Active Galactic Nuclei: What's in the name?

Active Galactic Nuclei: definition

- The term Active Galactic Nucleus (AGN) was first used by Ambaratsumian (1971) to describe violent motions of gaseous clouds, considerable excess radiation in the ultraviolet, relatively rapid changes in brightness, expulsion of jets and condensations. Originally intended to describe radio galaxies, then extended to encompass also the related phenomena of Seyfert galaxies and quasars

- Peterson 1997: existence of energetic phenomena in the nuclei, or central regions, of galaxies which cannot be attributed clearly and directly to stars

- More recently: AGN are objects emitting radiation which is fundamentally powered by accretion onto supermassive ($>10^8\ M_\odot$) black holes (actually, wide range of masses!)

- Observationally: (a) strong X-ray emission, (b) relatively strong (non-thermal) radio emission (and extended structures), (c) non-stellar UV through IR emission, (d) broad emission lines over a wide wavelength range - **Not necessarily all these properties at the same time** → overall, **large variety of properties** (depending also on the AGN classification, see AGN unified model)

Active Galactic Nuclei: energy output

$$E \gtrsim 10^{47} erg/s \times 10^{7} yrs \sim 3 \times 10^{61} erg$$

↓ bolometric luminosity ↓ time of activity

$$E = \epsilon m c^2$$

If ε=efficiency=0.7%=0.007 as from thermonuclear fusion (not true!), then

$$m = \frac{E}{\epsilon c^2} \sim 4 \times 10^{42} g \sim 2 \times 10^{9} M_{\odot}$$

'mass supply' for BH accretion

//

Schwarzschild radius ↑

$$R_s = \frac{2GM}{c^2} = \frac{2GM_{\odot}}{c^2} \frac{M}{M_{\odot}} \sim \frac{2 \times 6.7 \times 10^{-8} \times 2 \times 10^{33}}{9 \times 10^{20}} \frac{M}{M_{\odot}} cm \sim 6 \times 10^{14}\ cm$$

i.e., the matter "transformed" into radiation to provide the energy reported above would be of the same order of that contained in the Schwarzschild radius. The *gravitational binding energy* is *far higher than the energy released from nuclear burning* in virtue of a *higher efficiency* → **gravitational energy production is the basis of the emission from AGN** (full explanation later in the course)

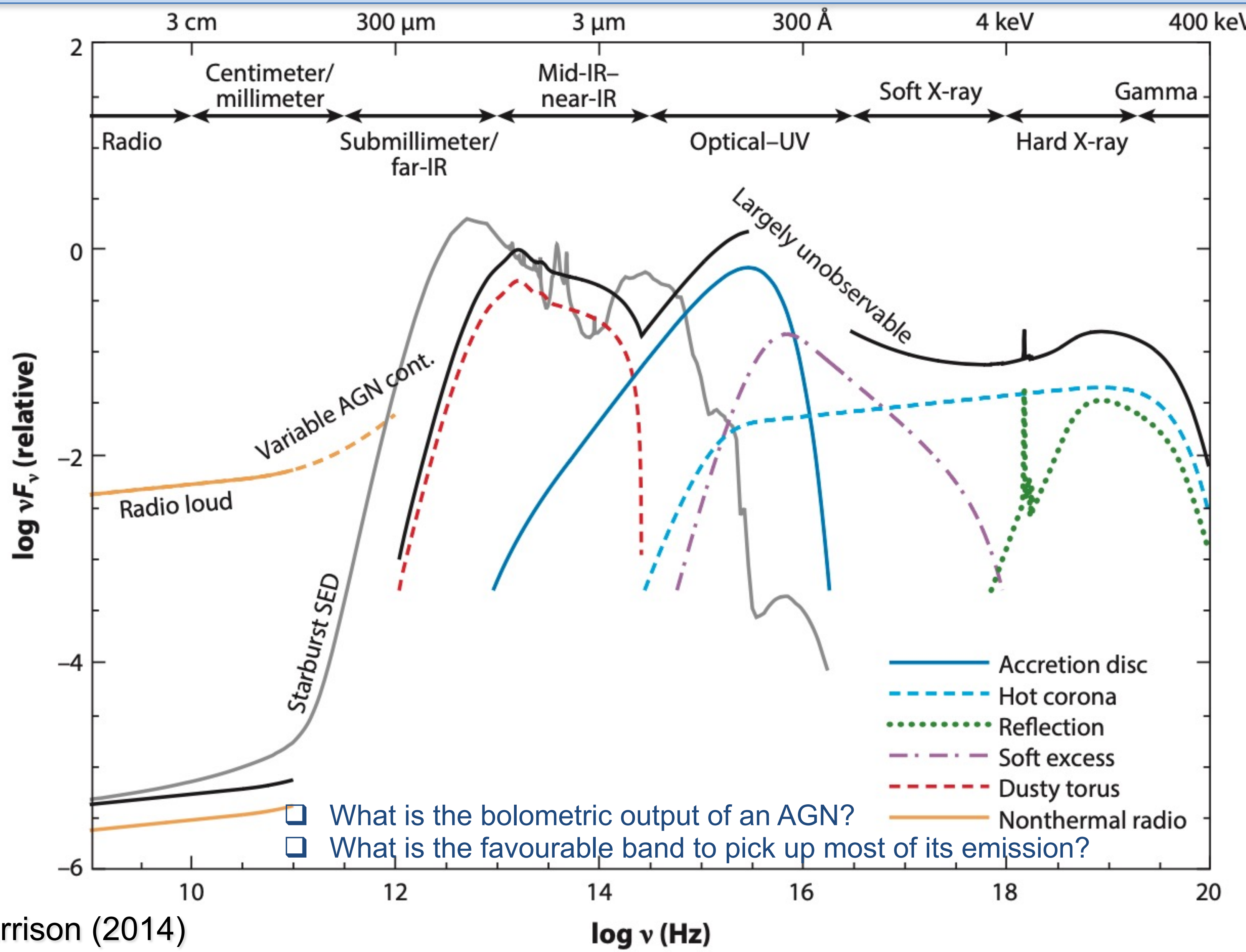
AGN Emission

- ❑ What is the bolometric output of an AGN?
- ❑ What is the favourable band to pick up most of its emission?

⬇

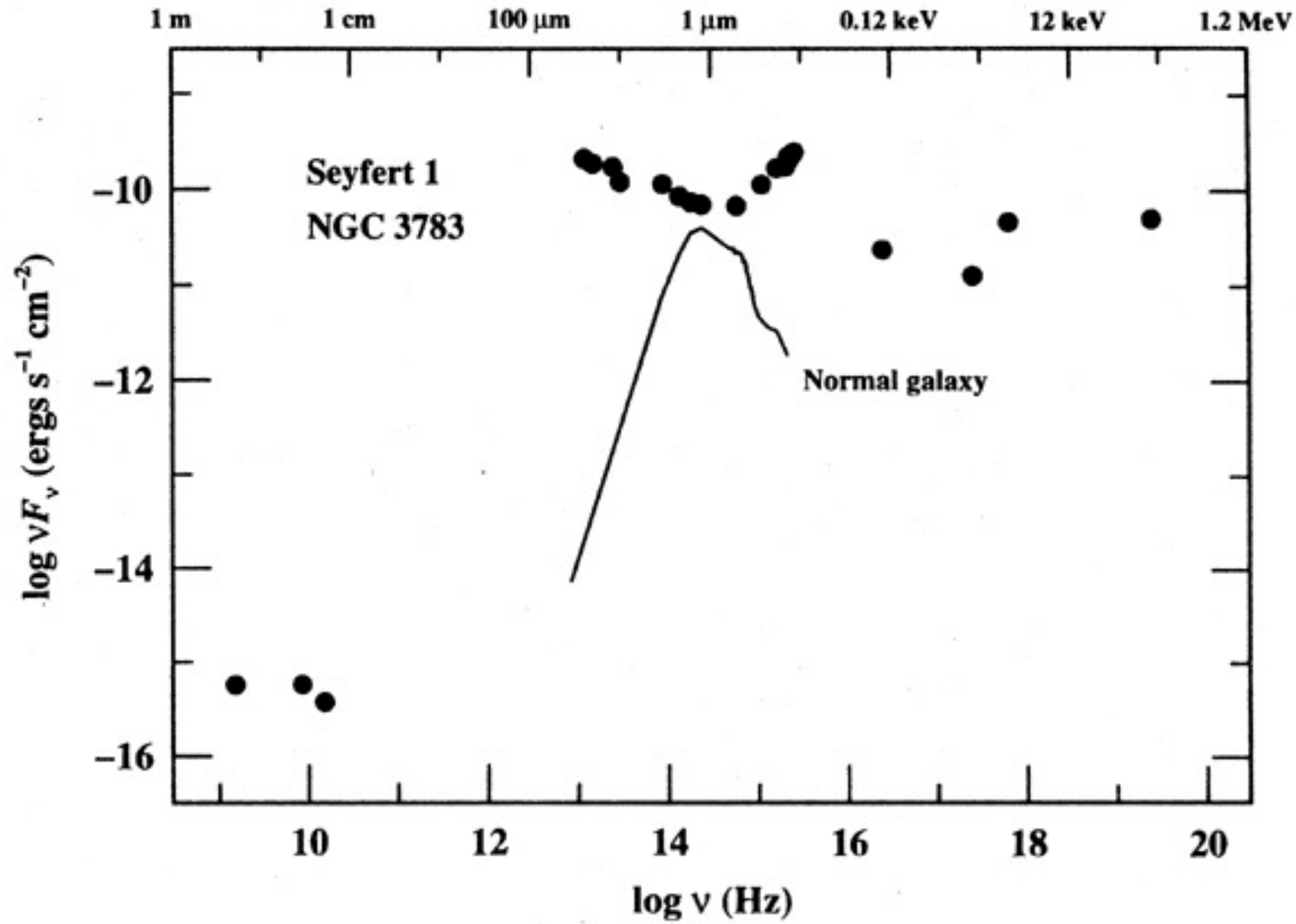
- ➢ Capability of detecting accretion-related phenomena (survey flux limits, etc.) vs. dilution effects (from the host galaxy) → proper choice of the observing band
- ➢ Capability of summing up all the emissions due to accretion and count them in the proper way [spectral energy distribution (SED), i.e. photon flux vs. wavelength/frequency/energy studies are important!]
- ➢ Effects of obscuration: the "best" band is not necessarily the most appropriate one to derive a proper estimate of the accretion power

