‘The most irrelevant explanations often serve to allay the feeble curiosity of the reader’ (E.N. Parker)

# Radiatively inefficient accretion flows

(tomorrow: transition from cool disk to radiatively ineff. flow)

## *radiatively inefficient flow*

Accretion time scale: $t_{\rm acc} = t_{\rm visc} = \frac{r^2}{\nu} = \frac{1}{\alpha\Omega}(\frac{r}{H})^2$

*If* $H/r \ll 1$, *then* $t_{\rm acc}$ long,
*then* cooling efficient, *then* $H/r \ll 1$ : *circular argument*

What if $H/r \sim \mathcal{O}(1)$ and accretion time short?
⇒ *radiatively inefficient accretion flows* $\int Q_{\rm visc}{\rm d}z \neq 2\sigma T^4$

→ *disk is not thin*

*advection of internal energy with the flow important*

2 types: (Begelman, Blandford, Phinney & Rees 1982)

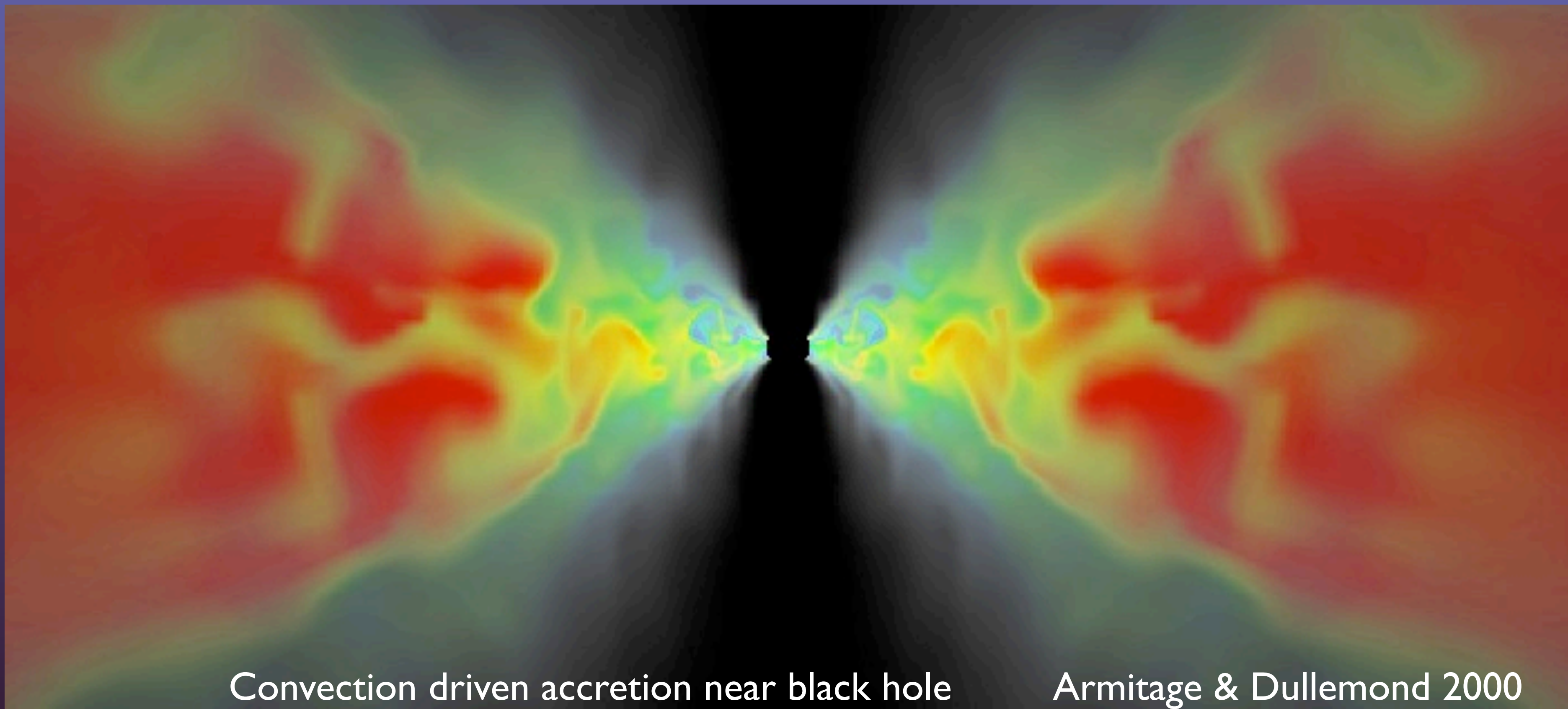
$$\left.\begin{array}{l}\text{- optically thick: \textit{radiation supported} accretion flow (`radiation torus')}\\ \text{- optically thin: \textit{ion supported} accretion flow (`ion torus')}\end{array}\right\}\text{`ADAF'}$$

