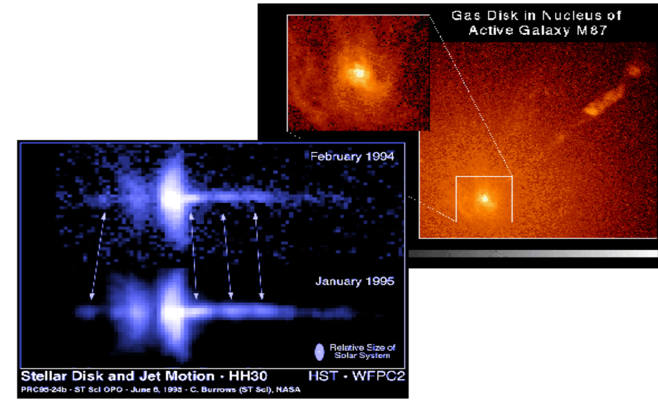
Henrik Beuther & Christian Fendt

Outflows & Jets: Theory & Observations



10.10 Introduction & Overview ("H.B." & C.F.)
17.10 Definitions, parameters, basic observations (H.B.)
24.10 Basic theoretical concepts & models I (C.F.): Astrophysical models, MHD
31.10 Basic theoretical concepts & models II (C.F.) : MHD, derivations, applications
07.11 Observational properties of accretion disks (H.B.)
14.11 Accretion, accretion disk theory and jet launching (C.F.)
21.11 Outflow-disk connection, outflow entrainment (H.B.)
28.11 Outflow-ISM interaction, outflow chemistry (H.B.)
05.12 Theory of outflow interactions; Instabilities (C.F.)
12.12 Outflows from massive star-forming regions (H.B.)
19.12 Radiation processes - 1 (C.F.)
26.12 and 02.01 Christmas and New Year's break
09.01 Radiation processes - 2 (H.B.)
16.01 Observations of AGN jets (C.F.)
23.01 Some aspects of AGN jet theory (C.F.)
30.01 Summary, Outlook, Questions (H.B. & C.F.)

Accretion history

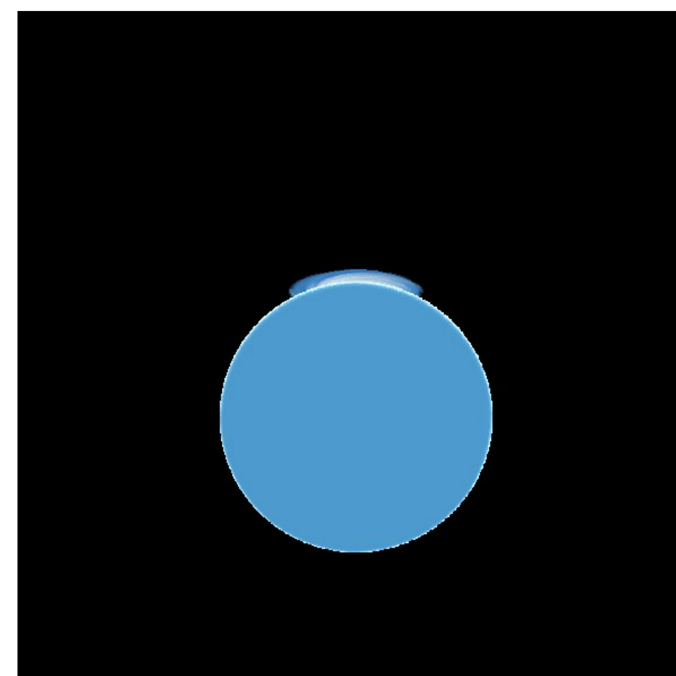


Brief history of accretion disks (examples):

Disks commonly found in various astrophysical sources:

-> YSO, AGN, m-quasars, pulsars, CV (white dwarfs), HMXB, LMXB,
-> many of these disk systems have jets (but not all)
-> all jet/outflow sources have disks

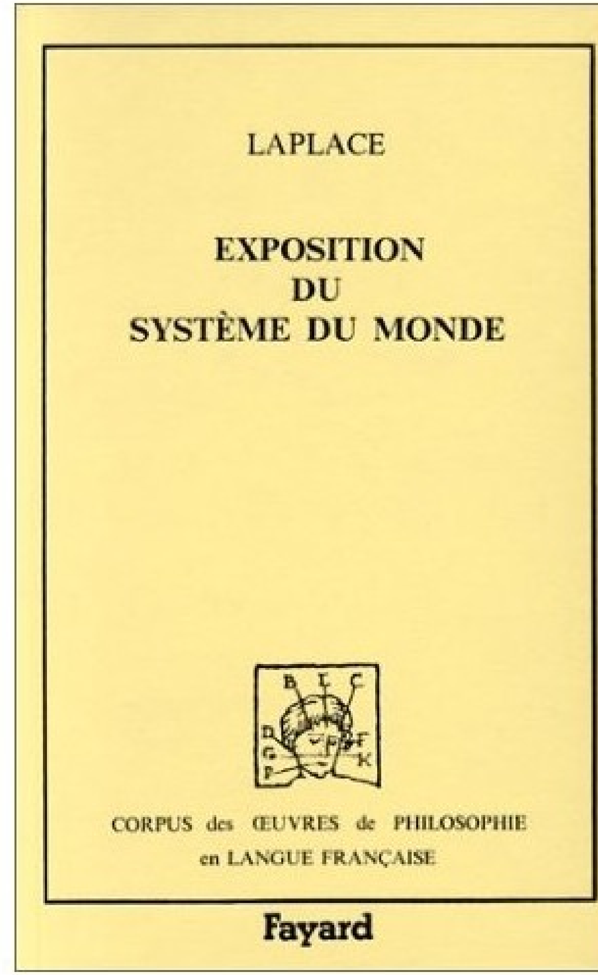
Disk basics:



-> mass "infall" under angular momentum conservation
-> almost Keplerian rotation, almost axisymmetry
-> drift of matter in (-r)-direction if angular momentum loss in outward direction (accretion)
-> angular momentum removal by viscosity / turbulence / disk wind / magnetic field
-> heating / luminosity by viscos friction
-> disk temperature profile / disk spectral energy distribution

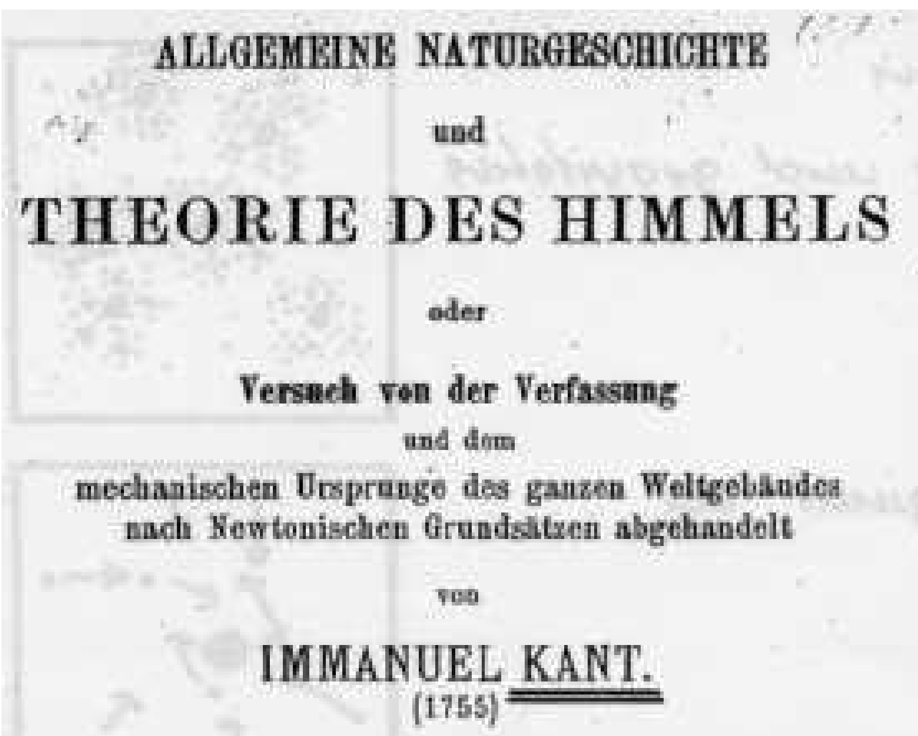
Accretion history

Example history of accretion disks:



Kant (1755):

- "Urnebel", nebula in stochastic motion, flatened by rotation
- collisions -> energy loss
  -> central condensation (Sun)
- planets originate from local concentrations



ALLGEMEINE NATURGESCHICHTE

und

THEORIE DES HIMMELS

oder

Versuch von der Verfassung

und dem

mechanischen Ursprunge des ganzen Weltgebäudes
nach Newtonischen Grundsätzen abgehandelt

von

IMMANUEL KANT.
(1755)

Laplace (1799):

- planet formation from hydrodynamic continuum
- rings expelled from solar surface, rings contracts to spherical bullets
- no differential rotation, no condensations

Accretion history

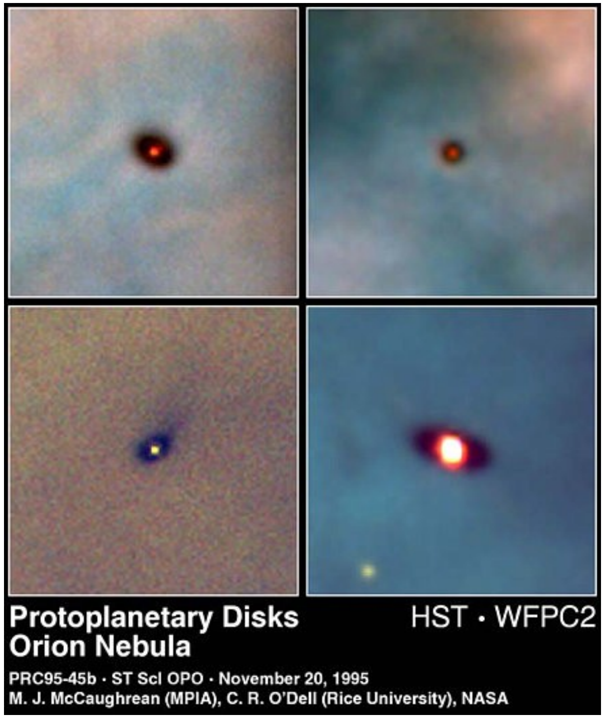
Example history of accretion disks:

Kant (1755): Erstes Hauptstück

Von dem Ursprunge des planetischen Weltbaues überhaupt und den Ursachen ihrer Bewegungen ...
Wenn demnach ein Punkt in einem sehr grossen Raume befindlich ist, wo die Anziehung der daselbst befindlichen Elemente stärker als allenthalben um sich wirkt: so wird der in dem ganzen Umfange ausgebreitete Grundstoff elementarischer Partikeln sich zu diesem hinsenken.
Die erste Wirkung dieser allgemeinen Senkung ist die Bildung eines Körpers ... Wenn die Masse dieses Centralkörpers so weit angewachsen ist, dass die Geschwindigkeit, womit er die Theilchen von grossen Entfernungen zu sich zieht, durch die schwachen Grade der Zurückstossung, womit selbige einander hindern, seitwärts gebeugt, in Seitenbewegungen ausschlägt, die den Centralkörper vermittelst der Centerfliehkraft in einem Kreise zu umfassen im Stande sind: so erzeugen sich grosse Wirbel von Theilchen, deren jedes für sich krumme Linien durch die Zusammensetzung der anziehenden und der seitwärtsgelenkten Umwendungskraft beschreibt; .... Indessensind diese auf mancherlei Art unter einander streitende Bewegungen natürlicher Weise bestrebt, einander zur Gleichheit zu bringen, ...
Dieses geschieht erstlich, indem die Theilchen eines des andern Bewegung so lange einschränken, bis alle nach einer Richtung forgehen; zweitens, dass die Partikeln ihre Verticalbewegung, vermittelst der sie sich dem Centro der Attraction nähern, so lange einschränken, bis sie alle horizontal , d. i. in parallel laufenden Zirkeln um die Sonne als ihren Mittelpunkt bewegt, einander nicht mehr durchkruezen und durch die Gleichheit der Schwungskraft mit der senkenden sich in freien Zirkelläufen in der Höhe, da sie schweben,immer erhalten .... In diesem Zustande, da alle Theilchen nach einer Richtung und in parallellaufenden Kreisen, nämlich in freien Zirkelbewegungen, durch die erlangte Schwungskräfte um den Centralkörper laufen, ist der Streit under der Zusammenlauf der Elemente gehoben, und alles ist in dem Zustande der kleinsten Wechselwirkung. Dieses ist die natürliche Folge, darein sich allemal eine Materie, die instreitenden Bewegungen begriffen ist, versetzt.

