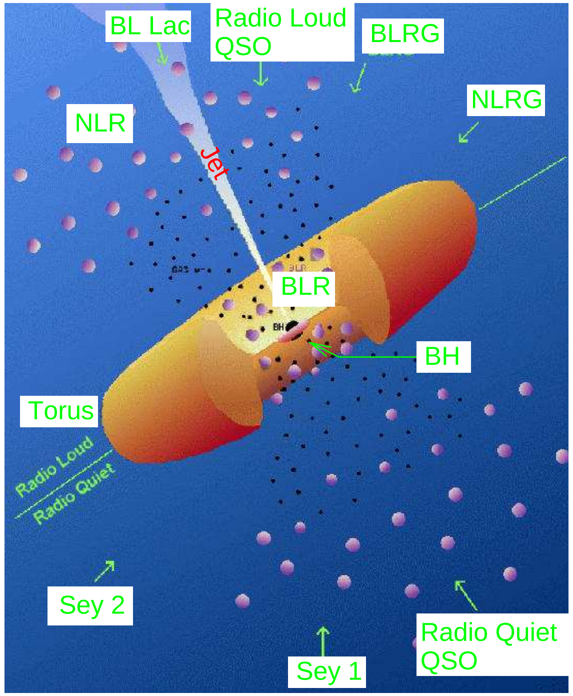
Space Densities

Current space densities of various AGN (Peterson, 1997; Marzke et al., 1994):

Type	Density (Gpc^{-3})
Total Galaxy Density	
Spirals	$1.5 \times 10^7\, h_0^3$
Ellipticals	$1.0 \times 10^7\, h_0^3$
Radio Quiet AGN	
Sy 2	$8 \times 10^5\, h_0^3$
Sy 1	$3 \times 10^5\, h_0^3$
QSO	$800\, h_0^3$
Radio Loud AGN	
FR 1	$2 \times 10^4\, h_0^3$
BL Lac	$600\, h_0^3$
FR 2	$80\, h_0^3$
Radio loud QSOs	$20\, h_0^3$

$\Longrightarrow$ ∼10% of all galaxies are AGN.

$\Longrightarrow$ ∼2% of all AGN are radio loud.



Physical properties of components:

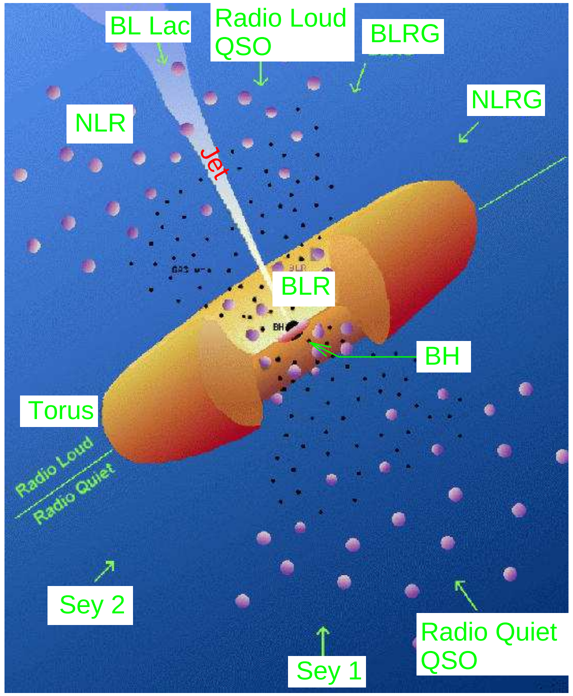
Accretion disk: $r \sim 10^{-3}$ pc,
$n \sim 10^{15}\,\mathrm{cm}^{-3}$,
$kT \sim 50\,\mathrm{eV} \cdot r^{-3/4}$,
$v \sim 0.3c$ at inner edge.

Broad Line Region (BLR):
$r \sim$ 0.01–0.1 pc (=light days),
$n \sim 10^{10}\,\mathrm{cm}^{-3}$,
$v \sim$ 1000–5000 km s^{-1},
$T \sim 10^4$ K

Torus: $r \sim$ 1– few 10 pc,
$n \sim 10^3$–$10^6\,\mathrm{cm}^{-3}$,
T: cold

Narrow Line Region (NLR):
$r \sim$ 100–1000 pc,
$n \sim 10^3$–$10^6\,\mathrm{cm}^{-3}$,
$v \sim$ few · 100 km s^{-1},
$T \sim 10^4$ K

See, e.g., Antonucci (1993) for a review.



Unified Model: All AGN types are due to the same physics, different phenomenology just due to different viewing angle.

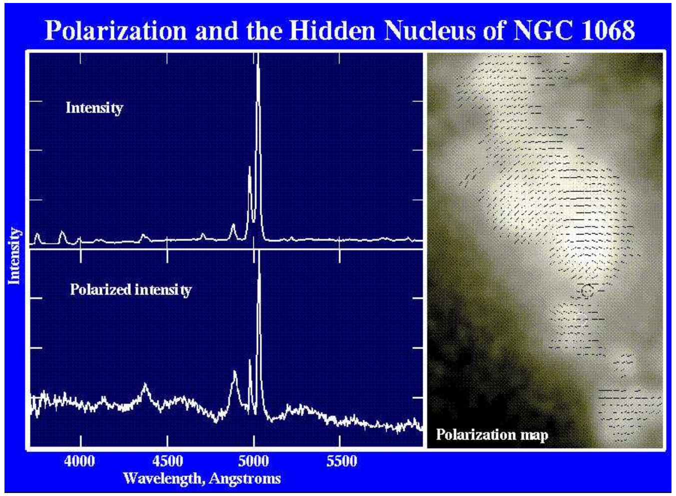
(Urry & Padovani, 1995, NOTE: logarithmic length scale!)