AGN Spectral Energy Distribution



- ❑ What is the bolometric output of an AGN?
- ❑ What is the favourable band to pick up most of its emission?

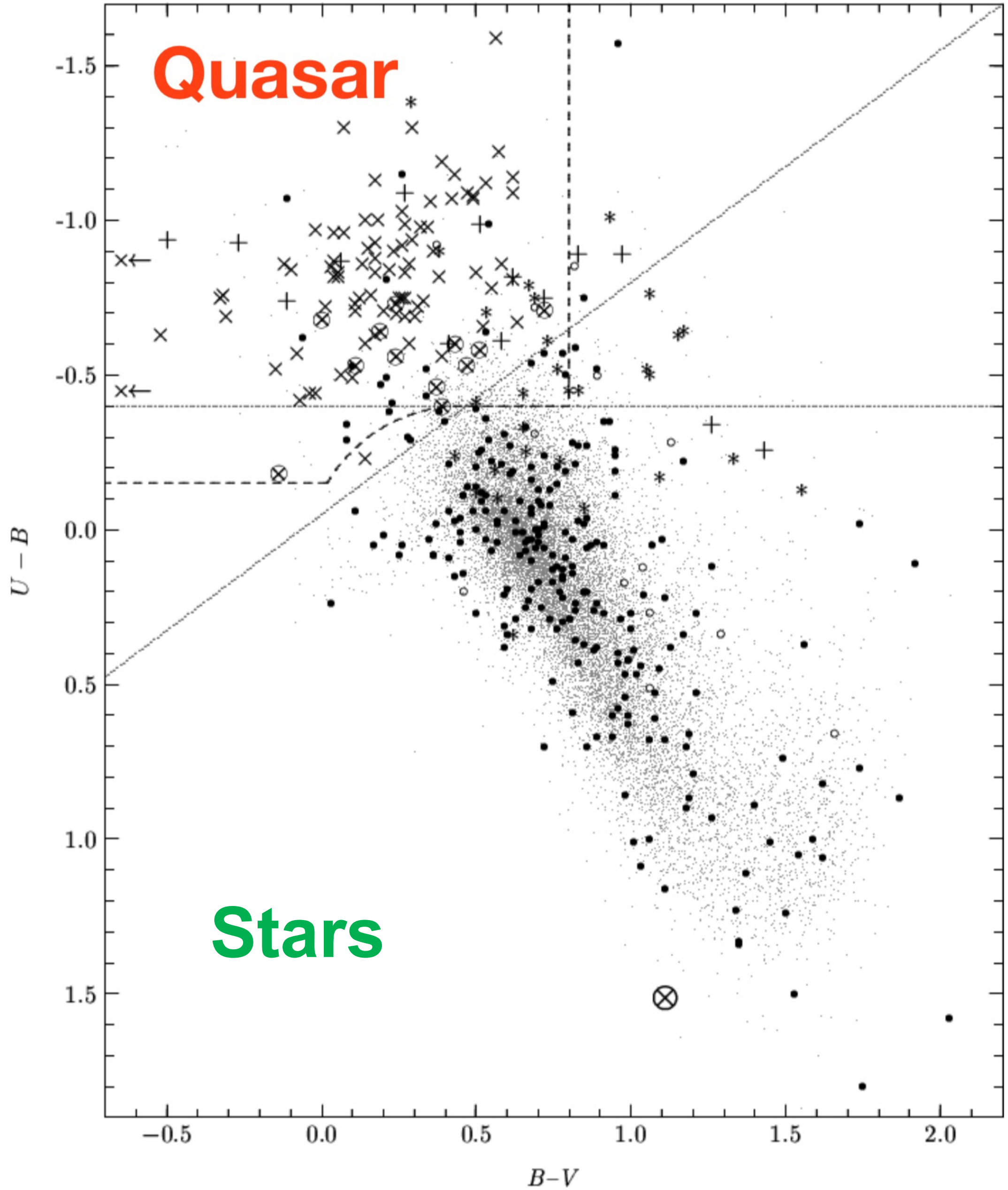
Harrison (2014)



Alloin et al. (1995)

SED of Seyfert 1 galaxy vs. SED of a normal galaxy (peaking at ~1 μm because of the old stellar population)

Optical/UV continuum in an AGN has non-stellar origin



AGN (Type 1, unobscured, see following lessons) typically are blue objects
U-B<-0.44 was the selection of Palomar-Green (PG) quasars, similar colors for SDSS quasars