Dieser Körper in dem Mittelpunkte der Attraction, der diesem zu zufolge das Hauptstück des planetischen Gebäudes durch die Menge seiner versammelten Materie geworden ist, ist die Sonne, ob sie gleich diejenige flammende Gluth alsdann noch nicht hat, die nach völlig vollendeter Bildung auf ihrer Oberfläche hervor bricht.

Accretion history



Example history of accretion disks:

von Weizsäcker (1943, 1948):
- formation of Sun & planets from gaseous disk
- turbulent disk. angular momentum transport outwards

Lynden-Bell, Pringle, Rees (1969, 1972, 1974):
accretion disks in AGN & quasars, compact X-ray sources

Shakura & Sunyaev (1973):
- structure, luminosity, temperature profile of disks
- invention of turbulent viscosity parametrisation

Ichimaru (1977) : sub-Eddington and very low opacity disk (~ADAF)

Paczynsky & Wiita (1980): thick disk araound black holes

Abramowicz et al. (1988): slim disks

Beckwith et al. (1990): survey (1.3mm) of TT disks --> masses, temperature profiles

Balbus & Hawley (1991): magneto-rotational instability (MRI) causes disk turbulence

Narayan & Yi (1994, 1995): advection dominated accreation disks (ADAFs)

O'Dell, McCaughrean et al. (1993, 1996): direct imaging of disks around young stars

Miyoshi et al. (1995): evidence for a BH in jet source NGC 4258, Kepler disk, 3.6^7 Mo BH

Literature: Frank, King, Raine (2002). Accretion power in astrophysics
Pringle (1981), Accretion discs in astrophysics, ARA&A 19,137

Spherical accretion

Simplest case of accretion: **Free fall:** only gravity

Radiation of source: **Eddington limit:** gravity balanced by radiation pressure

-> photon scattered by free electrons (Thompson scattering): $\dfrac{d\sigma_T}{d\Omega} = r_e^2 \sin^2\theta$

$$\sigma_T = \frac{8\pi}{3} r_e^2 = 6.65 \times 10^{-25} \mathrm{cm}^2 \qquad r_e \equiv \left(\frac{e^2}{m_e c^2}\right) = 2.8 \times 10^{-13} \mathrm{cm}^2$$

-> momentum of photon with energy E is p = E/c;
star with luminosity L has photon momentum flux $\dfrac{dp}{dtdA} = \dfrac{L}{4\pi c r^2}$.

-> momentum transfer rate on electron by phtoton is $\dfrac{dp}{dt} = \sigma_T \dfrac{dp}{dtdA} = \sigma_t \dfrac{L}{4\pi c r^2}$.

-> $\sigma_t \dfrac{L}{4\pi c r^2} \leq \dfrac{GMm_p}{r^2}$ (radiation force < gravitational force)

-> limiting luminosity for accretion $L \leq \dfrac{4\pi G m_p c}{\sigma_T} M \equiv L_{edd}$.

Eddington luminosity: $L_{edd} = 1.2 \times 10^{38} \left(\dfrac{M}{M_\odot}\right)$ erg/sec,

Spherical accretion

Bondi accretion: (Bondi 1952, Hoyle & Lyttleton 1939, Bondi & Hoyle 1944)

Accretion considering gravity and gas pressure, no rotation (see also Parker wind):

-> stationary HD equations -> mass conservation -> accretion rate: $\dot{M} = 4\pi r^2 \rho v$

stationary equation of motion: $v(dv/dr) = -(1/\rho)(dp/dr) - GM/r^2$

-> integration of e. o. m. (energy conservation): $\frac{v^2}{2} + \int \frac{dp'}{\rho(p')} - \frac{GM}{r} = const \equiv E$

-> with polytropic gas law $p = K\rho^\gamma$ and sound speed $a^2 \equiv dp/d\rho = \gamma p/\rho$

Bernoulli equation:
(wind equation,
energy equation)

$$\frac{v^2}{2} + \frac{1}{\gamma - 1}a^2 - \frac{GM}{r} = E = \frac{1}{\gamma - 1}a_\infty^2$$

-> Bondi 1952: different mass fluxes result in different solution branches of Bernoulli eq.
Interpretation: Infall solution: starts with low speed at large radii, accelerates to high velocity at small radii (free fall for r -> 0)
Outflow solution: starts with low speed at small radii

Spherical accretion

Bondi accretion: (Bondi 1952, Hoyle & Lyttleton 1939, Bondi & Hoyle 1944)

-> re-arrange energy equation and equation of motion:

$$\rho'/\rho + v'/v + 2/r = 0, \qquad vv' + a_s^2\rho'/\rho + GM/r^2 = 0$$

gives derivatives: $v' = D_1/D, \quad \rho' = -D_2/D$ with

$$D_1 = (2a^2/r - GM/r^2)/\rho, \quad D_2 = (2v^2/r - GM/r^2)/v, \quad D = (v^2 - a_s^2)/\rho v$$

Note: potential singularities in these equations (the derivatives) at r = rs

rs is "critical point" -> regular condition for solution: D1 = D2 = D = 0 at rs

-> $$v_s^2 = a_s^2 = GM/2r_s \quad \text{and} \quad v_s^2 = a_s^2 = 2a_\infty^2/(5-3\gamma),$$

at $$r_s = ((5-3\gamma)/4)GM/a_\infty^2$$ **-> critical point is sonic point**

-> Mass loss rate from $\rho = \rho_\infty(a/a_\infty)^{2/(\gamma-1)}$

-> $\dot{M} = 4\pi\rho_\infty v_s r_s^2(a/a_\infty)^{2/(\gamma-1)} = 4\pi\lambda_s(GM/a_\infty^2)^2\rho_\infty a_\infty$ -> solve for Eigenwert λ

-> $\lambda_s = 0.25$ for $\gamma = 5/3$

Spherical accretion

Bondi accretion:

(Bondi 1952, Fig.2.)

Velocity u(x),
normalised to
sound speed;

Radius x = r / r_B
r_B = GM / a^2_infty
(Bondi radius)

$r_s = \frac{1}{2}$ r_B

Note : $\gamma = 7/5$

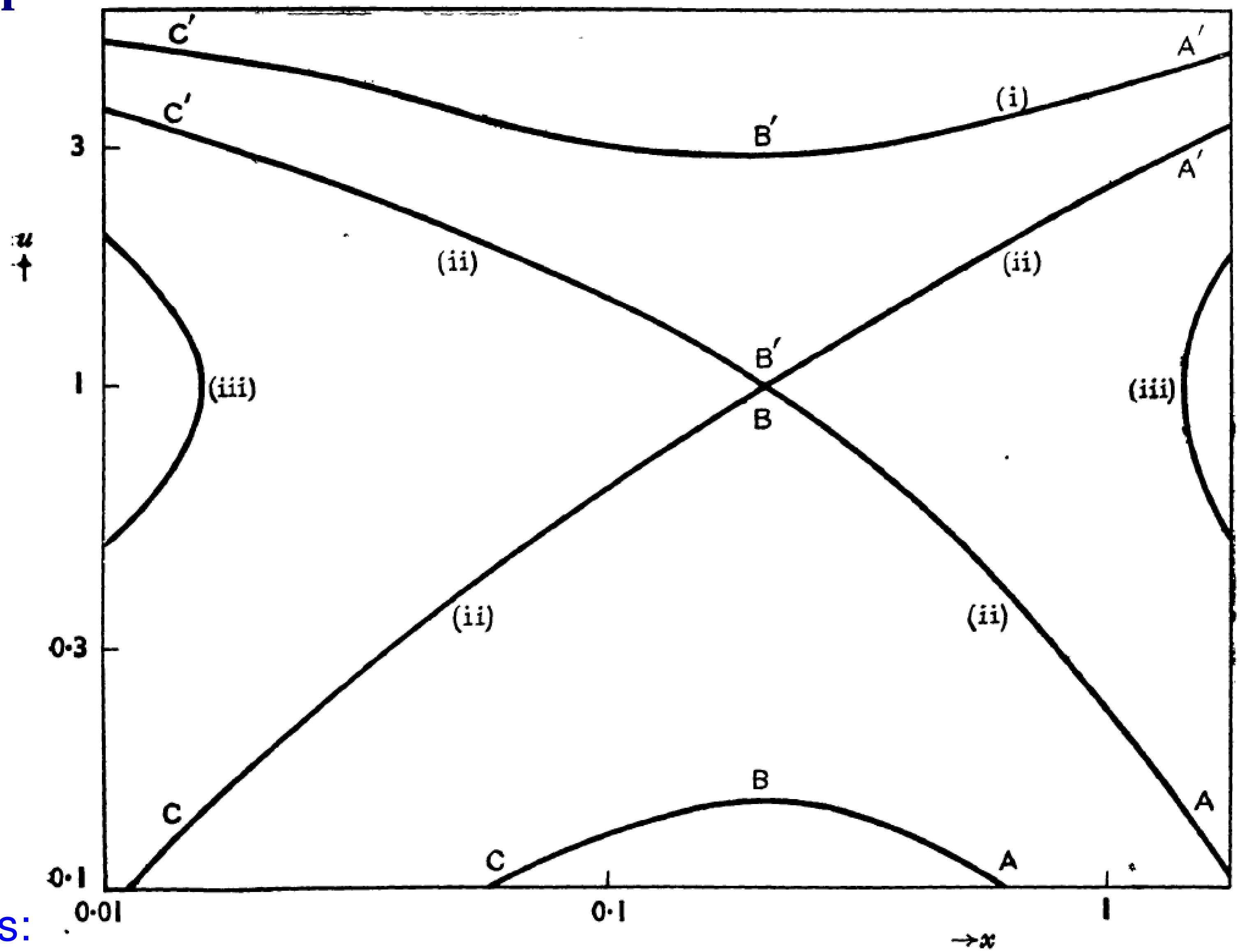
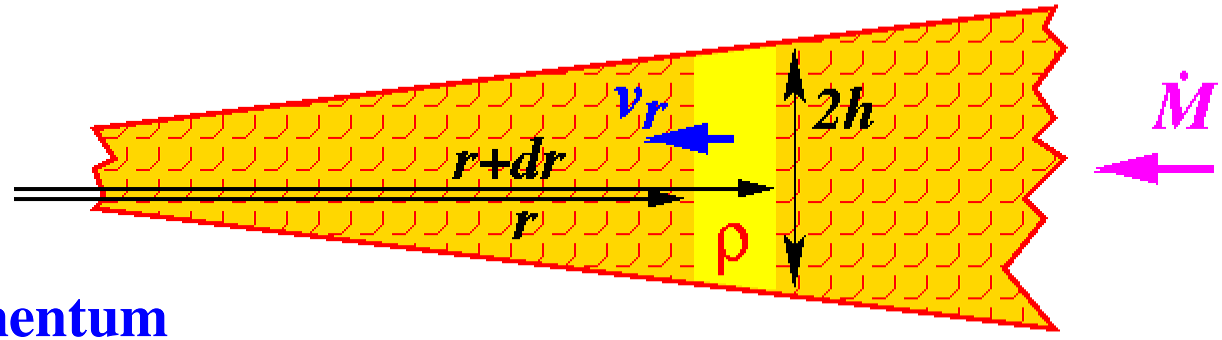


FIG. 2.—*u as function of x for* $\gamma = \frac{7}{5}$.
(i) $\lambda = \frac{1}{4}\lambda_c$;
(ii) $\lambda = \lambda_c$;
(iii) $\lambda = 4\lambda_c$.