- hydrodynamics the same

$$t_{\rm acc} = t_{\rm visc} = \frac{r^2}{\nu} = \frac{1}{\alpha\Omega}(\frac{r}{H})^2$$

Angular momentum transport easier in thick accretion

(also easier to simulate numerically)



Convection driven accretion near black hole    Armitage & Dullemond 2000

Thin disks are more difficult numerically than thick ones

*time scale problem:*

$$\frac{1}{\Omega} \ll \frac{r}{c_{\rm s}} (= \frac{1}{\Omega}\frac{r}{H}) \ll \frac{1}{\alpha\Omega}(\frac{r}{H})^2$$

orbital  sound crossing  accretion time scale

*time step problem:* $\Delta t < \Delta x / v$ (Courant)

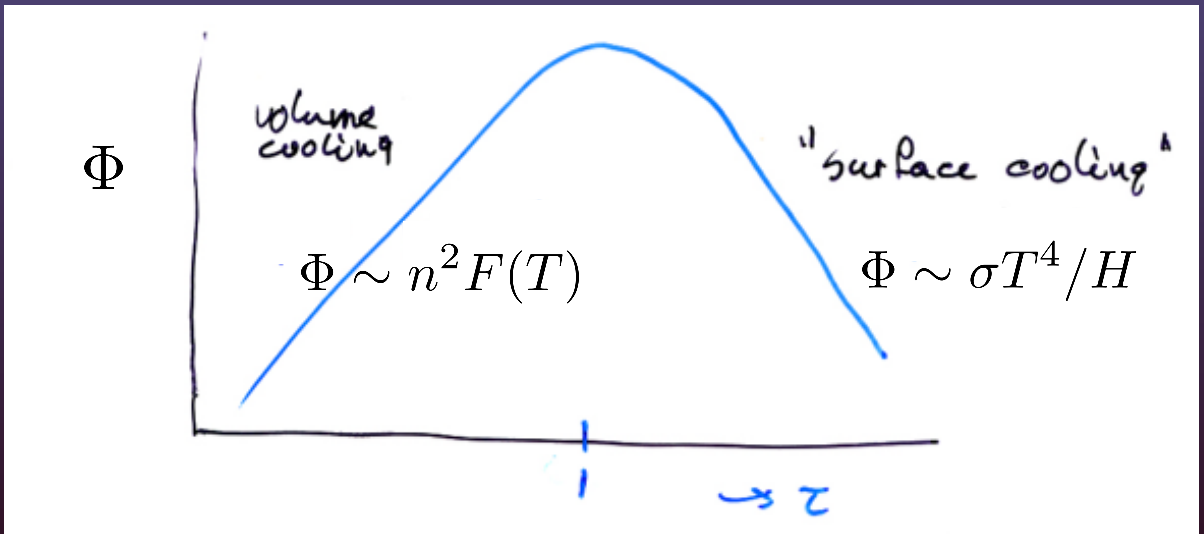
can be circumvented (FARGO: F. Masset 2000A&AS..141..165M)

(by separating purely orbital motion from the flow) *radiatively inefficient flow*

Cooling is ineffective:
- at very high optical depth: escape of heat too slow
- at low density: radiation processes to slow

*Cooling at low optical depth*: $\Phi_{\rm c} \sim n^2 F(T)$ erg cm$^{-3}$s$^{-1}$
Thermal energy density: $u \sim nkT$ erg cm$^{-3}$s

$$\rightarrow \; t_{\rm cool} \sim \frac{u}{\Phi_{\rm c}} \sim \frac{1}{n} \qquad (\tau \ll 1)$$




$F(T)$ : (optically thin) *cooling function* (atomic physics)

holds for ordinary thermal equilibrium plasma ( $\sim 10^4 - 10^8$ K )