Active Galactic Nuclei: a brief historical overview

Fath E.A., 1909

UNIVERSITY OF CALIFORNIA PUBLICATIONS

ASTRONOMY

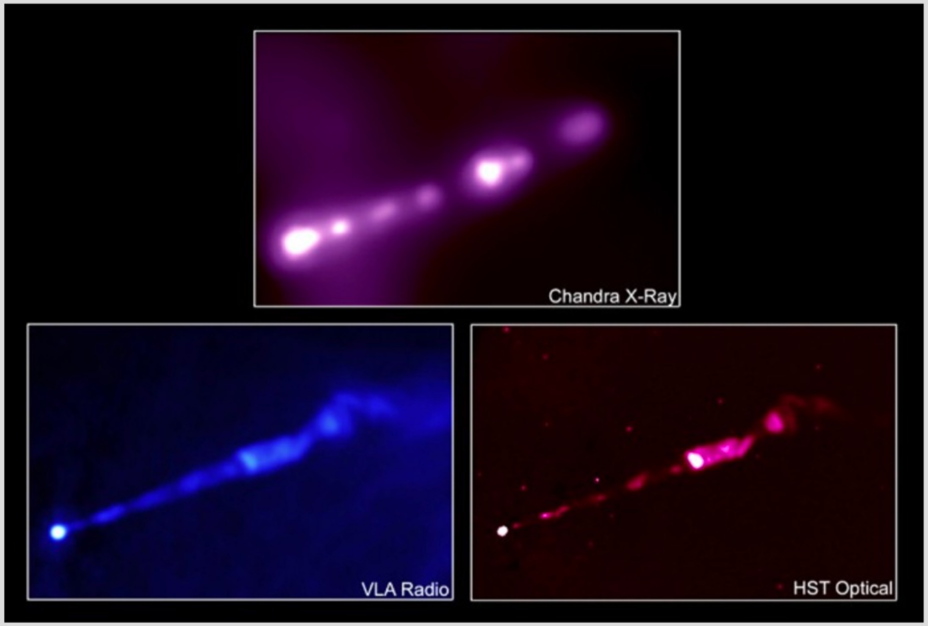
LICK OBSERVATORY BULLETIN

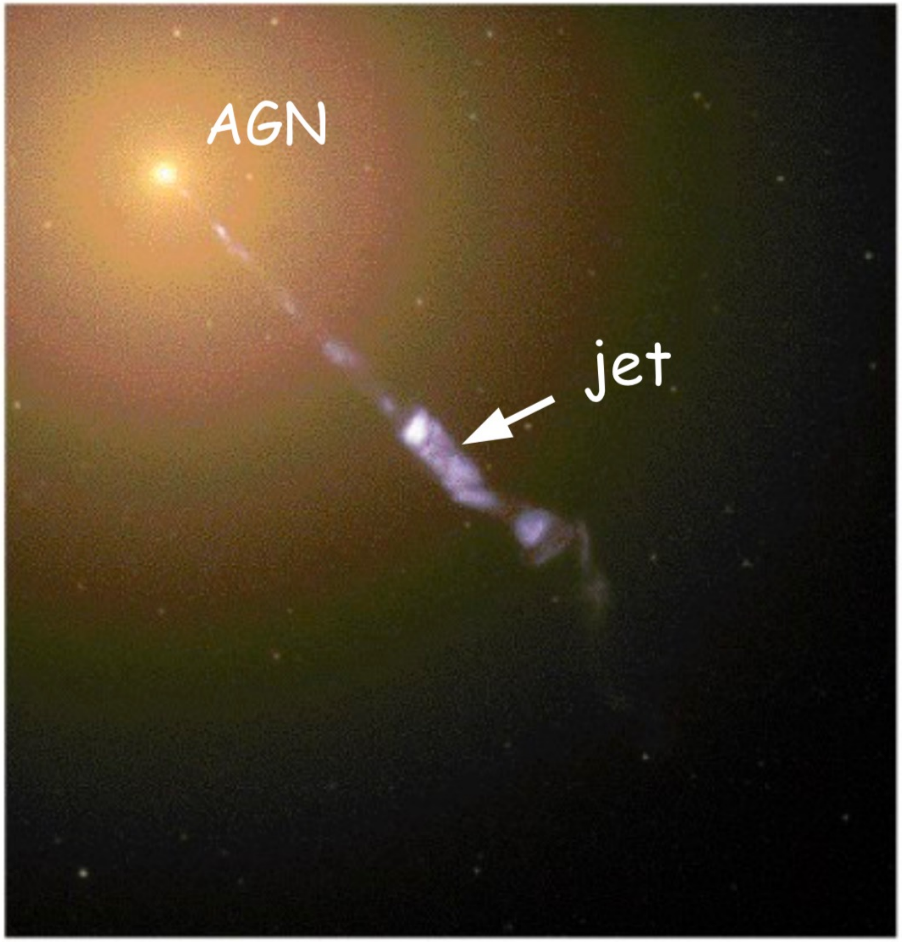
NUMBER 149

THE SPECTRA OF SOME SPIRAL NEBULAE AND GLOBULAR STAR CLUSTERS.*

Fath & Slipher detected strong emission lines similar to those of Pne, with witdth of several hundred km/s, in NGC1068

1913 – Detection of an optical jet in M87 by Curtis





PART I

DESCRIPTIONS OF 762 NEBULAE AND CLUSTERS PHOTOGRAPHED WITH THE CROSSLEY REFLECTOR

BY HEBER DOUST CURTIS

ASTRONOMER IN THE LICK OBSERVATORY

4486	12 25.8	+12 57	Exceedingly bright; the sharp nucleus shows well in 5^m exposure. The brighter central portion is about 0.'5 in diameter, and the total diameter about 2′; nearly round. No spiral structure is discernible. A curious straight ray lies in a gap in the nebulosity in p.a. 20°, apparently connected with the nucleus by a thin line of matter. The ray is brightest at its inner end, which is 11″ from the nucleus. 20 s.n.

M87, Curtis 1918

EXTRA-GALACTIC NEBULAE[1]

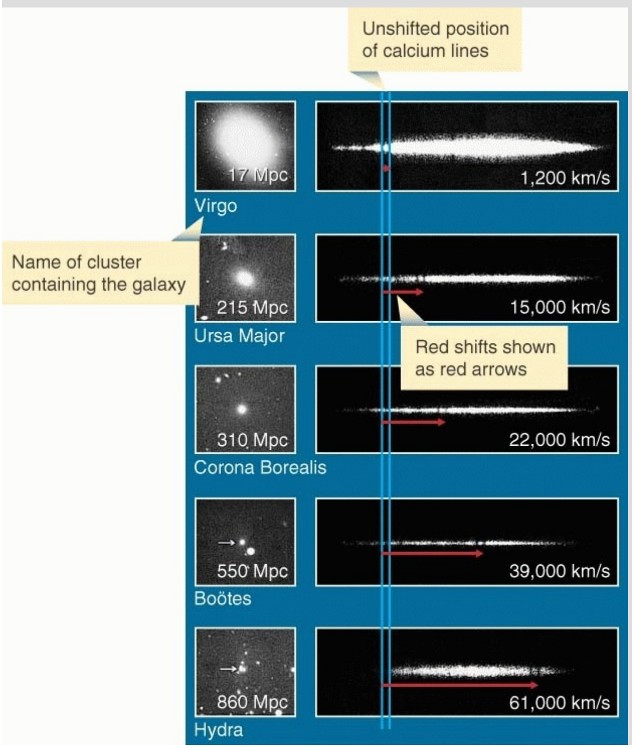
By EDWIN HUBBLE

ABSTRACT

This contribution gives the results of a statistical investigation of 400 extra-galactic nebulae for which Holetschek has determined total visual magnitudes. The list is complete for the brighter nebulae in the northern sky and is representative to 12.5 mag. or fainter.

The classification employed is based on the forms of the photographic images. About 3 per cent are irregular, but the remaining nebulae fall into a sequence of type forms characterized by rotational symmetry about dominating nuclei. The sequence is composed of two sections, the elliptical nebulae and the spirals, which merge into each other.

Luminosity relations.—The distribution of magnitudes appears to be uniform throughout the sequence. For each type or stage in the sequence, the total magnitudes are related to the logarithms of the maximum diameters by the formula,



1926 – Hubble finds that "nebulae" are extragalactic (galaxies)

Chepeid Distances showed that Nebulae were well outside our Milky Way.

NUCLEAR EMISSION IN SPIRAL NEBULAE*

1943

CARL K. SEYFERT†

ABSTRACT

Spectrograms of dispersion 37–200 A/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from λ 3727 to λ 6731 found in planetaries like NGC 7027 appear in the spectra of the two brightest spirals observed, NGC 1068 and NGC 4151.

Apparent relative intensities of the emission lines in the six spirals were reduced to true relative intensities. Color temperatures of the continua of each spiral were determined for this purpose.

The observed relative intensities of the emission lines exhibit large variations from nebula to nebula. Profiles of the emission lines show that all the lines are broadened, presumably by Doppler motion, by amounts varying up to 8500 km/sec for the total width of the hydrogen lines in NGC 3516 and NGC 7469. The hydrogen lines in NGC 4151 have relatively narrow cores with wide wings, 7500 km/sec in total breadth. Similar wings are found for the Balmer lines in NGC 7469. The lines of the other ions show no evidence of wide wings. Some of the lines exhibit strong asymmetries, usually in the sense that the violet side of the line is stronger than the red.

In NGC 7469 the absorption K line of *Ca* II is shallow and 50 A wide, at least twice as wide as in normal spirals.

Absorption minima are found in six of the stronger emission lines in NGC 1068, in one line in NGC 4151, and one in NGC 7469. Evidence from measures of wave length and equivalent widths suggests that these absorption minima arise from the G-type spectra on which the emissions are superposed.

The maximum width of the Balmer emission lines seems to increase with the absolute magnitude of the nucleus and with the ratio of the light in the nucleus to the total light of the nebula. The emission lines in the brightest diffuse nebulae in other extragalactic objects do not appear to have wide emission lines similar to those found in the nuclei of emission spirals.