Unification, III

Simplified Unification (Peterson, 1997)

Radio Properties	Orientation: Face-on	Orientation: Edge-on
Radio Quiet	Seyfert 1	Seyfert 2
	QSO	Far IR Galaxy?
Radio Loud	BL Lac	FR I
	BLRG	NLRG
	Quasar/OVV	FR II

Observational Evidence: NGC 1068



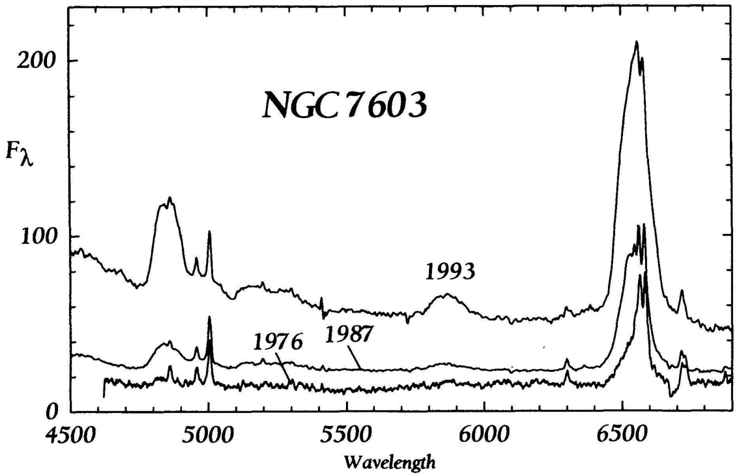
W. Keel

Antonucci & Miller (1985): In polarized light, the Seyfert 2 NGC 1068 shows broad lines and a spectrum similar to Seyfert 1 galaxies.

⟹ Scattered radiation from the BLR!

16% polarization ⟹ single scattering (multiple scatterings would depolarize!); note that lines from NLR are *not* polarized ⟹ no scattering!

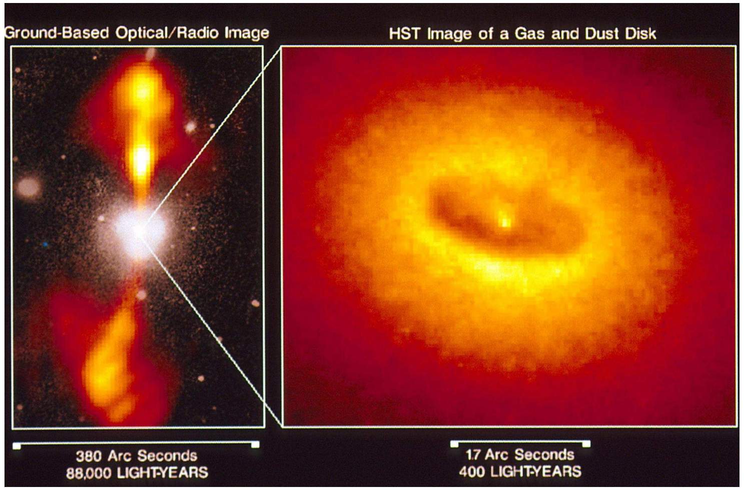
Observational Evidence: Spectral Variations



(Goodrich, 1995, Fig. 7)

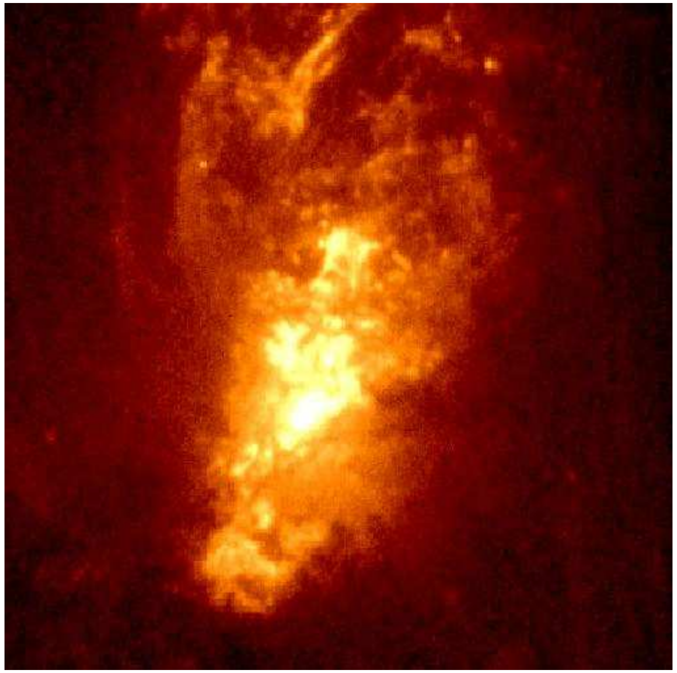
Some Seyferts change type, e.g., from Sy 2 to Sy 1 within a few years.

Observational Evidence: Imaging of the Torus?