## *Thermal instability*

Hot flows accrete faster:

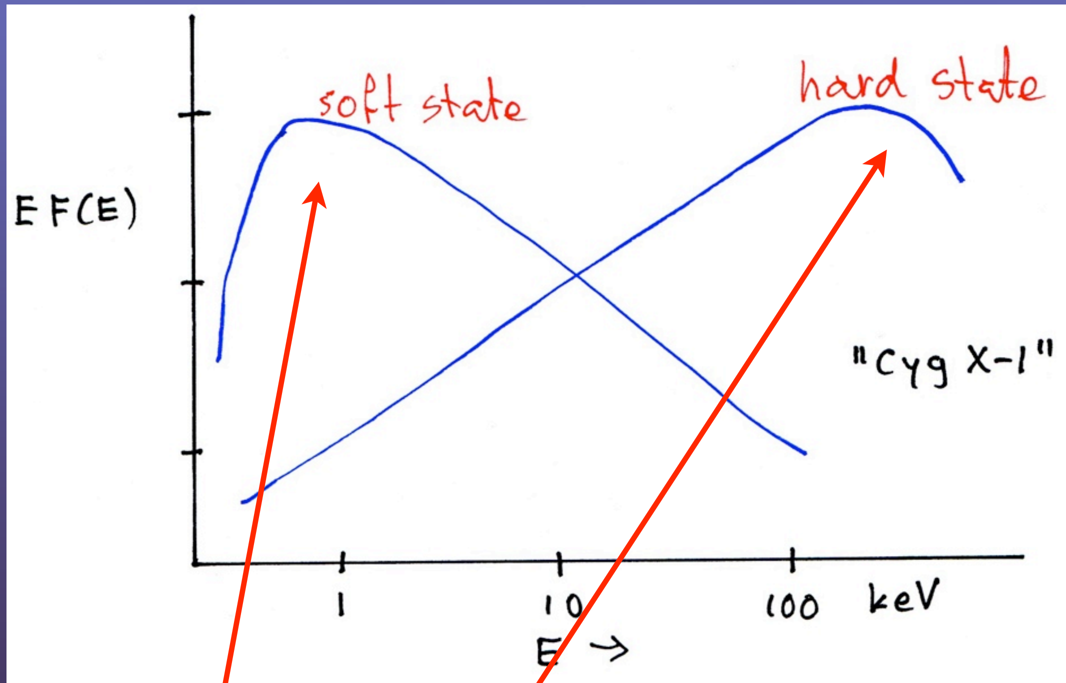
$$t_{\rm accr} = \frac{1}{\alpha\Omega}(\frac{r}{H})^2 = \frac{1}{\alpha\Omega}\frac{T_{\rm vir}}{T}$$

→ density lower (for given mass accretion rate)
→ *if cooling rate decreases* with decreasing density:
(thermal-viscous) *instability* (Lightman & Eardley)

→ if unstable, disk will cool down or heat up to a stable state.

Typical stable states:
- cool (Shakura-Sunyaev) disks
- radiatively inefficient flow: adiabatic (≠ *isentropic*)

Observations indicate existence of separate 'accretion states':




surprising: (optically thin) 100keV plasma *thermally unstable*

unsurprising: could be a thin (Shakura-Sunyaev disk) *optically thin radiatively inefficient flow, 'ion supported' accretion flow (ISAF)*

Optically thin, radiatively ineffective flow near N-star or BH

Physics:
- Coulomb interaction in ionized plasma
- interaction of electrons with radiation

if loss inefficient: $T \sim T_{\mathrm{vir}}$

if energy shared between electrons and ions:

$$T_{\mathrm{e}} = T_{\mathrm{ion}} \sim T_{\mathrm{vir}} \sim 150\ MeV\ \frac{r}{3r_{\mathrm{S}}}$$