Class of spiral galaxies with high-excitation optical emission lines

1959

EMISSION NUCLEI IN GALAXIES

L. Woltjer*
Yerkes Observatory, University of Chicago
Received February 16, 1959

ABSTRACT

Some galaxies which show wide emission lines in the spectra of their nuclei are discussed. It is shown that, on statistical grounds, the nuclear emission must last for several times 10^8 years at least. The nuclei are extremely narrow, of the order of 100 parsecs, and, if a normal mass-to-light ratio applies, extremely massive. The width of the emission lines, which indicates velocities of a few thousand kilometers per second, is probably due to fast motions, circular or random, in the gravitational fields of the nuclei. The high star density in the nuclei may provide a source of excitation. In the nucleus of our own Galaxy the radio source Sagittarius gives evidence of strong magnetic fields and large amounts of relativistic particles. A mass of a few times 10^8 solar masses is needed to prevent disintegration of the source. The Andromeda Nebula has a nucleus with a somewhat smaller mass. The occurrence of dense nuclei may be a common characteristic of many galaxies.

Objects must have very large masses (M/L arguments)

Some calculations (and interpretation) based on Woltjer et al. (1959) observational results

- Size of the narrow-line emitting region (unresolved): <100 pc
- If gas is gravitationally bound:

~1000 km/s

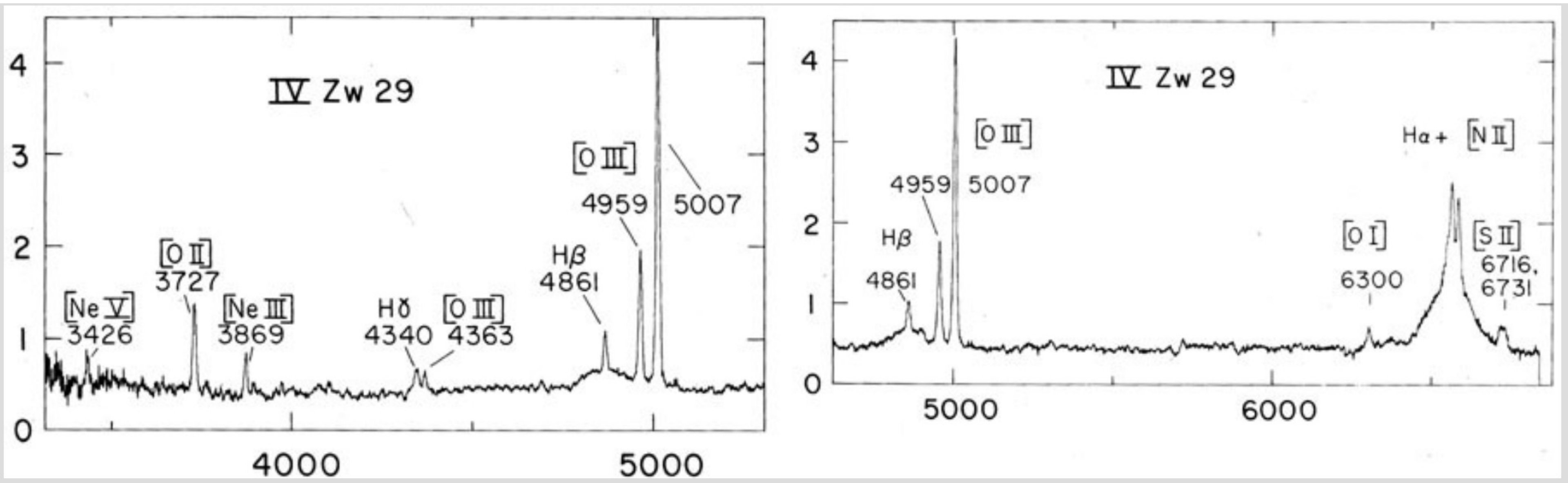
$$R = \frac{GM}{v^2} < 100pc \rightarrow M < \frac{Rv^2}{G} = \frac{3 \times 10^{20} (10^8)^2}{6.7 \times 10^{-8}} \sim 10^{10} M_\odot$$

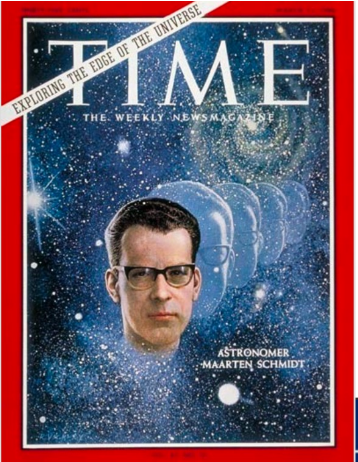
- The density of the clouds emitting narrow line is $<10^6$ cm^{-3}

$$L(H\beta) = \int dV d\Omega \; (n_e^2 \; \alpha_{H\beta}^{eff} \; \frac{h\nu}{4\pi}) \sim 5 \times 10^{-25} n_e^2 R^3 \; erg/s$$

- If L(Hβ)~10^{41} erg/s → **R>0.5 pc → M>10^8 M$_\odot$**

High-excitation and broad emission lines → nuclear mass should be very high if emission-line broadening is caused by bound material: $M \sim v^2 R/G$