-> 3 solution branches:
one is "physical" (ie. regular)
accretion solution with critical accretion rate

Disk accretion



-> take into account **angular momentum**

-> balance between gravity and centrifugal forces

-> stable Keplerian orbits -> no accretion

-> collision of infalling gas -> exchange of angular momentum

-> gas with same specific angular momentum orbits at same radius

$$\tilde{l} = \tilde{l}(r) = \sqrt{GMr}$$

-> Keplerian orbits

-> for accretion : angular momentum transfer within the disk

-> e.g. by collisions of disk material -> "friction"

-> if outward loss of angular momentum

-> mass accretion: $\dot{M} = d(\rho V)/dt) = \overline{\rho} A dr/dt = 2\pi r h \overline{\rho} v_r$

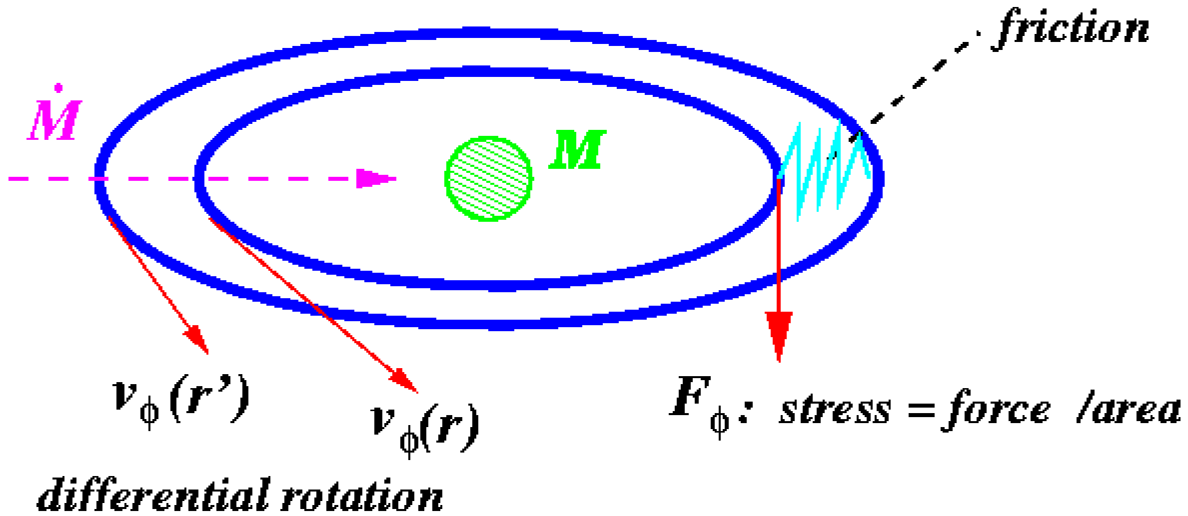
(mean density, disk height, surface density ...)

-> necessary angular momentum loss rate: $\dot{J} \simeq \dot{M}\tilde{l}(r_D) = \dot{M}\sqrt{GMr_D}$

(outer disk radius r_D)

-> for "Keplerian disk": $v_\phi = r\Omega \simeq \sqrt{GM/r} >> v_r$

Disk accretion



-> friction force between two orbiting rings of matter:

-> stress: $|\mathbf{F}_\phi| = -t_{r\phi}$

-> viscous stress tensor: transport of i-momentum in j-direction:

$$t_{ij} = \rho\nu\left(\partial_{x_j} v_i + \partial_{x_i} v_j - (2/3)(\nabla\cdot\mathbf{v})\delta_{ij}\right)$$

-> kinematic viscosity coefficient ν (model-dependent)

definition of visocity ν by stress (=force/area) = $F/A = \nu\,\rho\,V/L$ $[\nu]$: $cm^2\ s^{-1}$

-> stress tensor component for angular momentum exchange:

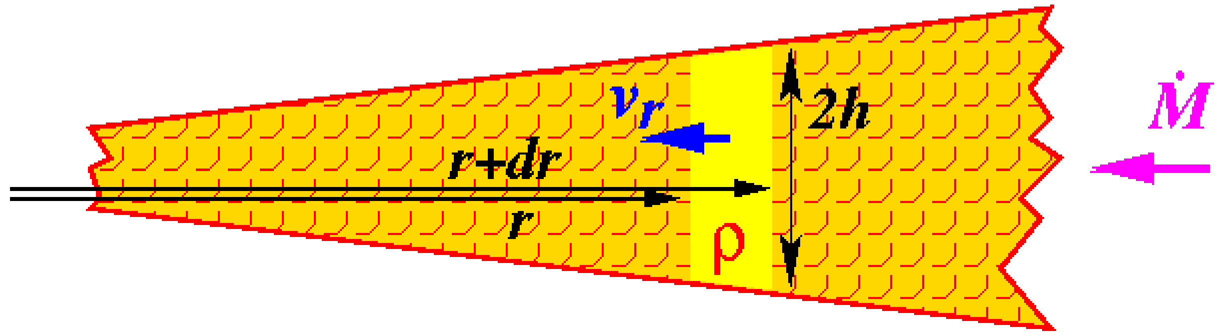
$$t_{r\phi} = \rho\nu\left(\partial_r v_\phi - v_\phi/r\right) = \rho\nu r\partial_r\Omega(r)$$

-> Keplerian disk: $t_{r\phi} = -(3/2)\rho\nu\Omega = -(3/2)\rho\nu\sqrt{GM/r^3}$

-> torque between two disk rings: $\mathcal{G} = \int r d\phi \int r t_{r\phi} dz = 2\pi r^3\rho\nu\Sigma\partial_r\Omega$

angular momentum transport outwards if $\partial_r\Omega < 0 : \rightarrow \mathcal{G} < 0$

Thin disks



Assumption: "disk height"

$h(r) << r$ (thin disk h/r < 0.1)

-> average over vertical disk profile:

surface density $\Sigma \equiv \int \rho(r,z)dz$ "disk height" $h = \Sigma / 2\overline{\rho}$

-> vertical gravitational force: $F_{G,z} = m_p G M z / r^3$

-> particle with $v = c_s$ may reach disk surface $h \simeq r c_s / v_K$

-> $h/r \simeq c_s / v_K$

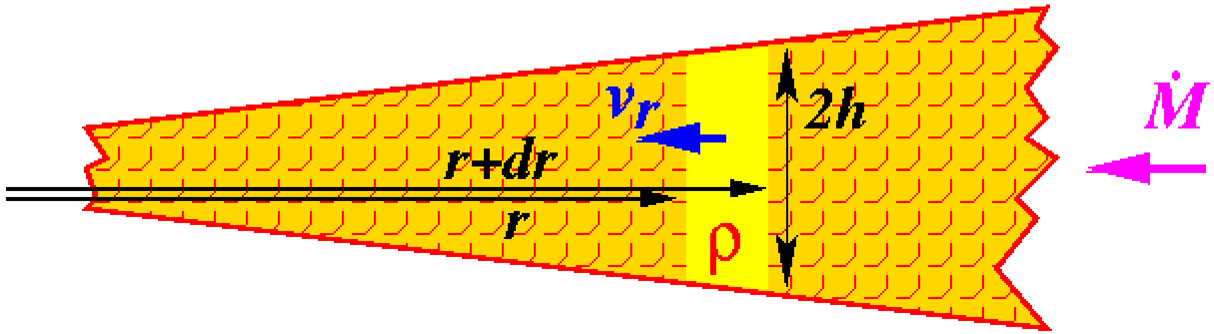
-> condition for thin disk is satisfied if thermal energy < potential energy

$k_B T << m_p G M / r$

-> OK for "cool disks"

-> thin disks require efficient radiative cooling

Thin disks



Time evolution of axisymmetric thin accretion disks:

-> system of HD equations de-couples ($v_z = 0$):

mass conservation: $\partial_t \rho + \nabla \cdot (\rho \mathbf{v}) = \mathbf{0}$ --> $\partial_t \Sigma + (1/r)\partial_r(r\Sigma v_r) = 0$

momentum equation: $\rho\left(\partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla)\,\mathbf{v}\right) + \nabla P + \rho \nabla \Phi = \nabla \cdot \mathsf{T}$

-> angular momentum concervation: $r\partial_t(r^2\Sigma\Omega) + \partial_r(r^3\Sigma\Omega v_r) = (1/2\pi)\partial_r \mathcal{G}$

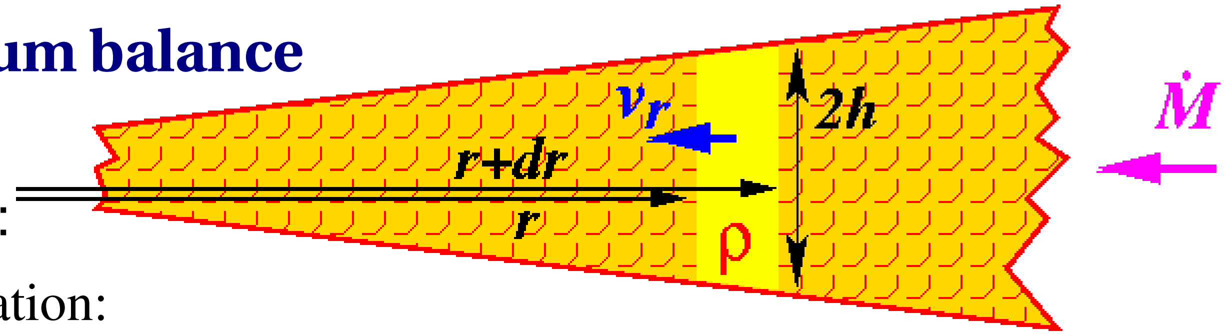
-> accretion velocity: depends on shear & viscosity: $v_r = \dfrac{\partial_r(r^3\nu\Sigma\partial_r\Omega)}{r\Sigma\partial_r(r^2\Omega)}$

-> surface density, time evolution: $\partial_t \Sigma = -\dfrac{1}{r}\partial_r\left(\dfrac{\partial_r(r^3\nu\Sigma\partial_r\Omega)}{\partial_r(r^2\Omega)}\right)$

-> needed is **model for viscosity:** molecular viscosity much too low !!