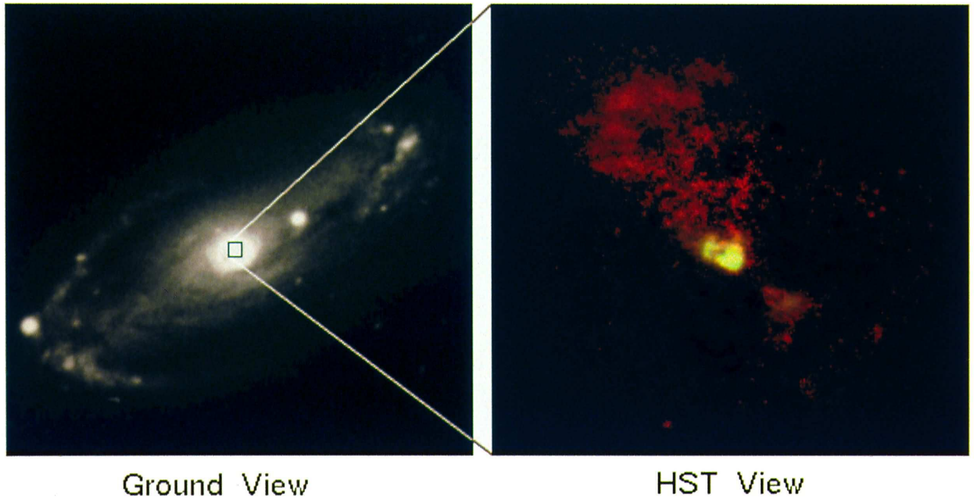


NGC 4261 (HST/WFPC)

Some nearby Seyferts show torus-like structures in their centers.



Ionization in the center of NGC 1068 (Sy 2; HST)



NGC 5728 (Sy 2, HST; green: [O III] $\lambda\lambda$ 4959, 5007 Å, red: Hα and [N II], $\lambda\lambda$ 6548, 6583 Å, plus continua)

Wilson et al. 1993

Ionization cone of NGC 5728: line emission of ionized species aligned with radio structure (to within 2°), *not* aligned with galaxy. Extent of structure: ~1.8 kpc

Observational Evidence: Ionization Cones, VII

Interpretation of ionization cones: gas ionized by hard continuum of nucleus.

Shape of cone due to blockage by the torus.

We can try to quantify things, assuming a pure hydrogen gas for simplicity.

The luminosity of Hβ line is given by

$$L(\mathrm{H}\beta) = \iint j_{\mathrm{H}\beta}\, d\Omega dV = \alpha^{\mathrm{eff}}_{\mathrm{H}\beta} h\nu_{\mathrm{H}\beta} \int n_{\mathrm{e}}^2 dV \qquad (3.16)$$

where $j_{\mathrm{H}\beta}$: emissivity, $\alpha^{\mathrm{eff}}_{\mathrm{H}\beta}$ coefficient of recombination (from atomic physics, see later; n_{e}: electron number density; $n_{\mathrm{e}}^2\alpha$: rate of recombinations).

Assuming photoionization equilibrium, the rate of ionizations of hydrogen equals the rate of photons which can ionize H emitted by the sorce, $Q(\mathrm{H})$, and the photoionization rate equals the recombination rate:

$$Q(\mathrm{H}) = \int_{\nu_1}^{\infty} \frac{L_\nu d\nu}{h\nu} = \alpha_{\mathrm{B}} \int n_{\mathrm{e}}^2 dV \qquad (3.17)$$

where $\alpha_{\mathrm{B}} n_{\mathrm{e}}^2$: total recombination rate ($\alpha_{\mathrm{B}} = 2.6 \times 10^{13}\,\mathrm{cm^3\,s^{-1}}$ for $T = 10^4$ K).

Therefore:

$$Q(\mathrm{H}) = \frac{L(\mathrm{H}\beta)}{h\nu_{\mathrm{H}\beta}} \frac{\alpha_{\mathrm{B}}}{\alpha^{\mathrm{eff}}_{\mathrm{H}\beta}} \sim 2.1 \times 10^{53} L_{41}(\mathrm{H}\beta)\ \mathrm{photons\,s^{-1}} \qquad (3.18)$$

Observational Evidence: Ionization Cones, VIII

The number of ionizing photons was

$$Q(\mathrm{H}) = \frac{L(\mathrm{H}\beta)}{h\nu_{\mathrm{H}\beta}} \frac{\alpha_{\mathrm{B}}}{\alpha^{\mathrm{eff}}_{\mathrm{H}\beta}} \sim 2.1 \times 10^{53} L_{41}(\mathrm{H}\beta)\ \mathrm{photons\,s^{-1}} \qquad (3.18)$$

while the observed ionizing production rate is:

$$Q_{\mathrm{obs}}(\mathrm{H}) = 4\pi d^2 \int_{\nu_1}^{\infty} \frac{F_\nu d\nu}{h\nu} \qquad (3.19)$$