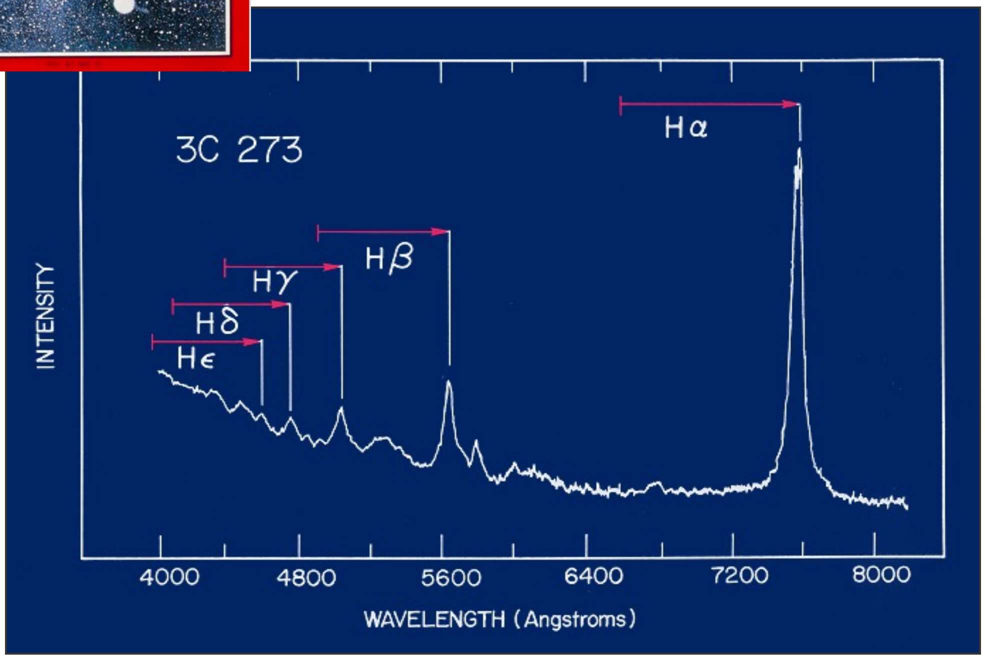


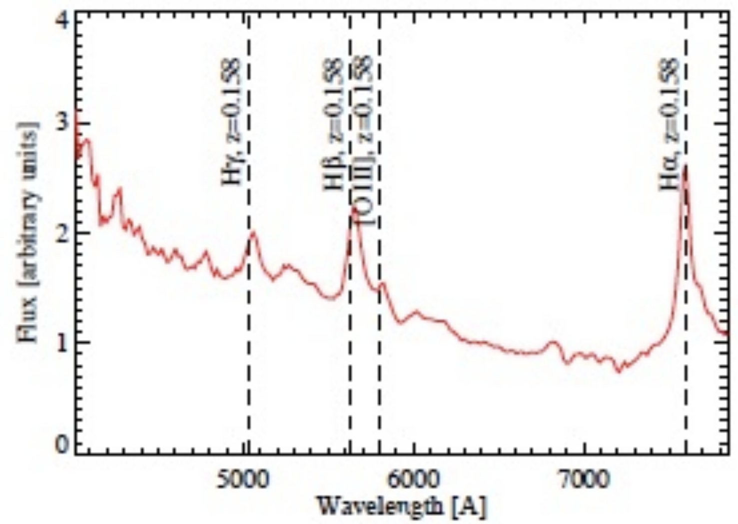


1955: radio emission from NGC1068 and NGC1275

First radio surveys and discovery of quasars

1963

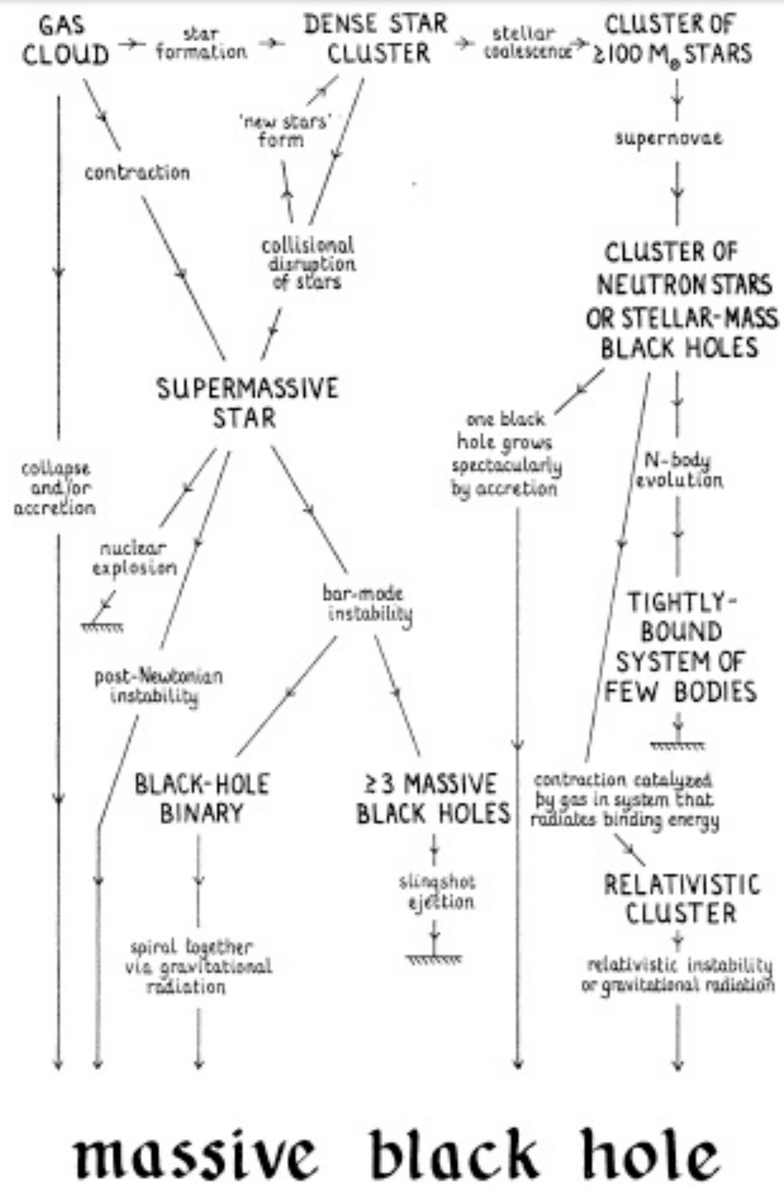




Schmidt et al. (1963; paper on *Nature*): 3C 273: z=0.158 (v_r = 47500 km/s)

→ This object is far away

How do massive black hole form?



Rees 1978, 1984
Lynden-Bell 1969

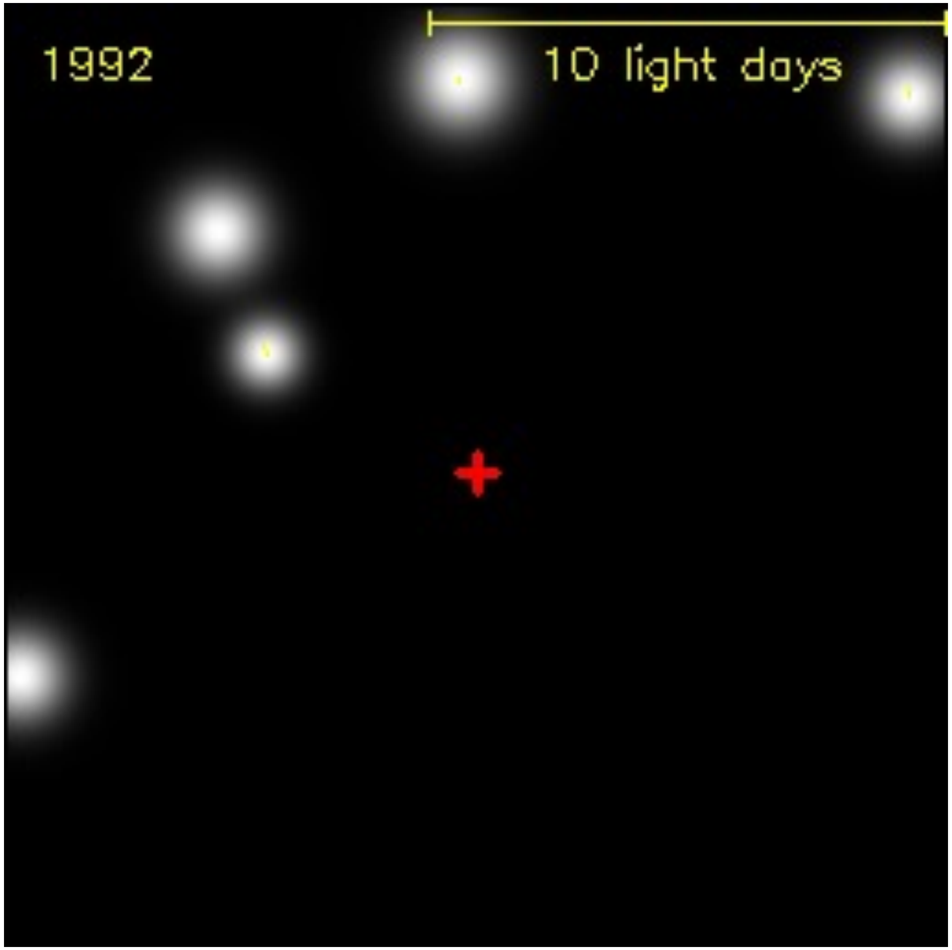
Energy output not explained by stellar processes ➔ accretion onto compact sources is the solution

Gravitational radiation is the solution

How can we infer the presence of a BH?

One way is via gravitational effects on nearby stars (but only for the Galactic Center, SgrA*).

Another way via its "hot" accretion disc and consequent high-energy emission



Variability

Almost all AGN were found to be variable, depending on the sampling and the intrinsic power of the AGN

Large-amplitude variations require that most of the source is involved in the process (i.e., the source is varying coherently)

The variability signal can propagate through a region with v~c → upper limit to the size of the source (light days in case of quasars)

The super-massive black hole paradigm

A super-massive black hole (SMBH) is present in most galaxies

• BH mass vs. galaxy bulge luminosity/velocity dispersion have confirmed this paradigm over the last 20 years (Magorrian relation; e.g., Gebhardt et al. 2000)

• The width of the broad emission lines reflects the presence of a deep potential

• Galaxy mergers/encounters may drive matter to the inner regions, thus providing the fuel for the SMBH, but "secular" (smooth) evolution is likely fundamental for most active galaxies