-> anomalous viscosity (turbulence)

Thin disks – angular momentum balance



Stationary axisymmetric thin disks:

-> Accretion rate from mass conservation:

$$\left(\dot{M} = \frac{dM}{dt} = \frac{d}{dt}(\rho V) = \overline{\rho}\,\frac{dV}{dt} = \overline{\rho} A \frac{dr}{dt} = -2\pi r 2h\overline{\rho} v_r = -2\pi r \Sigma v_r\right)$$

$$\frac{\partial \Sigma}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\Sigma v_r) = 0$$ -> $\dot{M} = -2\pi r \Sigma v_r = \text{constant}$

-> Integrate stationary angular momentum conservation -> $$\frac{\dot{M}\Omega}{2\pi} + \frac{C}{r^2} = -\int t_{r\phi} dz$$

-> integration constant $C = -r_i^2 \Omega(r_i) \dot{M}/2\pi$ defined at radius r_i with $t_{r\phi}(r_i) = 0$

e.g. co-rotation radius / stellar magnetosphere; stellar radius; marginally stable orbit / BH

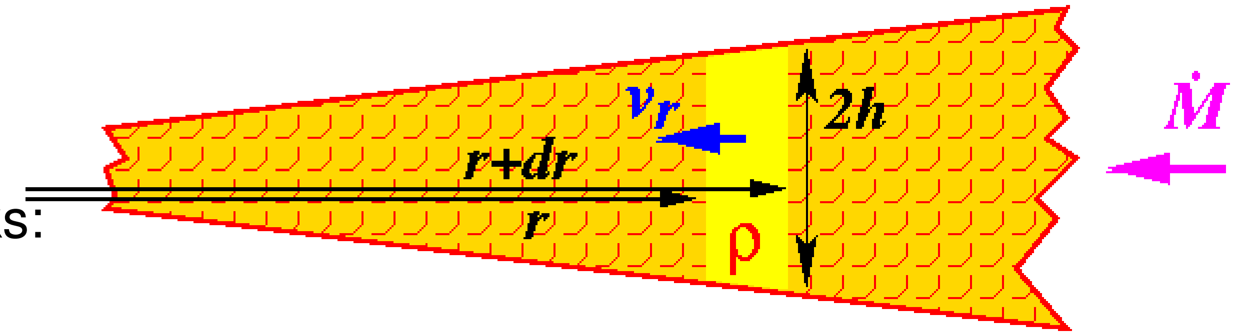
-> interpretation: C is angular momentum flux and conserved quantity:

$$\frac{\dot{M}\Omega}{2\pi} R(r) = -\int t_{r\phi} dz \qquad R(r) \equiv 1 - \left(\frac{r_i}{r}\right)^2 \frac{\Omega(r_i)}{\Omega(r)}$$

-> for Keplerian disk: $R(r) = 1 - \sqrt{r_i/r}$

-> radial profiles from turbulence model; M, dM / dt uniquely define stresses required

Thin disks - energy balance



Stationary axisymmetric thin disks:

-> energy conservation:

accretion: energy gain from potential energy

-> orbital rotational energy

-> angular momentum transport outwards

-> heating due to viscous friction

-> viscous shear locally generates heat Q with rate:

$$\dot{Q} \equiv \rho T \dot{s} = \nu \Sigma \left(r \frac{d\Omega}{dr} \right)^2 = \frac{\dot{M}\Omega^2}{2\pi} \left| \frac{d \ln \Omega}{d \ln r} \right| \left(1 - \left(\frac{r_i}{r} \right)^2 \frac{\Omega(r_i)}{\Omega(r)} \right)$$

-> Keplerian disk: $\dot{Q} = \frac{3}{4\pi} \frac{GMM}{r^3} \left(1 - \sqrt{\frac{r_i}{r}} \right)$

-> if heat is radiated away immediately in vertical direction:

-> total disk luminosity by integrating from r = infinity to $r = r_i$

$$L_{tot} = \frac{1}{2} \frac{GM\dot{M}}{r_i}$$

(factor ½ is for non-relativistic disks)

Thin disks – disk spectra

Stationary axisymmetric thin accretion disks: Spectral energy distribution

Spectral energy distribution

-> assumption LTE -> disk rings emit as black body $\dot{Q}^{-} = \sigma T_s(R)^4$

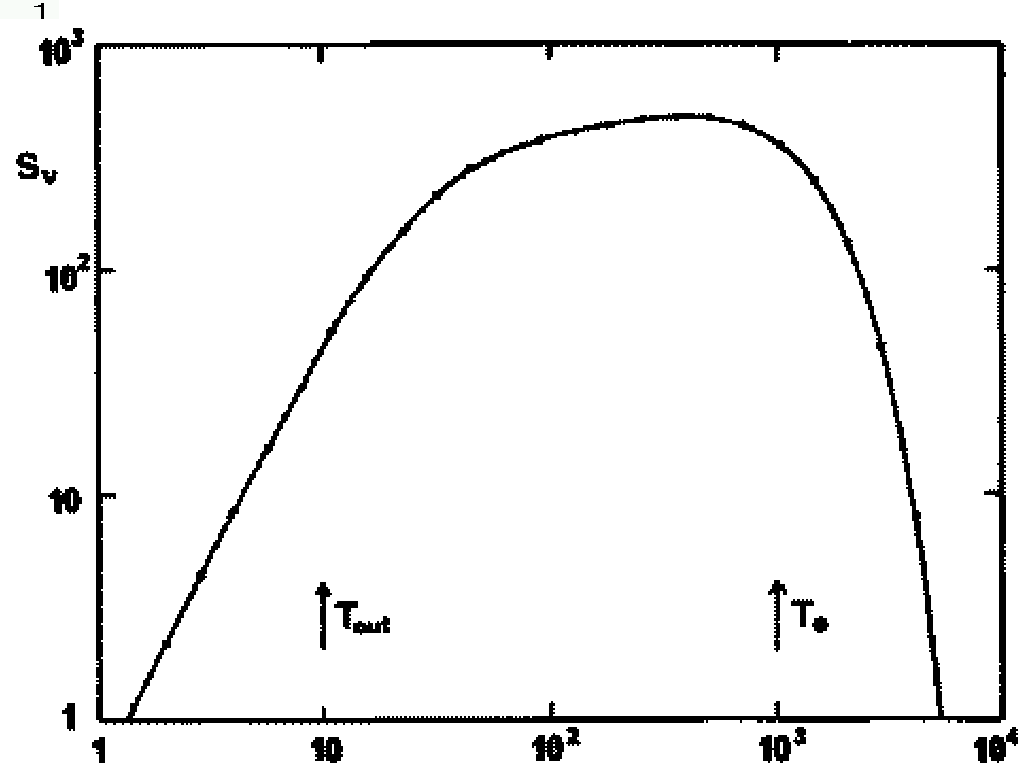
-> with $\dot{Q}^{+} = \dot{Q}^{-}$: $T_s = \left(\frac{3GM\dot{M}}{8\pi r^3 \sigma} \left(1 - \sqrt{r_i/r}\right) \right)^{1/4} \sim r^{-3/4}$

-> integration of local blackbody

$$B_\nu(T_s(r)) \sim \nu^3 \left(\exp(h\nu/kT_s(r)) - 1\right)^{-1}$$

-> disk spectrum:

$$S_\nu \sim \int_{r_i}^{r_{out}} B_\nu(T_s(r))\, 2\pi r\, dr$$



Sν (T(r)), normalized units
(Pringle 1981)

Thin disks - α-parametrisation

Shakura Sunyaev (1973): a-parametrisation for viscosity (3400 citations as of Nov23, 2006)

(4124 citations as of Nov11, 2008)

-> molecular viscosity too low: effective viscosity $\nu = v\,l$

l = 10 cm (mean free path), $v = v_{therm}$

-> viscous accretion time scale $\tau \sim r^2 / \nu \sim 10^{15}$ yrs

-> anomalous viscosity is turbulent viscosity: friction of turbulent cells

-> typical length scale (size of cells): $l < h$ (= disk heigth)

-> typical velocity scale : $v < c_s$ (= sound speed)

->> $$\nu = \alpha c_s h$$

-> parameter $\alpha < 1$ may be adjusted to different disk systems; "observational parameter"

-> may be numerically calculated by MHD simulations (Brandenburg et al.)

-> $0.0001 < \alpha < 1$; some setups results in negative α

-> Note: so far physics of viscosity not defined, just hidden in α

-> extremely successful "trick":

observational proof by some of the disk systems ("hot disks" in CVs),

not very good fit for protostellar disks (temperature profiles) -> "flared disks"

Thin disks - α-parametrisation

Shakura & Sunyaev (1973): α-parametrisation for viscosity

-> application: solve HD equations for thin disk structure:

$$\Sigma = \int \rho dz \simeq 2h\rho, \qquad \dot{M} = 2\pi r \Sigma v_r, \qquad (\dot{M}\Omega/2\pi) R(r) = -\int t_{r\phi} dz$$

$$L_{tot} = \frac{1}{2}\frac{GM\dot{M}}{r_i}, \qquad h = c_s/\Omega, \qquad f_\phi = \alpha P, \qquad \kappa^{-1}(\rho,T) \simeq \kappa_{scat}^{-1} + \kappa_{abs}^{-1}$$

$$P(\rho,T) = 2\rho k_B T/m_p + (1/3)aT^4, \qquad F(r) \simeq acT^4/\kappa\Sigma$$