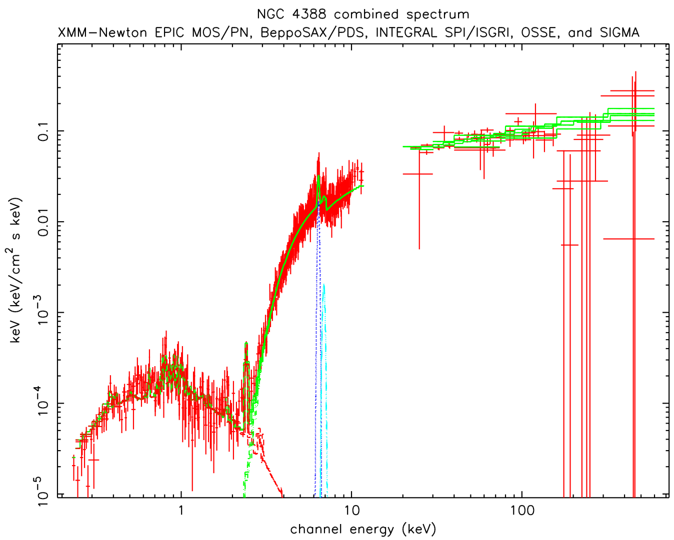
Observations show: $Q(\mathrm{H})/Q_{\mathrm{obs}}(\mathrm{H}) > 1$, i.e., cone sees more luminous continuum
$\Longrightarrow$ blockage due to torus?

But note: calculation ignores that cone probably consists of clouds

$\Longrightarrow$ need to modify $Q(H)$ to take geometry into account. Gives factor $r_{\mathrm{cloud}}/(\epsilon r_{\mathrm{cone}})$, where ϵ is unknown filling factor

$\Longrightarrow$ large uncertainty!

Observational Evidence: Absorption

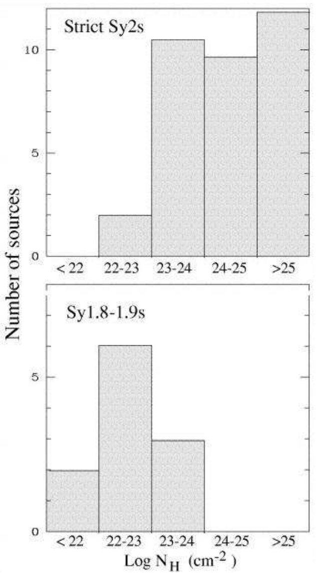


X-ray spectroscopy allows to penetrate even high columns of absorbing gas.

(Beckmann et al., 2004)

Reason: photo-absorption cross section is $\propto E^{-3}$, crosses Thomson cross section at ~10 keV.

Observational Evidence: Absorption



Risaliti, Maiolino & Salvati (1999): From X-ray studies:

- 75% of Seyfert 2's are heavily obscured, i.e., have $N_\mathrm{H} \geq 10^{23}\,\mathrm{cm}^{-2}$.
- 50% of Seyfert 2's are Compton thick, i.e., have $N_\mathrm{H} \geq 10^{24}\,\mathrm{cm}^{-2}$.
- N_H for Sy 2 is higher than that for Sy 1.8, 1.9.

where N_H is the column density of Hydrogen,

$$N_\mathrm{H} = \int_0^r n_\mathrm{H} dr \tag{3.20}$$

determined from X-ray absorption.

(Risaliti, Maiolino & Salvati, 1999, Fig. 5)

Summary

- Puzzling zoo of AGN can be described by simple geometric model: black hole surrounded by obscuring torus
- Radio loud vs. radio quiet: presence of jet
- Observations mainly support unified model

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Accretion and Accretion Disks

Introduction

AGN are powered by accretion $\Longrightarrow$ need to look at accretion as a physical mechanism.

Unfortunately, this will have to be somewhat theoretical, but this cannot be avoided. . .

Structure of this chapter:

1. Accretion Luminosity: Eddington luminosity
2. Accretion Disks: Theory
3. Accretion Disks: Confrontation with observations

Literature

- J. Frank, A. King, D. Raine, 2002, Accretion Power in Astrophysics, 3rd edition, Cambridge Univ. Press

  The standard textbook on accretion, covering all relevant areas of the field.

- T. Padmanabhan, 2001, Theoretical Astrophysics, II. Stars and Stellar Systems, Cambridge Univ. Press

  See introduction to this lecture.

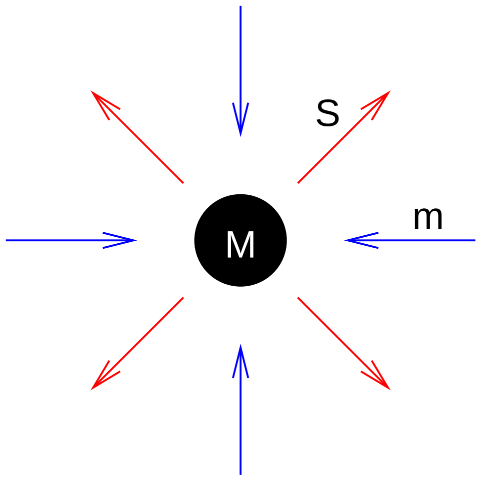
- N.I. Shakura & R. Sunyaev, 1973, Black Holes in Binary Systems. Observational Appearance. Astron. Astrophys. **24**, 337

  The fundamental paper, which *really* started the field.

- J.E. Pringle, 1981, Accretion Disks in Astrophysics, Ann. Rev. Astron. Astrophys. **19**, 137

  Concise review of classical accretion disk theory.

Eddington luminosity, IV

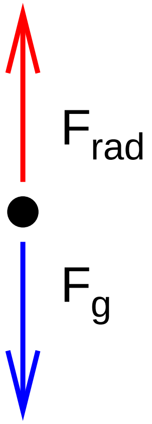


Assume mass M spherically symmetrically accreting ionized hydrogen gas.