ions: subrelativistic

electrons: $\gamma \sim 500$

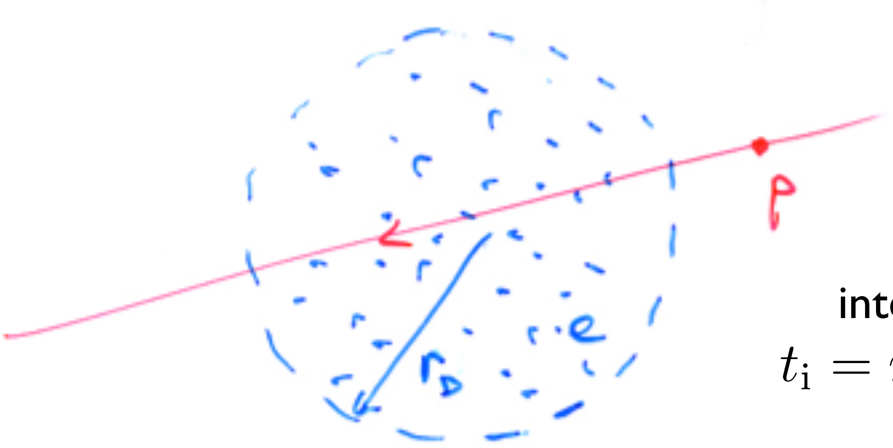
energy loss of electrons (inverse Compton) $\sim \gamma^2$

→ optically thin plasma cannot be in thermal equilibrium at this temperature

electrons radiate, → $T_{\mathrm{e}} \ll T_{\mathrm{ion}}$ 'two-temperature flow'

*optically thin radiatively inefficient flow*

Coulomb interaction in two-temperature plasma $T_{\rm ion} \gg T_{\rm e}$
interaction *decreases* with ion temperature:



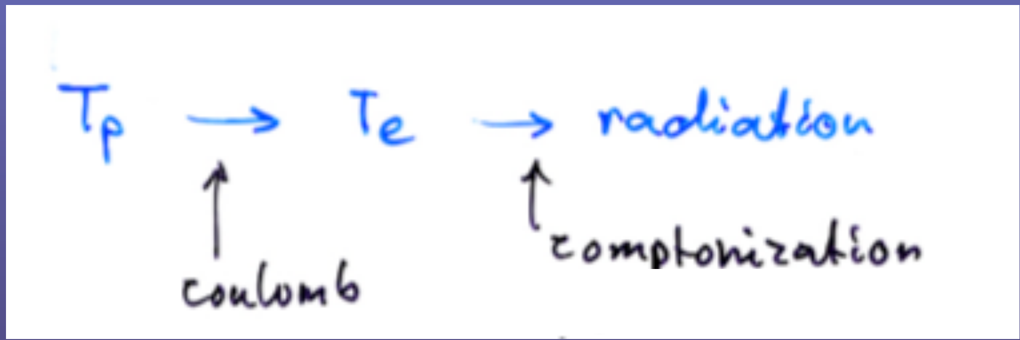

interaction time in $r_{\rm D}$ :

$$t_{\rm i} = r_{\rm D}/v_{\rm ion} \sim (T_{\rm ion})^{-1/2}$$

$r_{\rm D}$ Debye sphere: "effective range" of electrostatic interaction in an ionized plasma

*optically thin radiatively inefficient flow*

Electrons loose energy by inverse Compton on radiation field of accretion flow




Loss of equilibrium p-e when radiation loss high
Ions heat up → transfer to electrons reduced → runaway disequilibrium

Shapiro, Lightman & Eardley 1976

Two-temperature accretion flow ('ion supported torus')
Ions loose little energy: $T_{\rm ion} \approx T_{\rm vir}$ (MeV's)
Electrons cool by inverse Compton. How cool?
Theory: depends on geometry of radiation environment.
*Observed:* $T_{\rm e} \sim 50 - 200\ {\rm keV}$

Energy carried by ions. 'Thick' flow: 'ADAF'
- Thin disk approximation does not apply
- Internal energy advected with flow to be accounted for
- Inefficient radiator (bottleneck Coulomb energy transfer ions → electrons

*optically thin radiatively inefficient flow*

near a BH or n-star 2 accretion states:
- optically thick cool disk $T_{\rm s} \sim 0.1 - 1 \ {\rm keV} \quad (10^6 - 10^7 \ {\rm K}) \quad (\ll T_{\rm vir})$
- optically thin ion supported flow $T_{\rm ion} \approx T_{\rm vir}, T_{\rm e} \sim 30 - 100 \ {\rm keV}$

X-ray observations
- 'soft state' spectrum $\sim 0.1 - 1 \ {\rm keV}$
- 'hard state' spectrum $\sim 100 \ {\rm keV}$

Problems:
- what determines which state chosen & when.
- geometry of the ion supported flow, source of soft radiation comptonized by the electrons.