-> nine equations for nine variables:

$$\rho(r), h(r), \Sigma(r), v_r(r), P(r), T(r), f_\phi(r), \kappa(r), F(r)$$

-> opacities & pressure contribution -> three regions of solutions:

a) inner region: radiation pressure; electron scattering
b) intermediate region: gas pressure; electron scattering
c) outer region: gas pressure; free-free absorption

plus d) cooler outer regions: dust opacities, atomic/molecular opacities

Thin disks - α-parametrisation

Shakura & Sunyaev (1973): α-parametrisation

-> power law profiles for three regions
(note: normalization is for black holes)

a) $P_r \gg P_g,\ \sigma_T \gg \sigma_{ff}$

$$z_0[\mathrm{cm}] = \frac{3}{8\pi}\frac{\sigma_T}{c}\dot{M}(1-r^{-1/2}) = 3.2\cdot 10^6 \dot{m} m\,(1-z^{-1/2}) \qquad (2.8)$$

$$u_0\left[\frac{\mathrm{g}}{\mathrm{cm}^2}\right] = \frac{64\pi}{9\alpha}\frac{c^2}{\sigma^2}\frac{1}{\omega\dot{M}(1-r^{-1/2})} = 4.6\alpha^{-1}\dot{m}^{-1}r^{3/2}(1-r^{-1/2})^{-1},$$

$$\varepsilon\left[\frac{\mathrm{erg}}{\mathrm{cm}^3}\right] = 2\frac{c}{\sigma}\omega = 2.1\cdot 10^{15}\alpha^{-1}m^{-1}r^{-3/2},$$

$$n[\mathrm{cm}^{-3}] = \frac{u_0}{2m_p z_0} = 4.3\cdot 10^{17}\alpha^{-1}\dot{m}^{-2}m^{-1}r^{3/2}(1-r^{-1/2})^{-2}$$

$$v_r\left[\frac{\mathrm{cm}}{\mathrm{s}}\right] = \frac{\dot{M}}{2\pi u_0 R} = 7.7\cdot 10^{10}\alpha\dot{m}^2 r^{-5/2}(1-r^{-1/2})$$

$$H[\mathrm{Gauss}] \leq \sqrt{\frac{4\pi}{3}\alpha\varepsilon} = 10^8 m^{-1/2}r^{-3/4}.$$

b) $P_g \gg P_r,\quad \sigma_T \gg \sigma_{ff}$

$$\begin{aligned}
u_0 &= 1.7\cdot 10^5\alpha^{-4/5}\dot{m}^{3/5}m^{1/5}r^{-3/5}(1-r^{-1/2})^{3/5}\\
T &= 3.1\cdot 10^8\alpha^{-1/5}\dot{m}^{2/5}m^{-1/5}r^{-9/10}(1-r^{-1/2})^{2/5}\\
z_0 &= 1.2\cdot 10^4\alpha^{-1/10}\dot{m}^{1/5}m^{9/10}r^{21/20}(1-r^{-1/2})^{1/5} \qquad (2.16\\
n &= 4.2\cdot 10^{24}\alpha^{-7/10}\dot{m}^{2/5}m^{-7/10}r^{-33/20}(1-r^{-1/2})^{2/5}\\
\tau^* &= \sqrt{\sigma_{ff}\sigma_T}\,u_0 = 10^2\alpha^{-4/5}\dot{m}^{9/10}m^{1/5}r^{3/20}(1-r^{-1/2})^{9/10}\\
v_r &= 2\cdot 10^6\alpha^{4/5}\dot{m}^{2/5}m^{-1/5}r^{-2/5}(1-r^{-1/2})^{-3/5}\\
H &\leqq 1.5\cdot 10^9\alpha^{1/20}\dot{m}^{2/5}m^{-9/20}r^{-51/40}(1-r^{-1/2})^{2/5}.
\end{aligned}$$

c) $P_r \ll P_g,\quad \sigma_{ff} \gg \sigma_T$

$$\begin{aligned}
u_0 &= 6.1\cdot 10^5\alpha^{-4/5}\dot{m}^{7/10}m^{1/5}r^{-3/4}(1-r^{-1/2})^{7/10}\\
T &= 8.6\cdot 10^7\alpha^{-1/5}\dot{m}^{3/10}m^{-1/5}r^{-3/4}(1-z^{-1/2})^{3/10}\\
z_0 &= 6.1\cdot 10^3\alpha^{-1/10}\dot{m}^{3/20}m^{9/10}r^{9/8}(1-r^{-1/2})^{3/20} \qquad (2.1\\
n &= 3\cdot 10^{25}\alpha^{-7/10}\dot{m}^{11/20}m^{-7/10}r^{-15/8}(1-r^{-1/2})^{11/20}\\
\tau &= \sigma_{ff}u_0 = 3.4\cdot 10^2\alpha^{-4/5}\dot{m}^{1/5}m^{1/5}(1-r^{-1/2})^{1/5}\\
v_r &= 5.8\cdot 10^5\alpha^{4/5}\dot{m}^{3/10}m^{-1/5}r^{-1/4}(1-r^{-1/2})^{-7/10}\\
H &\lesssim 2.1\cdot 10^9\alpha^{1/20}\dot{m}^{17/40}m^{-9/20}r^{-21/16}(1-r^{-1/2})^{17/40}
\end{aligned}$$

Thin disks - α-parametrisation

Shakura & Sunyaev (1973): α-parametrisation

-> examples: SS disks of different sources

1) particle density of circumstellar & circumplanetary disks

$$n(r) = 1.6 \times 10^{14}\ \mathrm{cm^{-3}} \alpha^{-7/10} \left(\frac{\dot{M}}{6 \times 10^{-5}\ M_{\rm J}\, \mathrm{yr^{-1}}} \right)^{11/20} \times \left(\frac{M}{M_{\rm J}} \right)^{5/8} \left(\frac{r}{15\, R_{\rm J}} \right)^{-15/8}$$

$$= 2.8 \times 10^{14}\ \mathrm{cm^{-3}} \alpha^{-7/10} \left(\frac{\dot{M}}{1.2 \times 10^{-7}\ M_\odot\, \mathrm{yr^{-1}}} \right)^{11/20} \times \left(\frac{M}{M_\odot} \right)^{5/8} \left(\frac{r}{15\, R_\odot} \right)^{-15/8}$$

2) mass density of stellar mass BH disk

$$\rho \left[\mathrm{g\, cm^{-3}} \right] = 7.2 \times 10^{-4} \left(\frac{\alpha_{\rm v}}{0.001} \right)^{-1} \left(\frac{\dot{M}}{M_{\rm Edd}} \right)^{-2} \times \left(\frac{r}{3 r_{\rm S}} \right)^{3/2} \times \left(\frac{M}{M_\odot} \right)^{-1} \left(1 - \left(\frac{r}{3 r_{\rm S}} \right)^{-1/2} \right)^{-2}$$

Accretion disks - disk viscosity

Question of accretion disk viscosity

-> molecular viscosity too low -> viscous accretion time scale ~ $r^2 / \nu \sim 10^{15}$ yrs

-> **what causes anomalous (turbulent) viscosity ??**

-> Schwarzschild criterium for gravitational instability $(\delta l^2 / \delta r) > 0$ not satisfied for Keplerian disk

$\boxed{\textbf{-> Magnetorotational instability, MRI} \text{ (Balbus \& Hawley 1991)}}$

Other suggestions for angular momentum transport / removal in accretion disks:

-> Molecular viscosity (Pringle 1981)

-> Convective turbulence (Lin & Papaloizou 1980, Ryu & Goodman 1992, Stone & Balbus 1996)

-> Outflows (Wardle & Königl 1993)

-> Tidal effects (Vishniac & Diamond 1989)

-> Electron viscosity (Paczynski & Jaroszynski 1978)

Accretion disks - MRI

Magnetorotational instability (MRI):

Velikhov (1959): MRI discovered for vertically magnetized Couette flow (diff. rot. cylinders)

Chandrasekhar (1960): MRI generalisation, variational principle (no practical application)

Fricke (1969): application to stars, local instability, dispersion relation

Safranov (1969): turbulisation of accretion disks by magnetic shear instability

Balbus & Hawley (1991, see review Balbus & Hawley 1999):

-> break-through of MRI application in accretion disks:
- shown that MRI manifests itself locally under very general conditions
- give a relatively simple derivation
- provide a detailed explanation of the underlying physical processes
- present limitations of the theory
- suggest MRI as cause for large viscosity in accretion disks
- numerical MHD disk simulations to prove analytical derivations

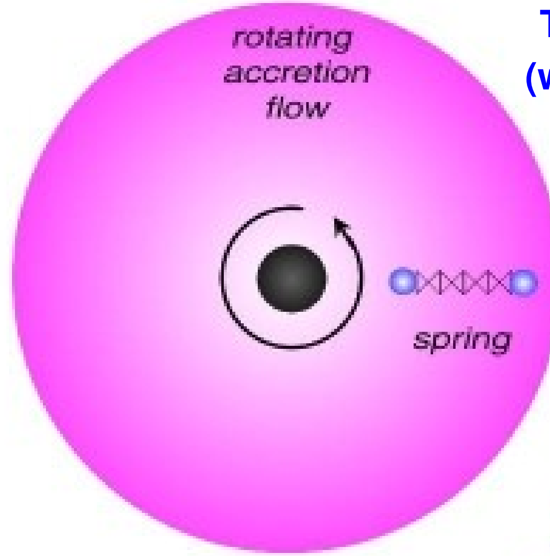
-> MRI excited by moderate magnetic field strength:
- strong fields stabilizes differential rotation,
- weak field limit by dissipation (natural length of instability scales inversely with field strength)

-> exponential growth till saturation

Accretion disks - MRI

Taken from Andreas Mueller (www.mpe.mpg.de/~amueller/)

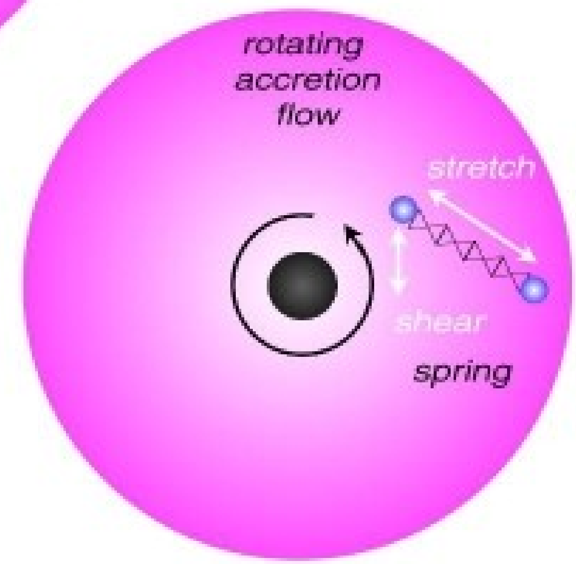
Magnetorotational instability:



Principle, simplified:

1) Failing approach maneuvre of spacecraft:

-> spacecraft on inner orbit is faster
  -> braking of inner spacecraft
    -> angular momentum loss
-> inner spacecraft sinks to even lower orbit & departs from outer spacecraft

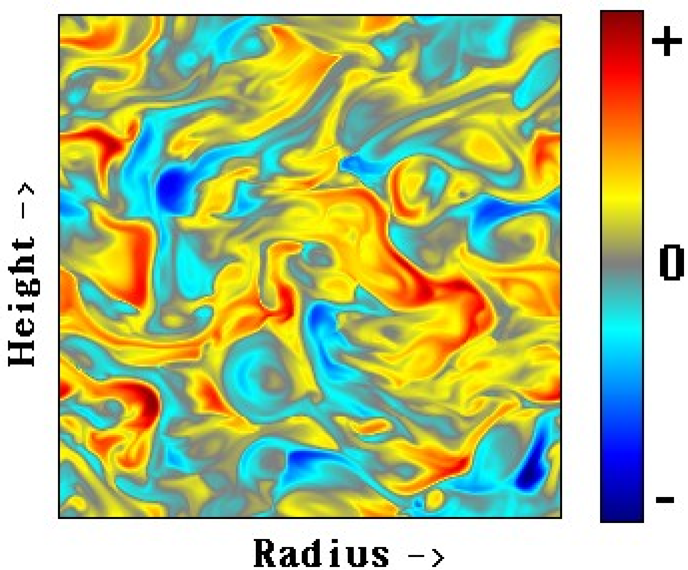


2) Bodies on Kepler orbits, connected by a "spring"

-> differential rotation: inner/outer body orbits faster/slower
(angular momentum of inner body $<$ a.m. of outer body)
  -> spring is stretched, shear forces exert braking/accelerating torque on inner/outer body;
    -> inner/outer body looses/gains angular momentum, moves inwards/outwards
      -> differential rotation becomes even stronger
        -> stronger torques & more angular momentum loss in outward direction