At radius r, accretion produces energy flux S.

Important: Interaction between accreted material and radiation!

Eddington luminosity, VIII



Force balance on accreted electrons and protons:

Inward force: gravitation:

$$F_g = \frac{GMm_p}{r^2}$$

Outward force: radiation force:

$$F_{rad} = \frac{\sigma_T S}{c}$$

where energy flux S is given by

$$S = \frac{L}{4\pi r^2}$$

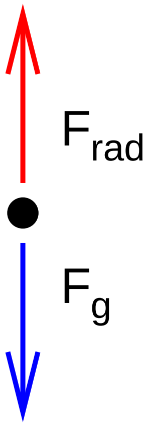
where L: luminosity.

Note: $\sigma_T \propto (m_e/m_p)^2$, so negligable for protons.

But: strong Coulomb coupling between electrons and protons

$\Longrightarrow$ F_{rad} also has effect on protons!

Eddington luminosity, IX



Accretion only possible if gravitation dominates:

$$\frac{GMm_p}{r^2} > \frac{\sigma_T S}{c} = \frac{\sigma_T}{c} \cdot \frac{L}{4\pi r^2}$$

and therefore

$$L < L_{Edd} = \frac{4\pi GMm_p c}{\sigma_T}$$

or, in astronomically meaningful units

$$L < 1.3 \times 10^{38}\,\mathrm{erg\,s^{-1}} \cdot \frac{M}{M_\odot}$$

where L_{Edd} is called the Eddington luminosity.

But remember the assumptions entering the derivation: spherically symmetric accretion of fully ionized pure hydrogen gas.

Eddington luminosity, X

Characterize accretion process through the accretion efficiency, η:

$$L = \eta \cdot \dot{M}c^2$$

where $\dot{M}$: mass accretion rate (e.g., $\mathrm{g\,s^{-1}}$ or $M_\odot\,\mathrm{yr^{-1}}$).

Therefore maximum accretion rate ("Eddington rate"):

$$\dot{m} = \frac{L_{Edd}}{\eta c^2} \sim 2 \cdot \left(\frac{M}{10^8\,M_\odot}\right)\,M_\odot\,\mathrm{yr^{-1}}$$

(for $\eta = 0.1$)

Emitted spectrum

Characterize photon by its radiation temperature, T_{rad}:

$$h\nu \sim kT_{rad} \quad \Longrightarrow \quad T_{rad} = h\nu/k$$

Optically thick medium: blackbody radiation

$$T_b = \left(\frac{L}{4\pi R^2 \sigma_{SB}}\right)^{1/4}$$

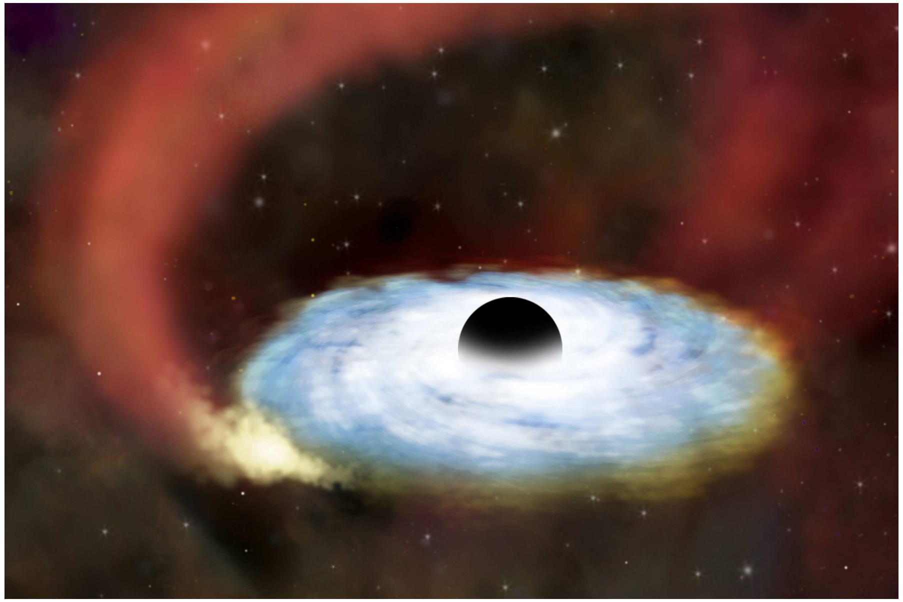
Optically thin medium: L directly converted into radiation without further interactions $\Longrightarrow$ mean particle energy

$$T_{th} = \frac{GMm_p}{3kR}$$

Plugging in numbers for a typical solar mass compact object (NS/BH):

$$T_{rad} \sim 1\,\mathrm{keV} \quad \text{and} \quad T_{th} \sim 50\,\mathrm{MeV}$$

Accreting objects are broadband emitters in the X-rays and gamma-rays.



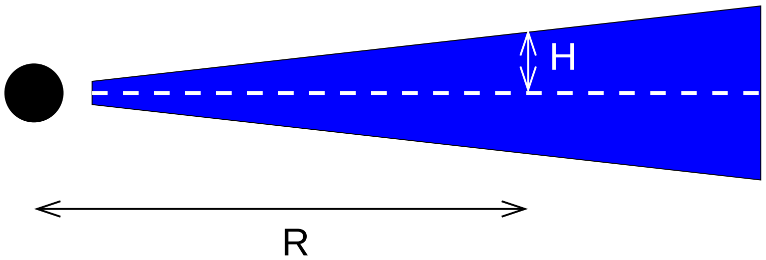
NASA/CXC/SAO

Source of matter: probably disrupted stars

$\Longrightarrow$ accreted matter has angular momentum

$\Longrightarrow$ accretion disk forms.