The Soltan argument in a nutshell

complete treatment later in the course

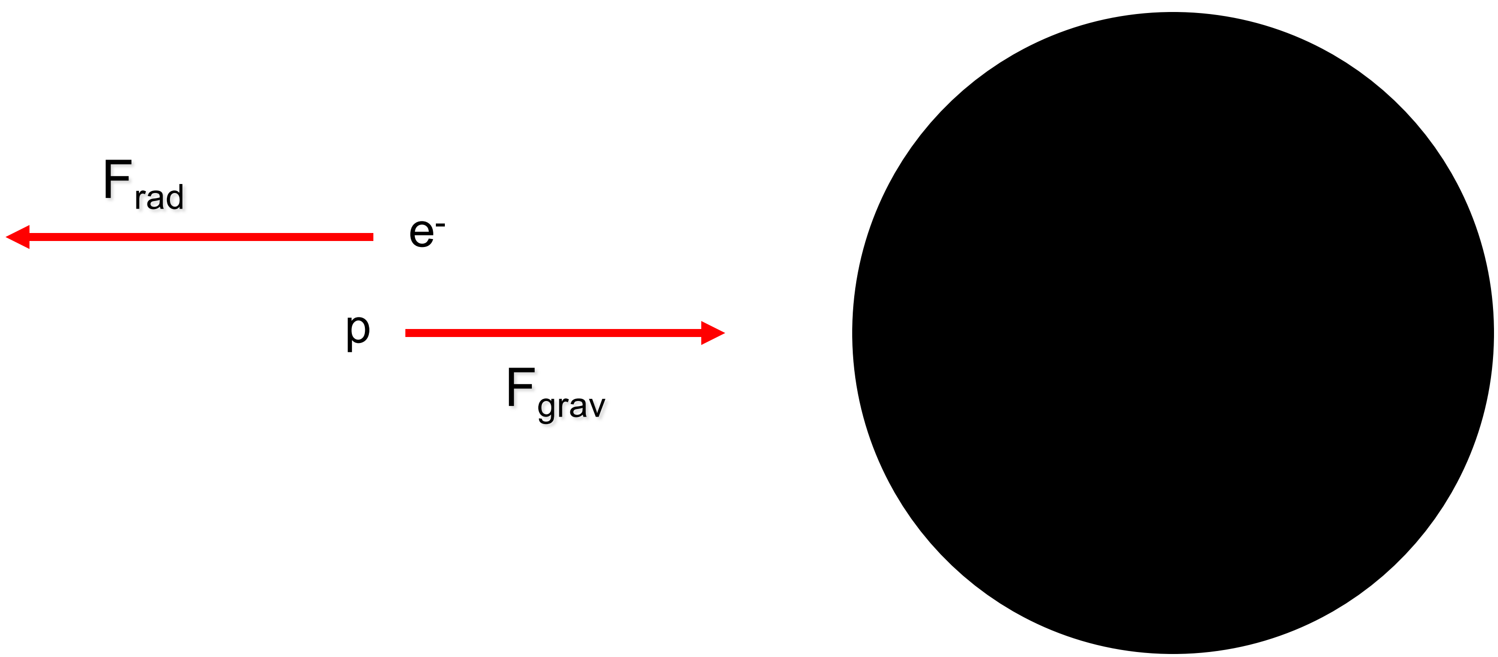
- It deals with the BH mass density in the Universe derived by considering the radiation emitted by all AGN across cosmic times (the mass in black holes today is simply related to the AGN population integrated over luminosity and redshift, i.e., the AGN luminosity function)
- Integrated AGN luminosities give $L = \eta \dot{M} c^2$ (terms described in the following slides)
- Lower limit to the overall L due to accretion processes in the history of the Universe, since we cannot observe the faintest AGN
- → Lower limit to density of all mass accreted by AGN
- → lower limit to BH mass M per galaxy
- → Big galaxies must have $M_{BH} > 10^8 M_\odot$
- Need to grow masses

A super-massive black hole (SMBH) is present in most galaxies

Some pills on accretion onto BHs
(in-depth discussion later in the course)

How luminous can an accreting BH be? Eddington luminosity and related quantities

ASSUMPTION: spherically symmetric steady-state radial infall of ionized H



$$P_{\mathrm{rad}} = \frac{F_{\mathrm{rad}}}{\mathrm{c}} = \frac{L}{4\pi R^2 c}$$

Outward momentum flux = radiation pressure

$$F_{\mathrm{rad}} = \frac{L\sigma_T}{4\pi R^2 c}$$

Outward radiation force on a single electron
(σ_T=Thomson cross section)

$$F_{\mathrm{grav}} = \frac{G(m_p + m_e)M}{\mathrm{R}^2} \approx \frac{G m_p M}{R^2}$$

Gravitational energy acting on a proton

Eddington luminosity (limit)
max luminosity allowed under the defined assumptions

$$F_{\mathrm{rad}} \le F_{\mathrm{grav}} \rightarrow \frac{L\sigma_T}{4\pi R^2 c} \le \frac{GMm_p}{R^2} \rightarrow L \le \frac{4\pi G c m_p}{\sigma_T} M$$

$$\rightarrow L_{\mathrm{Edd}} = 1.26 \times 10^{38} \left(\frac{M}{M_{\mathrm{sun}}}\right) \mathrm{erg/s}$$

there are cases where this luminosity is likely exceeded (e.g., note the input conditions – e.g., spherical accretion vs. disc accretion, discussed later in the course)

Gravitational radius

$$R_g = \frac{GM}{c^2} = 6.7 \times 10^{-8} \; \frac{2 \times 10^{33}}{9 \times 10^{20}} \; (\frac{M}{M_\odot}) = 1.5 \times 10^5 (\frac{M}{M_\odot})$$ [cm]

$$R_g = 1.5 \times 10^{13} \;\; M_8$$ [cm]

$M_8 = M_{BH}$ in units of 10^8 $M_\odot$

[cgs system]
$m_p = 1.7 \times 10^{-24}$ g
$M_\odot = 2 \times 10^{33}$ g
$\sigma_T = 6.65 \times 10^{-25}$ cm^2
$G = 6.67 \times 10^{-8}$ cm^3/g/s^2

The gravitational radius = ½ × Schwarzschild radius, is the radius below which the gravitational attraction between the particles of a body must cause it to undergo irreversible gravitational collapse ($mv^2 \sim GMm/R$, where $v=c$)

Gravitation radius as a sort of “boundary” for the accretion (Schwarzschild vs. Kerr BH solutions discussed later)

Eddington accretion luminosity and accretion rate

Accretion luminosity: luminosity released by gravitational energy due to gas falling onto a star/compact object with mass M and radius R

$$L = \frac{GM\dot{M}}{R} = \eta \dot{M} c^2$$

η=**efficiency** of the conversion of gravitational energy into radiation (**ε** is also often used with the same meaning)

[cgs system]
$m_p=1.7\times10^{-24}$ g
$M_\odot=2\times10^{33}$ g
$\sigma_T=6.65\times10^{-25}$ cm^2
$G=6.67\times10^{-8}$ cm^3/g/s^2
1 yr =3.1536×10^{7} s

$$L_{Edd} = \frac{4\pi G c m_p M}{\sigma_T} = \frac{GM\dot{M}_{Edd}}{R} \rightarrow \dot{M}_{Edd} = \frac{4\pi c m_p}{\sigma_T} R$$

$$\dot{M}_{Edd} \sim \frac{4\pi c m_p}{\sigma_T} R = \frac{4\pi c m_p}{\sigma_T} \left(\frac{R}{R_g}\right) R_g = \frac{4\pi c m_p}{\sigma_T} \left(\frac{R}{R_g}\right) (1.5\times10^{13}\ M_8)$$

$$\dot{M}_{Edd} \sim 0.2 \left(\frac{R}{R_g}\right) M_8\ M_\odot/yr$$

The Eddington accretion rate for a BH of 10^8 $M_\odot$ is of the order of a solar mass/yr (after converting g/s into $M_\odot$/yr). Consider that the efficiency is not considered here

Eddington accretion rate in a SMBH

$$L_{Edd} = \eta \dot{M} c^2 = 1.3 \times 10^{38} \left(\frac{M}{M_\odot}\right) [erg/s]$$

$$\eta_{0.1} = \frac{\eta}{0.1}$$

$$M_8 = \frac{M}{10^8 M_\odot}$$

$$[erg] = \left[\frac{g\ cm^2}{s^2}\right]$$

$$\frac{g}{s} = \frac{M_\odot}{2\times 10^{33}} \times \frac{365\times 24\times 3600}{yr} = 1.58 \times 10^{-26} \left[\frac{M_\odot}{yr}\right]$$

$$\dot{M}_{Edd} = \frac{L_{Edd}}{\eta c^2} = \frac{1.3\times 10^{38}(M/M_\odot)}{0.1\times \eta_{0.1}\times 9\times 10^{20}} \left[\frac{erg/s}{cm^2/s^2}\right] =$$

$$= \frac{1.44\times 10^{18}}{\eta_{0.1}} \left(\frac{M}{M_\odot}\right) [g/s] =$$

$$= \frac{1.44\times 10^{18}}{\eta_{0.1}} \times 1.58 \times 10^{-26} \left(\frac{10^8 M_\odot M_8}{M_\odot}\right) \left[\frac{M_\odot}{yr}\right] =$$

$$= \frac{2.2\times 10^{-8}}{\eta_{0.1}} \times 10^8 M_8 \left[\frac{M_\odot}{yr}\right] = \frac{2.2}{\eta_{0.1}} M_8 \left[\frac{M_\odot}{yr}\right]$$

$$\rightarrow \dot{M}_{Edd} = \frac{2.2}{\eta_{0.1}} M_8\ [M_\odot/yr]$$

M_8= M in units of $10^8\ M_\odot$
$\eta_{0.1}=\eta/0.1$

The case of accretion onto a NS: calculations for R=10 km

$$L_{\rm Edd} = \frac{4\pi G c m_p M}{\sigma_{\rm T}} = \frac{GM\dot{M}_{\rm Edd}}{\rm R} \rightarrow \dot{M}_{\rm Edd} = \frac{4\pi c m_p}{\sigma_{\rm T}} R$$