Accretion disks – MRI

Magnetorotational instability:

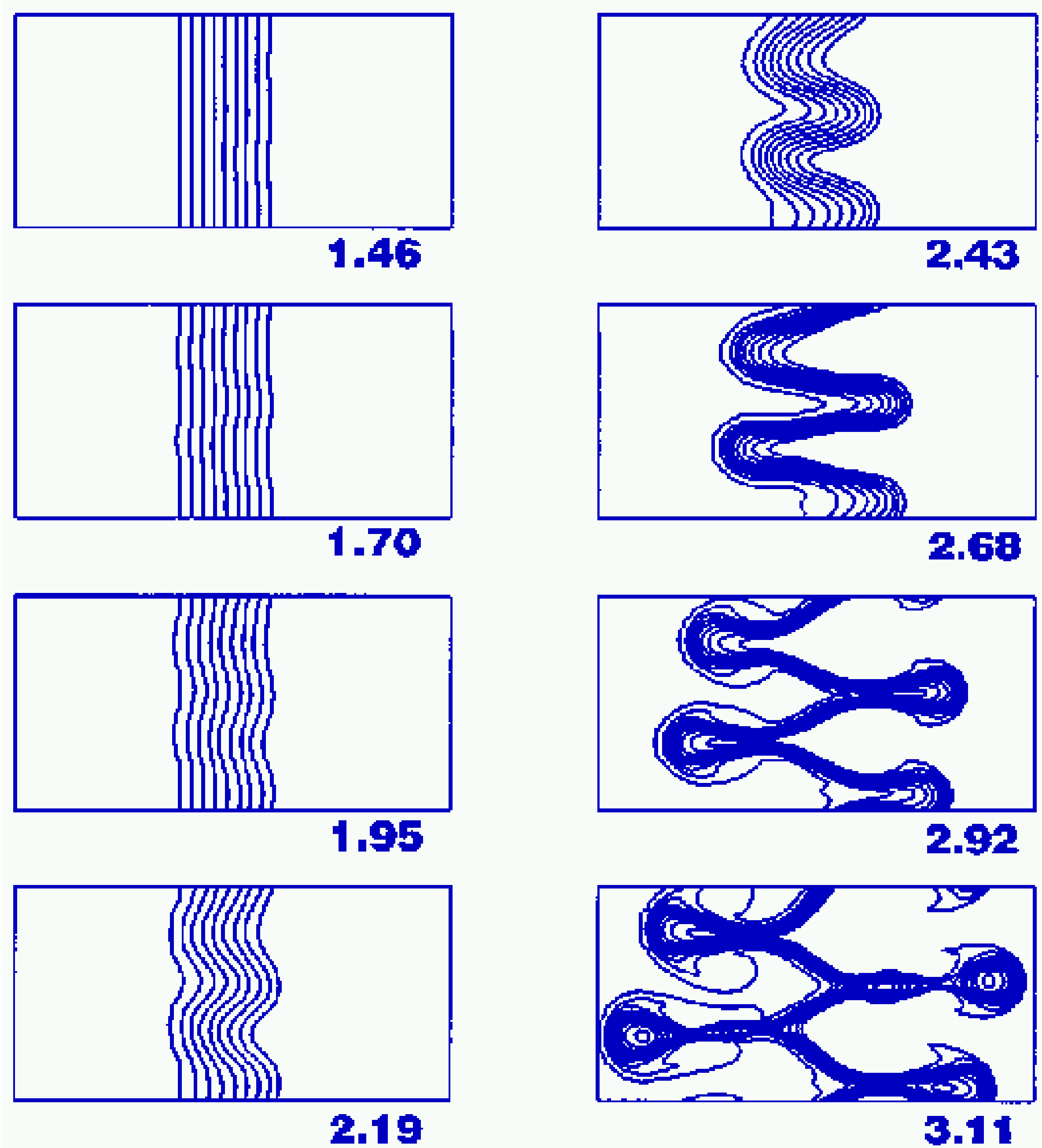


Simulation slice through a magnetized disk with MRI created turbulence

Blue: gas with less than Keplerian angular momentum

Red: gas with excess a. m.

"MRI is very effective at creating the angular momentum transport required to make accretion disks accrete" (Balbus & Hawley 1995)



Fieldline evolution

Accretion disks

"Other" accretion disks:

-> thick disks : h ~ r ; not local energy balance, heat transport in any direction,
potentially gravitationally unstable

-> rotation not uniquely defined by gravity -> "free" angular momentum distribution

--> not Keplerian anymore; split of HD eq. in radial and perp. part not possible

-> massive disks in YSO, very hot disks (AGN)

-> ADAFs: advection dominated accretion disks, inefficient cooling, hot,

- for BH: matter is accreted into BH before it radiates away energy
- for NS: energy release at NS surface

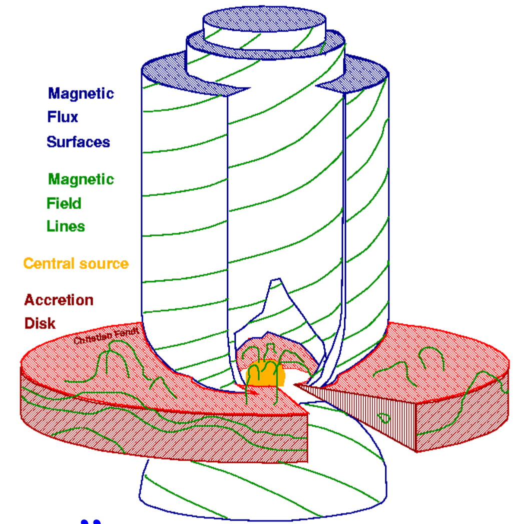
-> rather more similar to Bondi accretion than to thin accretion disk , h ~ r,
BUT viscous accretion!

-> slim disks: optically thick ADAF, ineffective cooling, advection cooled, super-Eddington

-> ADIOS: aadiabatic inflow outflow structures:
ADAF with wind/jet outflow taken into account, ADAF with high viscosity

-> CDAFs: convection dominated accretaion disks: ADAF with low viscosity, structure
very different from ADAFs, e.g. constant angular momentum per volume, no
accretion

Jet launching from accretion disks



How to divert radial accretion into outflow direction ?

-> "holy grail" of jet formation theory
-> so far mostly stationary models
-> MHD simulations beginning to succeed

Ferreira & Pelletier (1995-1997): "magnetic accretion-ejection structures":
-> investigate disk-jet transition region in stationary self-similar approximation
-> jet launching is completely magnetohydrodynamic process
(compared to e.g. magnetocentrifugal acceleration ...):

-> disk: quasi-magnetohydrostatic equilibrium,

turbulent magnetic diffusivity $\nu_m = \alpha_m v_A h$

-> magnetic torque in toroidal direction, $F_\phi = j_z B_r - j_r B_z$

-> Lorentz forces: use $I(r,z) = -\frac{c}{2}\, r B_\phi$ to get

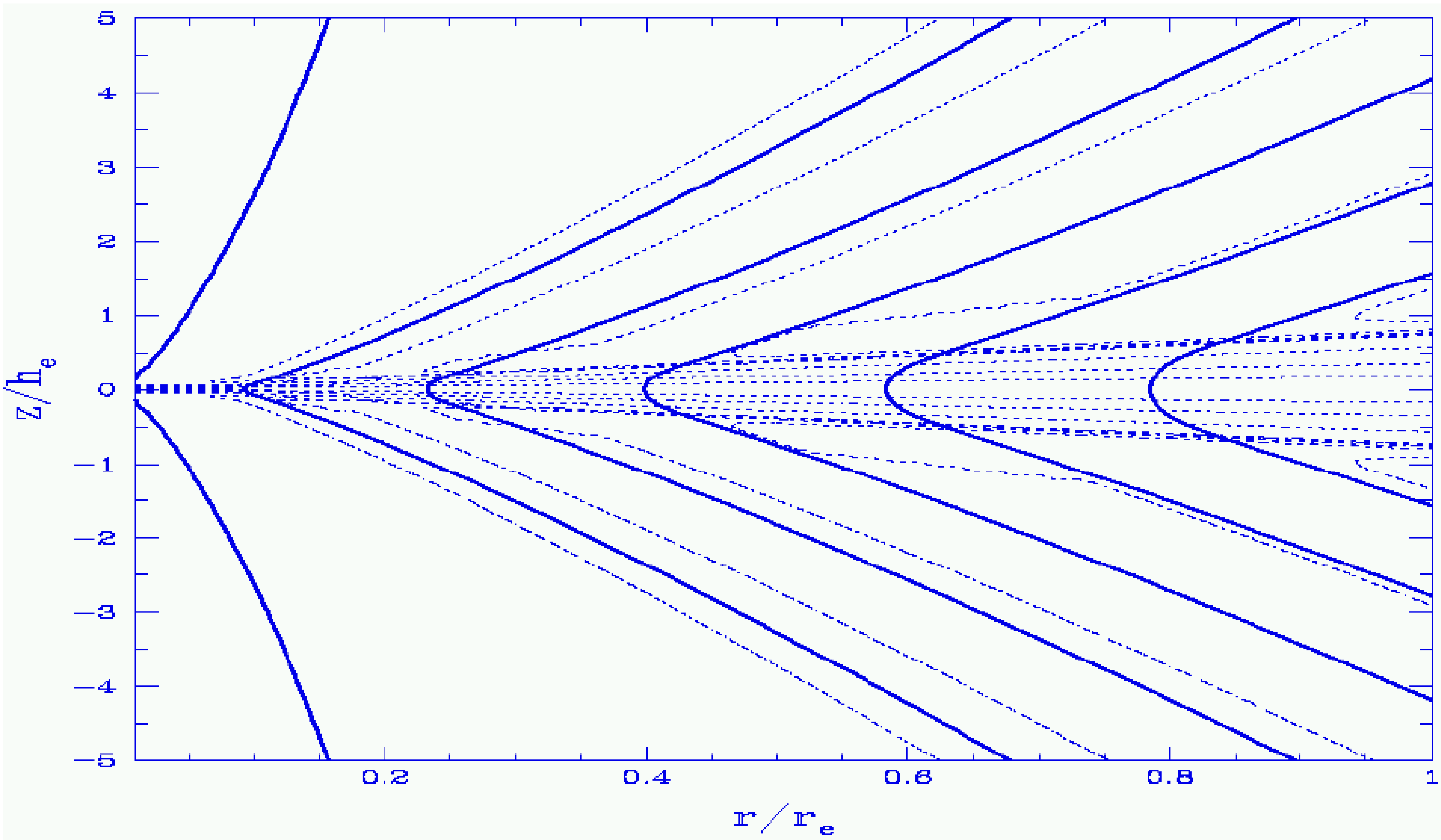
$$F_\phi = \frac{B_p}{2\pi r} \nabla_{||} I$$
$$F_{||} = -\frac{B_\phi}{2\pi r} \nabla_{||} I$$
$$F_\perp = B_p j_\phi - \frac{B_\phi}{2\pi r} \nabla_\perp I$$

>>> if $F_\perp$ decreases -> gas pressure gradient lifts plasma from disk surface
if F_ϕ increases -> centrifugal acceleration of plasma

Jet launching from accretion disks

"magnetic accretion-ejection structures" (Ferreira et al 1995-1997):