Thin Disks, I



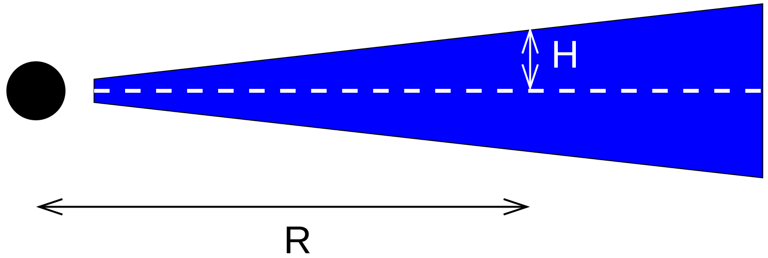
Most important case: thin accretion disks, i.e., vertical thickness, H, much smaller than radius R:

$$H \ll R$$

$\Longrightarrow$ Requires that radiation pressure is negligable

$\Longrightarrow L \ll L_{\text{Edd}}$

Thin Disks, II



Thin assumption: no radiation pressure

$\Longrightarrow$ gas pressure must support disk vertically against gravitation:

$$\frac{GM}{R^2}\frac{H}{R} = \frac{1}{\rho}\left|\frac{\partial P}{\partial z}\right| \sim \frac{P_{\text{c}}}{\rho_{\text{c}} H}$$

where P_{c} characteristic pressure, ρ_{c} characteristic density.

Thin Disks, III

Because the speed of sound is

$$c_{\text{s}}^2 = \frac{P}{\rho}$$

the condition for vertical support can be written as

$$\frac{GM}{R^2}\frac{H}{R} \sim \frac{P_{\text{c}}}{\rho_{\text{c}} H} = \frac{c_{\text{s}}^2}{H}$$

Therefore

$$c_{\text{s}}^2 = \frac{GM}{R}\frac{H^2}{R^2} = v_\phi^2 \cdot \frac{H^2}{R^2}$$

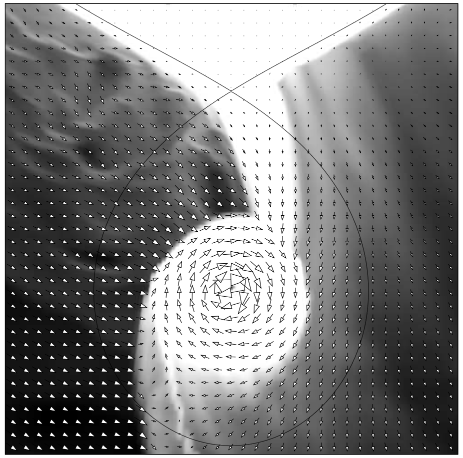
where $v_\phi = \sqrt{GM/R}$: Kepler speed.

Since $H/R \ll 1$:

$$c_{\text{s}} \ll v_\phi$$

Thin accretion disks are highly supersonic.

Thin Disks: Radial Structure



J. Blondin (priv. comm.; calculations for stellar accretion)

Radial acceleration due to pressure:

$$\frac{1}{\rho}\frac{\partial P}{\partial R} \sim \frac{P_\mathrm{c}}{\rho_\mathrm{c} R} \sim \frac{c_\mathrm{s}^2}{R} \sim \frac{GM}{R^2}\frac{H^2}{R^2} \ll \frac{GM}{R^2}$$

$\Longrightarrow$ radial acceleration due to pressure negligable compared to gravitational acceleration

Thin disk: fluid motion is Keplerian to very high degree of precision.

$\Longrightarrow$ for the radial velocity, v_R: $v_R \ll v_\phi$

Thin Disks: Vertical Structure and Mass Conservation

Amount of mass crossing radius R:

$$\dot{M} = -2\pi R \cdot \Sigma \cdot v_R$$

where Σ: surface density of disk,

$$\Sigma(R) = \int n(r)\,dz$$

and where $\dot{M}$: mass accretion rate

Since acceleration $\perp z$

$$F_z \propto \frac{GM}{R^2}\frac{z}{R} \propto z$$

vertical density profile

$$n(z) \propto \exp\left(-\frac{z}{H}\right)$$

where H: scale height (depends on details of accretion disk theory).

Thin Disks: Angular Momentum Transport, I

Most important question: angular momentum transport

Angular velocity in Keplerian disk:

$$\Omega(R) = \left(\frac{GM}{R^3}\right)^{1/2}$$

("differential rotation")

$\Longrightarrow$ angular momentum per mass ("specific angular momentum"):

$$\mathcal{L} = R \cdot v = R \cdot R\Omega(R) = R^2\,\Omega(R) \propto R^{1/2}$$

$\Longrightarrow$ decreases with decreasing R!