$$\rightarrow \dot{M}_{\rm Edd} \approx 1.5 \times 10^{-8} \left(\frac{R}{10\ \rm km}\right) M_{\rm sun}/{\rm yr}$$

for X-ray binaries
(with a NS at the center)

$$\dot{M}_{\rm Edd} = \frac{4\pi c m_p}{\sigma_{\rm T}} R = \frac{12.56\ 3\ 10^{10}\,({\rm cm/s})\ 1.7\ 10^{-24}\,({\rm g})}{6.65\ 10^{-25}\,({\rm cm}^2)} R =$$

$$= 9.63\ 10^{11}\ {\rm R\ (g/cm\ s)} = 9.63\ 10^{11} \left(\frac{R}{10\ \rm km}\right) 10^{6}\,({\rm cm}) \frac{3600 \times 24 \times 365\ ({\rm s})}{2\ 10^{33}\ ({\rm g})}\ [M_{\rm sun}/{\rm yr}] =$$

$$= \dot{M}_{\rm Edd} \approx 1.5 \times 10^{-8} \left(\frac{R}{10\ \rm km}\right) [M_{\rm sun}/{\rm yr}]$$

Similarities in the accretion processes between X-ray binaries (either with a neutron star at the center, i.e., with a "surface", or with a BH → compact object in any case) and SMBHs

Powering the AGN: disc vs. Bondy-Hoyle accretion

see Prof. L. Ciotti lessons on Bondi accretion

$$\dot{M} = \pi\, r_{acc}^2 v \rho$$

v, ρ: wind velocity and density if accretion is spherical and from a uniform ambient wind

$$r_{acc} = \frac{2GM}{v^2}$$

The effective accretion (capture) radius is linked to the escape velocity at a distance r from the BH

$$\dot{M} \approx \frac{4\pi\rho G^2 M_{BH}^2}{v^3}$$

actually

$$\dot{m}_{accr} = \alpha \frac{4\pi G^2 m_{BH}^2 \rho}{\left(c_s^2 + v^2\right)^{3/2}},$$

c_s: sound speed of the local medium; v: BH velocity relative to the local medium; α: adimensional parameter from simulations (≈100−300)

$$\dot{M} \approx 5\times 10^{-9} \left(\frac{M_{BH}}{10^8\ M_{sun}}\right)^2 M_{sun}/yr$$

vs.

$$\dot{M}_{Edd} \approx 2.2 \left(\frac{M_{BH}}{10^8\ M_{sun}}\right) / \eta_{0.1}\ M_{sun}/yr$$

→ **accretion via a disc is more efficient**

Eddington time for accretion

Eddington time: time taken by a body to radiate its entire mass at the Eddington rate

$$\dot{M}_{\rm Edd} = \frac{M}{t_{\rm Edd}} \rightarrow t_{\rm Edd} = \frac{M}{\dot{M}_{\rm Edd}} = \frac{M}{2.2 M_8/\eta_{0.1}} = \frac{10^8}{2.2}\eta_{0.1} = 4.5\times10^7 \eta_{0.1}\ \rm{yr}$$

Often the Eddington time is reported *without* the efficiency term η

$$t_{Edd} = \frac{\sigma_T\ c}{4\pi\ G\ m_P} \sim 0.45\ Gyr$$

$$M_8 = \frac{M}{10^8 M_\odot}$$

$$\dot{M}_{Edd} = 2.2\frac{M_8}{\eta_{0.1}}[M_\odot/yr]$$

$$t_{Edd} = \frac{M}{\dot{M}_{Edd}} = \frac{M}{2.2\frac{M_8}{\eta_{0.1}}[M_\odot/yr]} = \frac{M}{2.2\frac{M}{10^8 M_\odot \eta_{0.1}}[M_\odot/yr]} = \frac{10^8}{2.2}\eta_{0.1}[yr]$$

Characteristic timescales for BH growth

e-folding timescales typically associated to black hole growth

Eddington time

$$t_{Edd} = \frac{\eta \sigma_T c}{4\pi G m_P} \sim 4.5 \times 10^7 \eta_{0.1}\ yr$$

Salpeter time

$$\tau_{Salp} = \frac{\eta M_\bullet c^2}{L_{Edd}} = \frac{\eta M_\bullet c^2}{\frac{4\pi\ G\ c\ m_P M_\bullet}{\sigma_T}} = \frac{\eta \sigma_T c}{4\pi G m_P} \sim 4.5 \times 10^7 \eta_{0.1}\ yr$$

BH growth: mass increase over time. I

$$L_{acc} = \eta \dot{M}_{acc} c^2 \rightarrow \dot{M}_{acc} = L_{acc}/\eta c^2$$

$$\dot{M}_\bullet = (1-\eta)\dot{M}_{acc} = \frac{1-\eta}{\eta} L_{acc}/c^2$$

Accretion onto the BH
('what is not radiated is accreted', i.e. matter is the fuel for BH mass growth and emission)

$$\lambda_{Edd} = \frac{L_{acc}}{L_{Edd}} \rightarrow L_{acc} = \lambda_{Edd}\ L_{Edd}$$

Eddington ratio=L_{bol}/L_{Edd}

$$\frac{dM_\bullet}{dt} = \frac{1-\eta}{\eta} \frac{\lambda_{Edd} L_{Edd}}{c^2} = \frac{1-\eta}{\eta} \lambda_{Edd} \frac{4\pi G c m_P M_\bullet}{\sigma_T c^2}$$

$$\frac{dM_\bullet}{dt} = (1-\eta)\ \lambda_{Edd}\ \frac{M_\bullet}{\tau_{Salp}}$$

$$\int_{M_\bullet(t_0)}^{M_\bullet(t)} \frac{dM'_\bullet}{M'_\bullet} = \int_{t_0}^{t} (1-\eta)\ \lambda_{Edd}\ \frac{1}{\tau_{Salp}}$$

$$\Rightarrow\ M_\bullet(t) = M_\bullet(0)\ e^{(1-\eta)\ \lambda_{Edd} \frac{t}{\tau_{Salp}}}$$

How the BH mass evolves over time due to accretion

Accretion of matter is onto the BH is responsible for energy production (hence, radiation) and BH growth

assuming t_0=0

BH growth: mass increase over time. II

$$M_{BH}(t) = M_{BH_{seed}} \; exp\left((1-\eta) \; \lambda_{Edd} \frac{t}{\tau_{Salp}} \right)$$

M_0=$M_\bullet$(0) is often referred to as the mass of the **BH seed** (see lesson on the high-redshift AGN and the topic concerning the nature of their progenitors)

Often you may find the Salpeter time (Eddington time) without the efficiency value η=0.1. In such cases the previous formula becomes

$$M_\bullet(t) = M_\bullet(0) \; exp\left(\frac{1-\eta}{\eta} \; \lambda_{Edd} \frac{t}{\tau_{Salp}} \right)$$

$$M_\bullet(t) = M_\bullet(0) \; exp\left(\frac{1-\eta}{\eta} \; \lambda_{Edd} \frac{t}{t_{Edd}} \right)$$

In some cases λ_{Edd} may be implicitly assumed equal to 1 (BH radiating at the Eddington limit)

The central engine – few introductory steps

As described later in the lesson on accretion discs, the mass-energy conversion in small volumes on compact objects is highly efficient to produce energy: the gas in the disc loses angular momentum through viscosity and can fall onto the SMBH