1) disk material diffuses across magnetic field lines, 2) is lifted upwards by MHD forces, then 3) couples to the field and 4) becomes accelerated magnetocentrifugally and 5) collimated



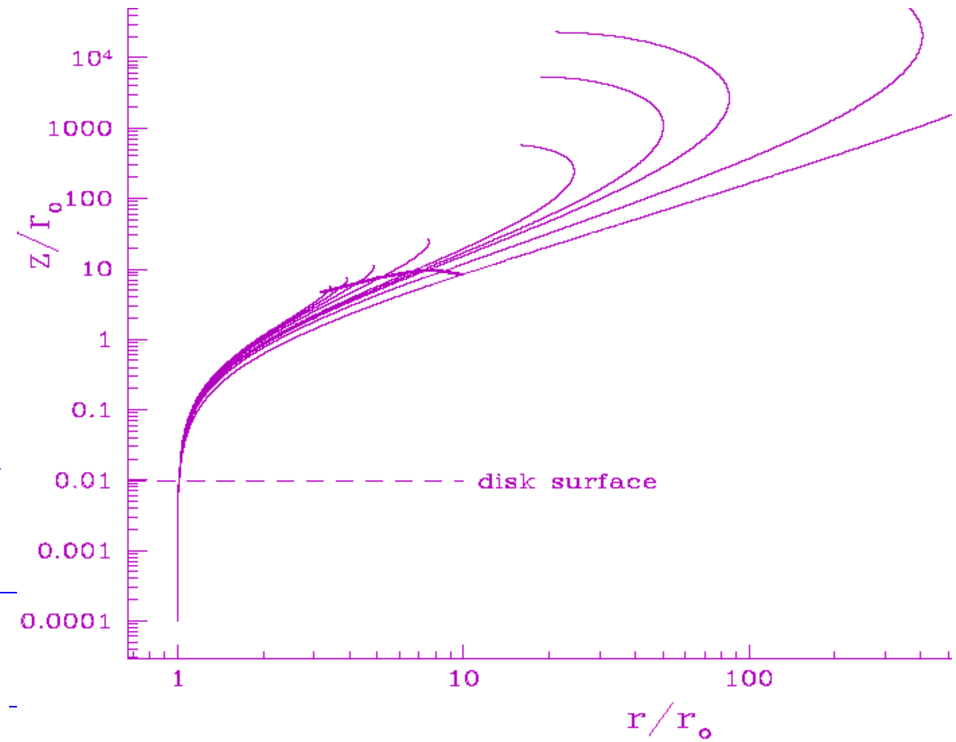
Poloidal magnetic field lines (thick) and poloidal streamlines (dashed)

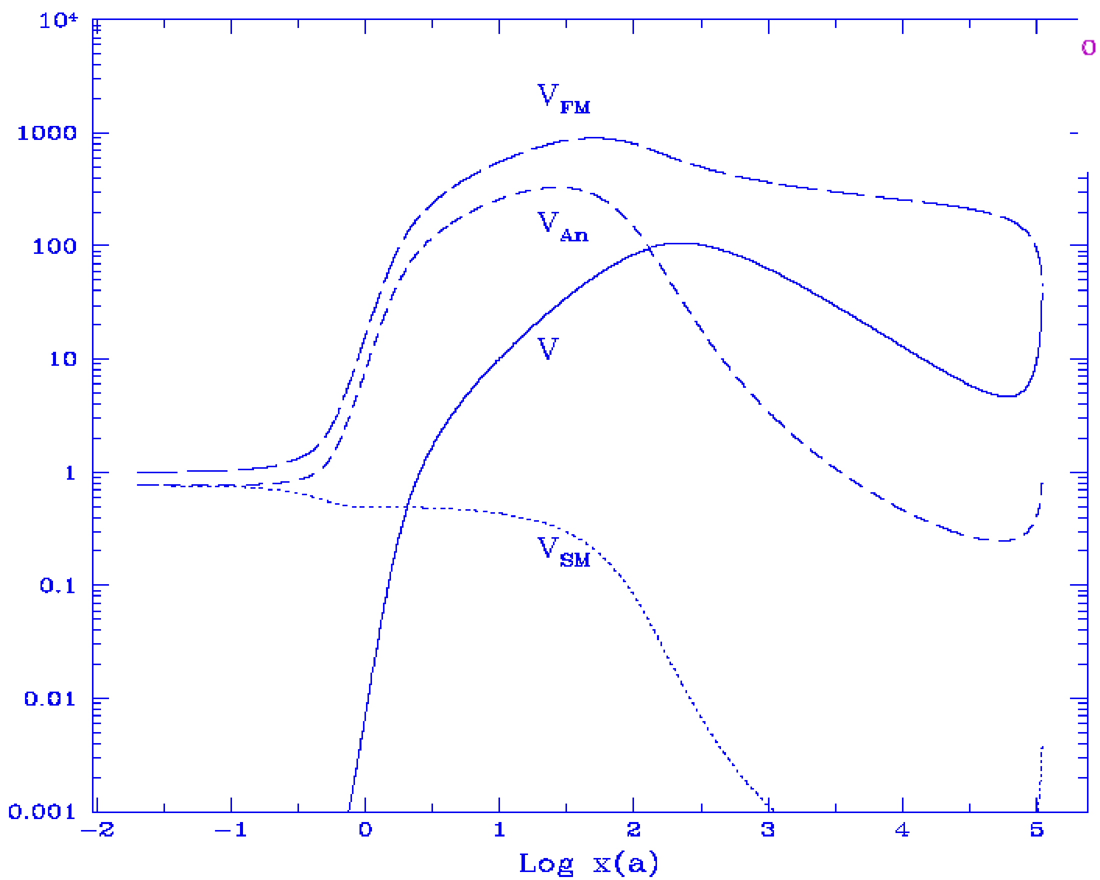
Jet launching from accretion disks

"magnetic accretion-ejection structures"

(Ferreira et al 1995-1997):

1) disk material diffuses across magnetic field lines, 2) is lifted upwards by MHD forces, then 3) couples to the field and 4) becomes accelerated magnetocentrifugally and 5) collimated





Field line structure (top) **z(r) for different mass flux per magnetic flux**

Poloidal velocity (left) **as function of distance along the field line.**

The disk wind becomes super slow-magnetosonic, super Alfenic and marginally magneotosonic.

Note: self-similar wind structures intrinsically re-collimate (see above)

(Ferreira 1997)

Jet launching from accretion disks

Numerical simulations of disk-jet interaction

Shibata et al. group :

Uchida & Shibata 1986 !!!!!

-> simulations incl. disk structure: short term, problem disk evolution

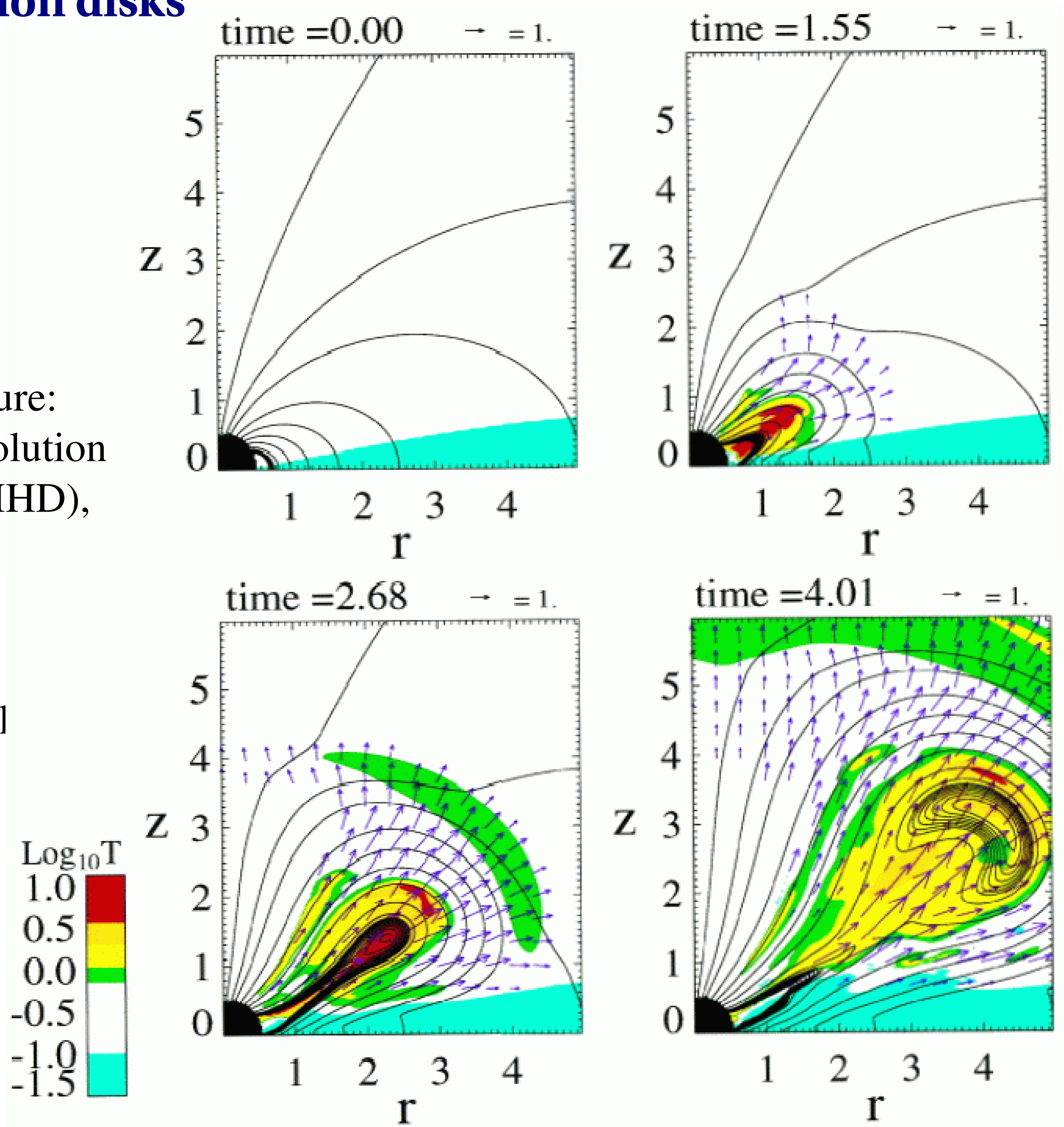
-> applications: sun, stars (MHD), BHs (GRMHD)

Difficult task:

- strong gradients in density, pressure, magnetic field, vel
- proper disk model? Ideal / diffusive MHD, turbulence, radiative transfer,