Total angular momentum lost when mass moves in unit time from $R + dR$ to R:

$$\frac{dL}{dR} = \dot{M} \cdot \frac{d(R^2\Omega(R))}{dR}$$

Thin Disks: Angular Momentum Transport, II

Since L changes: accreting matter needs to lose angular momentum. This is done by viscous forces excerting torques:

Force due to viscosity per unit length:

$$\mathcal{F} = \nu\Sigma \cdot \Delta v = \nu\Sigma \cdot R\frac{d\Omega}{dR}$$

where ν: coefficient of kinematic viscosity

Therefore total torque

$$G(R) = 2\pi R\mathcal{F} \cdot R = \nu\Sigma 2\pi R^3 \left(\frac{d\Omega}{dR}\right)$$

and the net torque acting on a ring is

$$\frac{dG}{dR}dR$$

$\Longrightarrow$ This net torque needs to balance change in specific angular momentum in disk.

Thin Disks: Angular Momentum Transport, III

Balancing net torque and angular momentum loss gives:

$$\dot{M}\frac{d(R^2\Omega)}{dR} = -\frac{d}{dR}\left(\nu\Sigma 2\pi R^3 \frac{d\Omega}{dR}\right)$$

Insert $\Omega(R) = (GM/R^3)^{1/2}$ and integrate:

$$\nu\Sigma R^{1/2} = \frac{\dot{M}}{3\pi}R^{1/2} + \text{const.}$$

const. obtained from no torque boundary condition at inner edge of disk at $R = R_*$: $dG/dR(R_*) = 0$, such that

$$\nu\Sigma = \frac{\dot{M}}{3\pi}\left[1 - \left(\frac{R_*}{R}\right)^{1/2}\right]$$

Therefore the viscous dissipation rate per unit area is

$$D(R) = \nu\Sigma\left(R\frac{d\Omega}{dR}\right)^2 = \frac{3GM\dot{M}}{4\pi R^3}\left[1 - \left(\frac{R_*}{R}\right)^{1/2}\right]$$

Thin Disks: Temperature Profile, I

The viscous dissipation rate was

$$D(R) = \nu\Sigma\left(R\frac{d\Omega}{dR}\right)^2 = \frac{3GM\dot{M}}{4\pi R^3}\left[1 - \left(\frac{R_*}{R}\right)^{1/2}\right]$$

If disk is optically thick: Thermalization of dissipated energy

$\Longrightarrow$ Temperature from Stefan-Boltzmann-Law:

$$2\sigma_{\text{SB}}T^4 = D(R)$$

(disk has *two* sides!) and therefore

$$T(R) = \left\{\frac{3GM\dot{M}}{8\pi R^3 \sigma_{\text{SB}}}\left[1 - \left(\frac{R_*}{R}\right)^{1/2}\right]\right\}^{1/4}$$

Thin Disks: Temperature Profile, IV

Inserting astrophysically meaningful numbers:

$$T(R) = \left\{\frac{3GM\dot{M}}{8\pi R^3 \sigma_{\text{SB}}}\left[1 - \left(\frac{R_*}{R}\right)^{1/2}\right]\right\}^{1/4}$$
$$= 6.8 \times 10^5\,\text{K} \cdot \eta^{-1/4}\left(\frac{L}{L_{\text{Edd}}}\right)^{1/2} L_{46}^{-1/4}\mathcal{R}^{1/4}x^{-3/4}$$

where $\eta = L_{\text{Edd}}/\dot{M}_{\text{Edd}}c^2$, $x = c^2R/2GM$, $\mathcal{R} = (1 - (R_*/R)^{1/2})$.

Radial dependence of T:

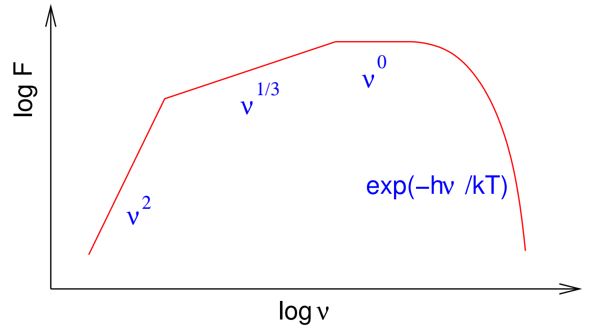
$$T(R) \propto R^{-3/4}$$

Dependence on mass (note: for NS/BH inner radius $R_* \propto M$!):

$$T_{\text{in}} \propto (\dot{M}/M^2)^{1/4}$$

$\Longrightarrow$ AGN disks are colder than disks around galactic BH

Thin Disks: Emitted Spectrum, I



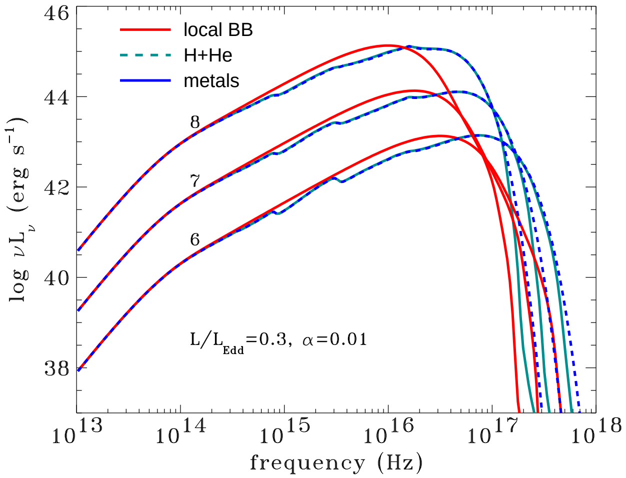
If disk is optically thick, then locally emitted spectrum is black body.