## *hydrodynamics of radiatively inefficient flow*

Thin disk approximation not valid: $H/r \approx 1$ because
2-temperature flow: $T_{\rm ion} \approx T_{\rm vir}$
radiation supported flow: disk inflated by radiation pressure.

Problem 2-D, 3-D
Simplifications:
Ignore vertical dimension anyway, but keep pressure terms (deviations from Kepler rotation, advection of thermal energy with flow). Steady flow:

$$\Sigma 2\pi r v_r = \dot{M} = \text{ cst.} \qquad \text{mass}$$

$$r\Sigma v_r \partial_r(\Omega r^2) = \partial_r(\nu\Sigma r^3\partial_r\Omega) \qquad \text{angular momentum}$$

$$v_r\partial_r v_r - (\Omega^2 - \Omega_{\rm K}^2)r = -\frac{1}{\rho}\partial_r P \qquad \text{radial}$$

$$\Sigma v_r T\partial_r S = q^+ - q^- \qquad \text{energy}$$

Entropy: $S = c_{\rm v}\ln(\frac{P}{\rho^\gamma})$ (ideal gas with constant ratio of specific heats $\gamma$)

$$q^+ = \int Q_{\rm visc}{\rm d}z; \quad q^- = \int {\rm div}\, F_{\rm rad}\,{\rm d}z$$

viscosity: keep $\nu = \alpha c_{\rm s}^{/}\Omega$

*hydrodynamics of radiatively inefficient flow*

## Self-similar solutions (Gilham 1981)

$$\Omega \sim r^{-3/2} \qquad (\Omega/\Omega_{\rm K} = {\rm cst.})$$

$$\rho \sim r^{-3/2}$$

$$H \sim r$$

$$T \sim 1/r \qquad (T/T_{\rm vir} = {\rm cst.})$$

solution for $\alpha \ll 1$ :

$$v_r = -\alpha\Omega_{\rm K} r(9\frac{\gamma-1}{5-\gamma})$$

$$\Omega = \Omega_{\rm K}(2\frac{5-3\gamma}{5-\gamma})^{1/2}$$

$$c_{\rm s}^2 = \Omega_{\rm K}^2 r^2 \frac{\gamma-1}{5-\gamma}$$

$$\frac{H}{r} = (\frac{\gamma-1}{5-\gamma})^{1/2}$$

Properties:

- $\Omega < \Omega_{\rm K}$ for $\gamma > 1$
- *no rotating solution for* $\gamma \geq 5/3$
- $H/r \rightarrow 0$ for $\gamma \downarrow 1$

*self-similar radiatively inefficient flows*

Special cases: $\gamma \downarrow 1, \ \gamma = 5/3$

$\gamma \downarrow 1$ ? $\quad \gamma = c_\mathrm{p}/c_\mathrm{v} = (\mathcal{R} + c_\mathrm{v})/c_\mathrm{v}$

large $c_\mathrm{v}$ : energy goes into internal degrees of freedom, → temperature low

fully ionized gas (nonrelativistic) has $\gamma = 5/3$

→ (steady, self-similar...) ion-supported flow should not rotate ?!

Why is this case special? look at entropy.

Self-similar scaling:

$$\begin{matrix} \rho \sim r^{3/2} \\ T \sim r^{-1} \end{matrix} \rightarrow P \sim r^{-5/2} \quad \rightarrow S \sim \ln P/\rho^\gamma \sim (-\frac{5}{2} + \frac{3}{2}\gamma) \ln r$$

If $\gamma < 5/3$ : Entropy increases inward. Consistent with dissipation taking place. $\gamma = 5/3$ : entropy constant. Possible only in absence of viscous dissipation → *rotation must vanish.*

## *self-similar radiatively inefficient flows: the case* $\gamma = 5/3$

Solution: (G. Ogilvie MNRAS 1999)
the flow is *time dependent*

Rotation slows down with time
(describes viscous spreading for thick accretion flows)

Time-dependent self-similar solution $f(\xi), \quad \xi = rt^{-2/3}$
$\Omega \downarrow 0 \quad (\xi \downarrow 0)$ boundary of slowly rotating inner region increases with time as $r \sim t^{2/3}$

→ *adiabatic accretion flow with* $\gamma = 5/3$ *does not rotate, or is time-dependent*