-> mass transfer disk to jet

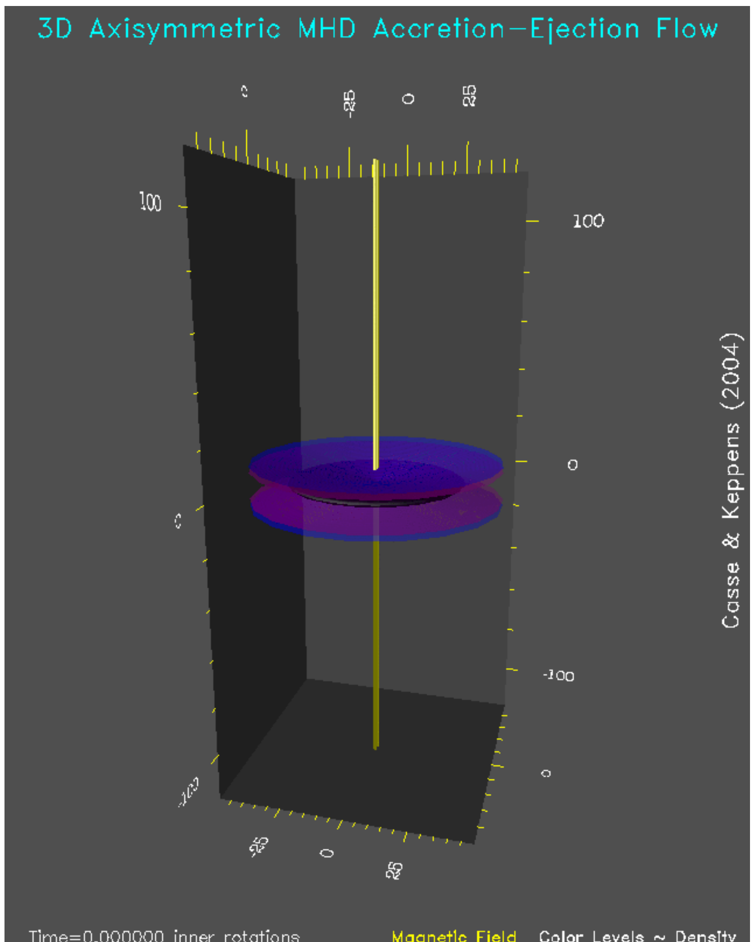
-> disk wind & disk structure

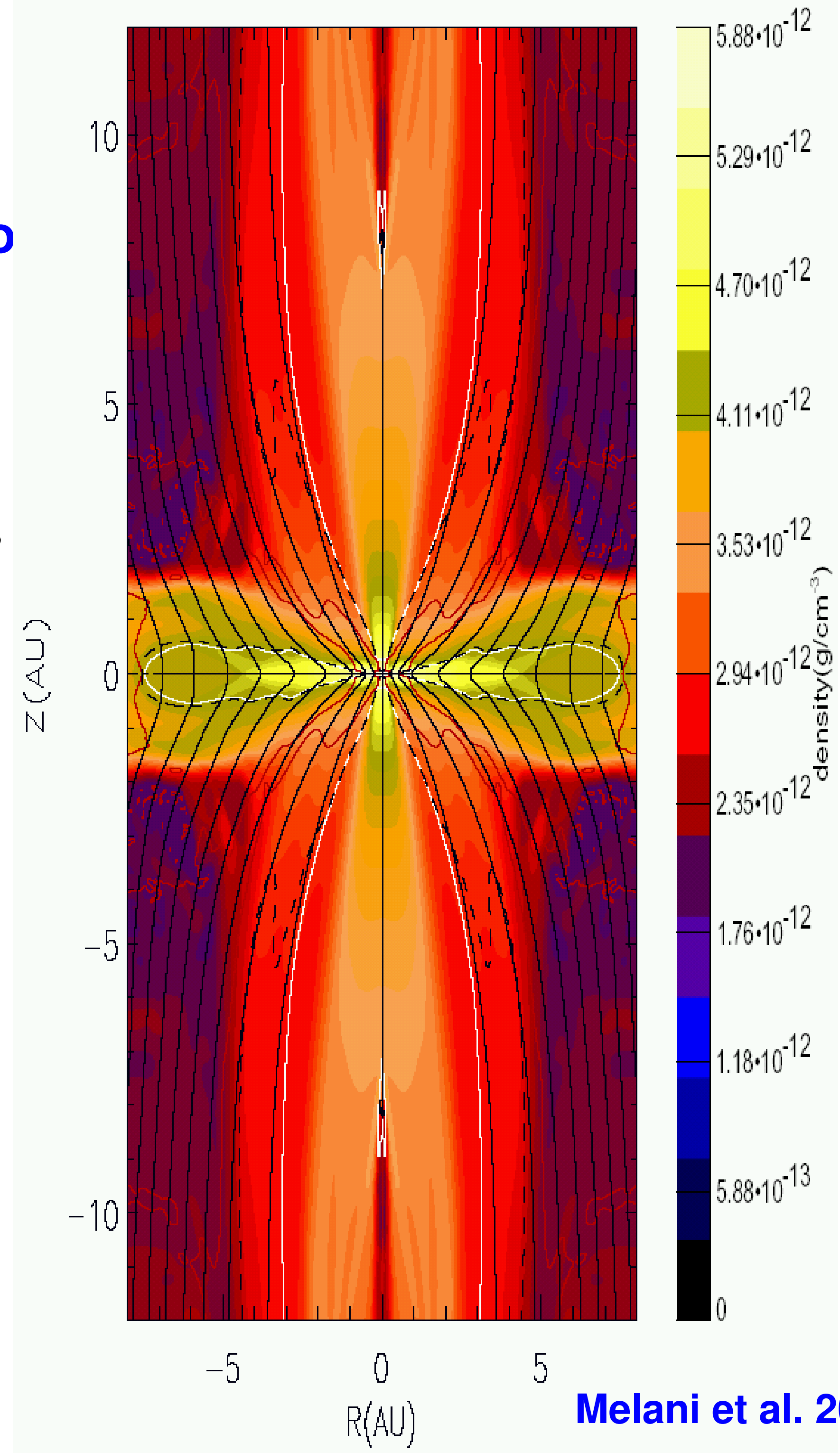


Jet launching from accretion disks

Numerical simulations of disk-jet interactio

Casse & Keppens 2002/04;
1st who get a time-dependent jet ejection from disk; long-term evolution until steady state
new stuff: Meliani et al. 2006: Zanni et al 1008;





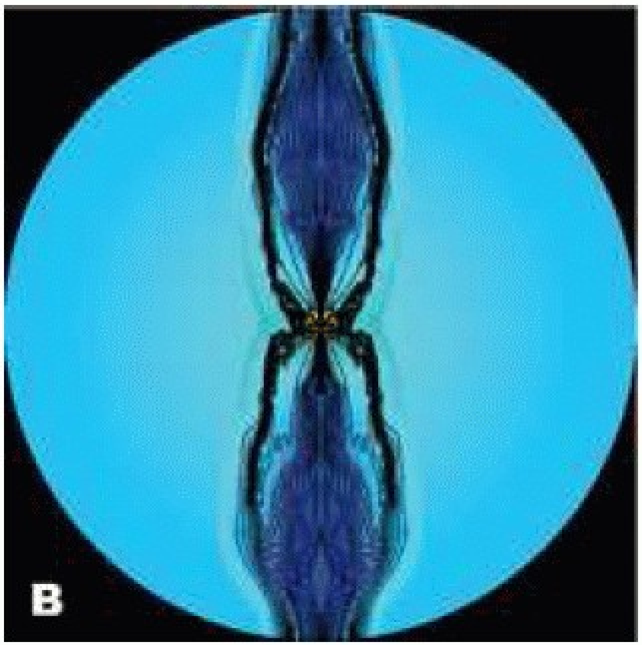
Melani et al. 2006

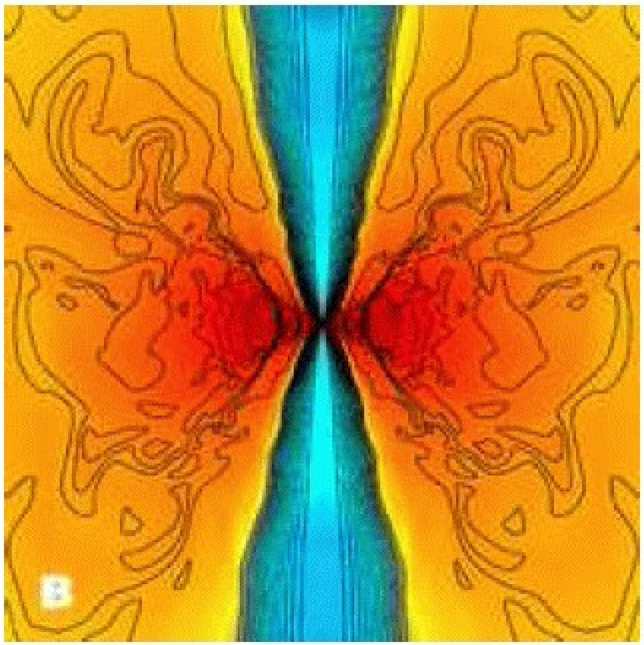
Jet launching from accretion disks

General relativistic simulations: e.g. McKinney (2006):

GRMHD code HARM (Gammie 2003), Kerr-Schild coordinates

Initial magnetic field inside initial torus, poloidal





t ~ 10^4 t_g
r ~ 10^4 r_g / 100 r_g
ρ_out ~ 10^-13 ρ_disk

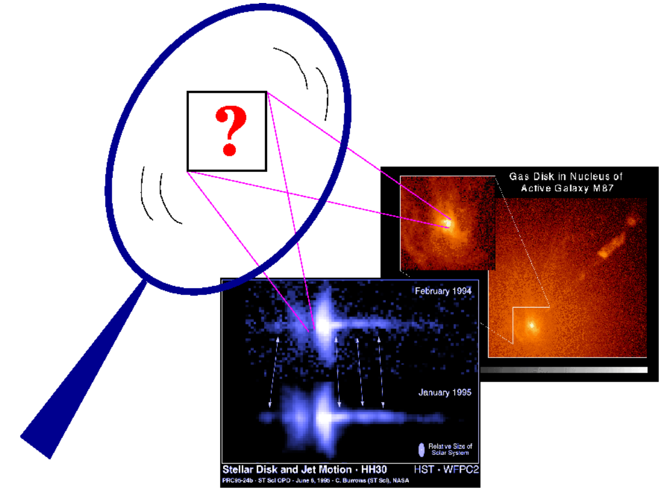
Shown lab frame density + fieldlines

Poynting dominated jet reaches $\Gamma\sim10$, fast within $\alpha < 5°$, slow within $\alpha < 30°$

Disk wind has collimated edge, $\Gamma < 1.5$

New “force-free” simulations, low density, reach Lorentz factors of 5000 (Tchekhovskoy, et al 2008)

Outflows & Jets: Theory & Observations



10.10 Introduction & Overview ("H.B." & C.F.)
17.10 Definitions, parameters, basic observations (H.B.)
24.10 Basic theoretical concepts & models I (C.F.): Astrophysical models, MHD
31.10 Basic theoretical concepts & models II (C.F.) : MHD, derivations, applications
07.11 Observational properties of accretion disks (H.B.)
14.11 Accretion, accretion disk theory and jet launching (C.F.)
21.11 Outflow-disk connection, outflow entrainment (H.B.)
28.11 Outflow-ISM interaction, outflow chemistry (H.B.)
05.12 Theory of outflow interactions; Instabilities (C.F.)
12.12 Outflows from massive star-forming regions (H.B.)
19.12 Radiation processes - 1 (C.F.)
26.12 and 02.01 Christmas and New Year's break
09.01 Radiation processes - 2 (H.B.)
16.01 Observations of AGN jets (C.F.)
23.01 Some aspects of AGN jet theory (C.F.)
30.01 Summary, Outlook, Questions (H.B. & C.F.)