Total emitted spectrum obtained by integrating over disk

$$F_\nu = \int_{R_*}^{R_{\text{out}}} B(T(R))\, 2\pi R\, dR$$

Resulting spectrum looks essentially like a stretched black body.

Thin Disks: Emitted Spectrum, II



Hubeny et al., 2001, Fig. 13

In reality: accretion disk spectrum depends on

- elemental composition ("metallicity")
- viscosity ("α-parameter")
- ionization state and luminosity of disk ($\dot{M}$)
- properties of compact object

and many further parameters

Until today: no really satisfactory disk model available.

Viscosity

Most important unknown in accretion disk theory: viscosity

even though it dropped out of $T(R)$!

Earth: viscosity of fluids typically due to molecular interactions (molecular viscosity).

Kinematic viscosity:

$$\nu_{\mathrm{mol}} \sim \lambda_{\mathrm{mfp}} c_{\mathrm{s}}$$

where the mean free path

$$\lambda_{\mathrm{mfp}} \sim \frac{1}{n\sigma} \sim 6.4 \times 10^4 \left(\frac{T^2}{n}\right) \mathrm{cm}$$

and the speed of sound

$$c_{\mathrm{s}} \sim 10^4 T^{1/2}\,\mathrm{cm\,s^{-1}}$$

such that

$$\nu_{\mathrm{mol}} \sim 6.4 \times 10^8\, T^{5/2} n^{-1}\,\mathrm{cm^2\,s^{-1}}$$

Viscosity

Viscosity important when Reynolds number small ("laminar flow"), where

$$\mathrm{Re} = \frac{\text{inertial force}}{\text{viscous force}} \sim \frac{\rho R v}{\rho \nu} = \frac{Rv}{\nu}$$

Follows from Navier-Stokes Equations

Using typical accretion disk parameters:

$$\mathrm{Re}_{\mathrm{mol}} \sim 2 \times 10^{14} \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{R}{10^{10}\,\mathrm{cm}}\right)^{1/2} \left(\frac{n}{10^{15}\,\mathrm{cm^{-3}}}\right) \left(\frac{T}{10^4\,\mathrm{K}}\right)^{-5/2}$$

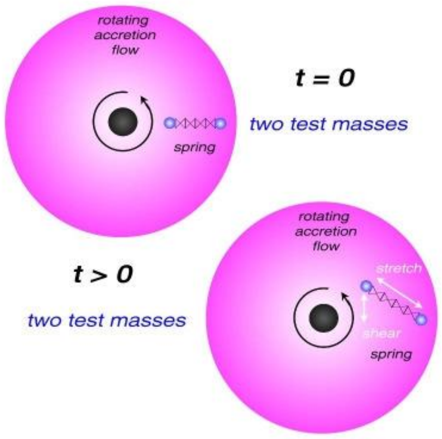
$\Longrightarrow$ Molecular viscosity is irrelevant for astrophysical disks!

since Re $\gtrsim 10^3$: turbulence $\Longrightarrow$ Shakura & Sunyaev posit turbulent viscosity

$$\nu_{\mathrm{turb}} \sim v_{\mathrm{turb}} \ell_{\mathrm{turb}} \sim \alpha\, c_{\mathrm{s}} \cdot H$$

where $\alpha \lesssim 1$ and $\ell_{\mathrm{turb}} \lesssim H$ typical size for turbulent eddies.

Viscosity



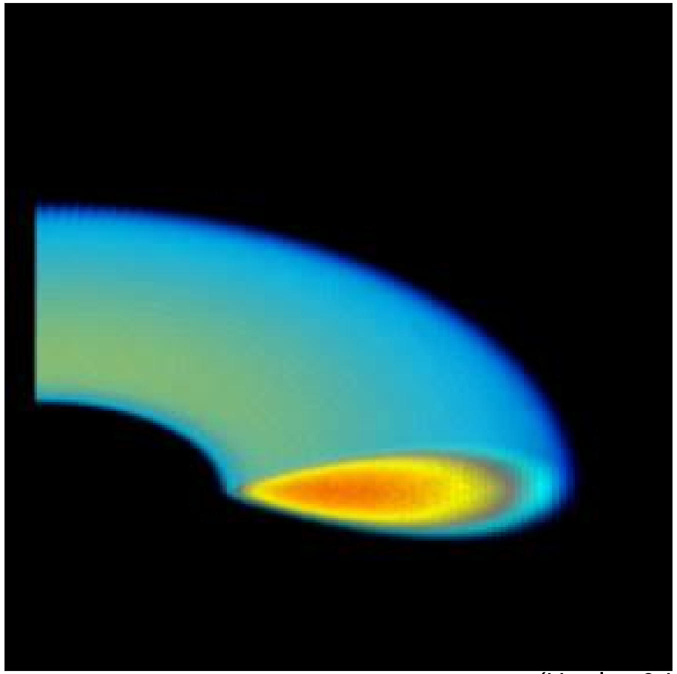
R. Müller

Mechanical analogy of MRI: spring in differentially rotating medium.

Physics of turbulent viscosity is unknown, however, α prescription yields good agreement between theory and observations.

Possible origin: Magnetorotational instability (MRI): MHD instability amplifying B-field inhomogeneities caused by small initial radial displacements in accretion disk $\Longrightarrow$ angular momentum transport

(Balbus & Hawley 1991, going back to Velikhov 1959 and Chandrasekhar (1961).



(Hawley & Krolik, 2002)