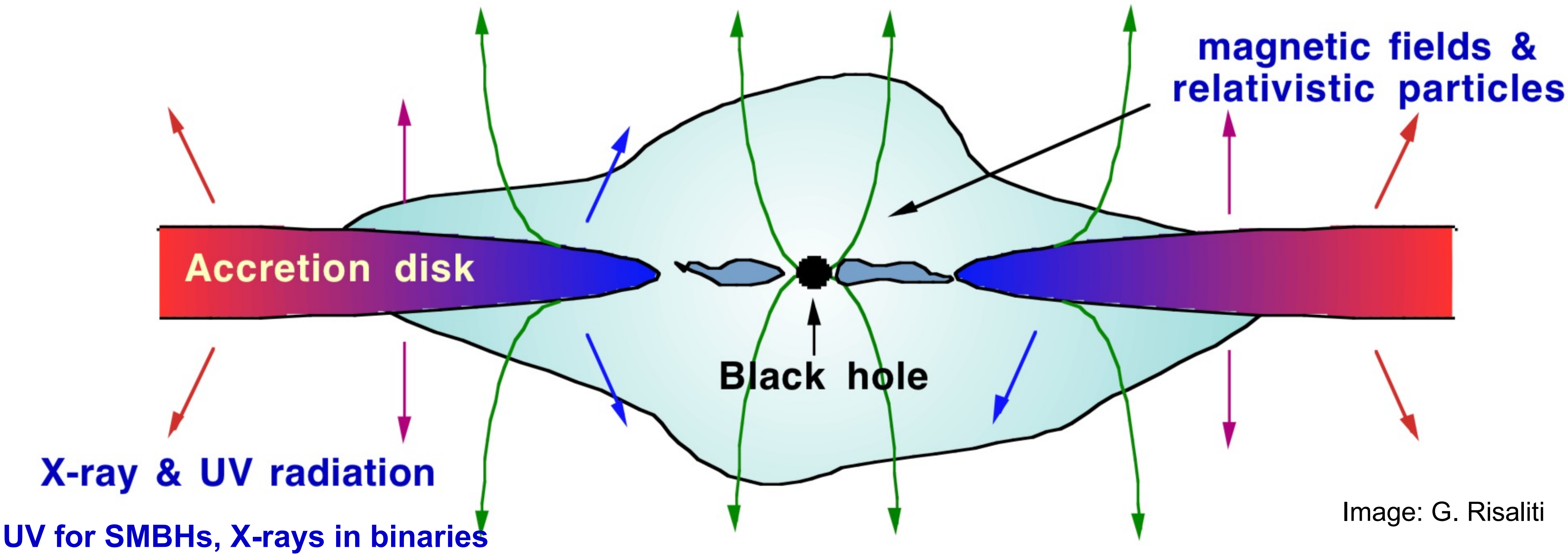
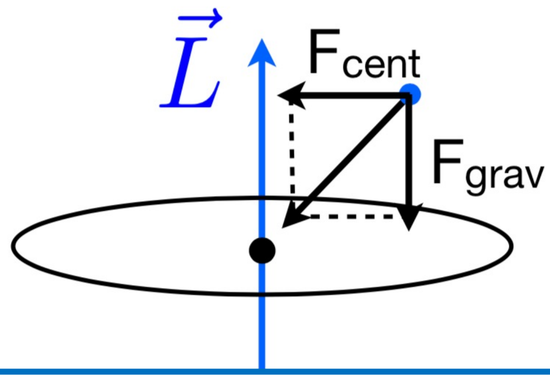


Image: G. Risaliti

Potential gravitational energy → kinetic energy of the infalling gas → heat (through viscosity among disc annuli) → thermal emission from the disc

The accretion disc. I

- The disc due to gas in accretion has a circular motion, with the rotation axis parallel to the angular momentum of the accreting gas
- Each gas element interacts with the surrounding elements, thus redistributing the energy and placing at the minimum state of energy corresponding to the circular orbit



$E_{heat}=E_{th}=$ 1/2 ΔE

ΔE=release of energy: half of this goes into heat (thermal energy)

$$dE_{th} = -\frac{1}{2}\,\frac{GMdm}{r+dr} - \left(-\frac{1}{2}\frac{GMdm}{r}\right)$$

Variation of the thermal energy of the mass element *dm* in going from the orbit *r+dr* to *r* = half of the potential energy (Virial theorem)

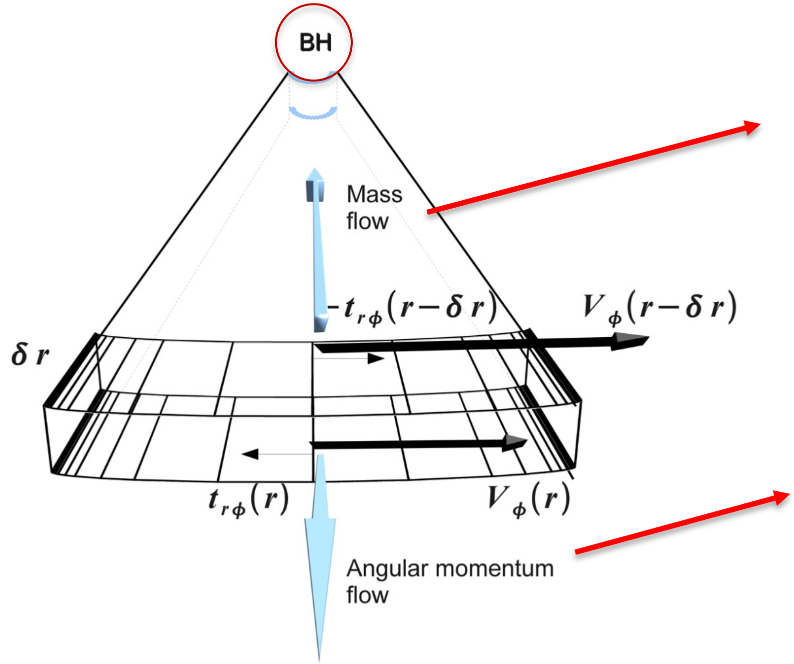
$$dE_{th} = -\frac{1}{2}GMdm\left(\frac{1}{r+dr} - \frac{1}{r}\right) = \frac{1}{2}GMdm\left(\frac{dr}{r(r+dr)}\right)$$

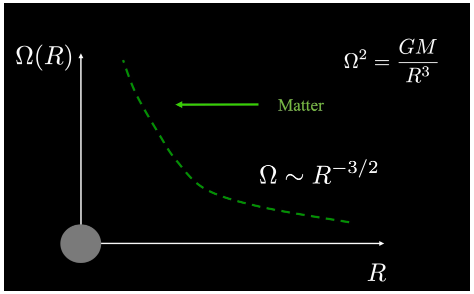
$$dL = \frac{dE_{th}}{dt} = \frac{1}{2}GM\dot{M}\frac{dr}{r^2}$$

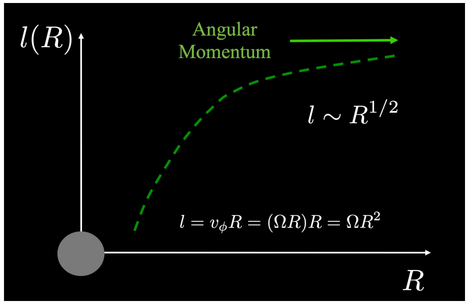
Half of the potential gravitational energy goes into kinetic energy (rotational energy) and half in heating the disc

Basic principles (further discussed in the standard accretion disc lesson)

- The gas has angular momentum, which should be brought in the outer part of the disc to allow gas accretion (i.e., gas moving to the inner parts of the disc)
- Through friction with other gas particles and by the resulting momentum transfer, the gas will assemble in a disc oriented perpendicular to the direction of the angular momentum vector
- The disc will locally rotate with approximately the Keplerian velocity (differential rotation: the angular velocity depends on radius) → heating of the disc by dynamical friction
- Conversion of potential energy into kinetic energy and internal (heat) energy (blackbody emission)







A little degression: the virial theorem. I

In its simplest form, the virial theorem says that, for an isolated dynamical system in a stationary state of equilibrium, the kinetic energy is half of the potential energy

$$2E_{kin} + E_{pot} = 0 \rightarrow E_{kin} = -\frac{1}{2}E_{pot}$$

$$2\,T + U = 0$$

$$E_{tot} = E_{kin} + E_{pot} = -\frac{1}{2}U + U = \frac{1}{2}U = -E_{kin}$$

A little degression: the virial theorem. II

Derivation in the case of stellar structure (basic principles + *hydrostatic equilibrium*: the inward pull of gravity is balanced by the upward force due to the gradient of the gas pressure)

$$\frac{dP}{dr} = \frac{-G\ M(r)\ \rho(r)}{r^2}$$

$$V(r)dr = \frac{4}{3}\pi r^3 dr \rightarrow V(r)dP = -\frac{1}{3}\frac{GM(r)}{r}[4\pi r^2 \rho dr] = -\frac{1}{3}\frac{GM(r)}{r}dM$$

mass of a shell of matter dM

E_{pot} of the shell dM at radius r

$$\int_{star} V(r)dP = -\frac{1}{3}\int_{star}\frac{GM(r)}{r}dM = \frac{U}{3}$$

E_{pot} of the all shells divided by 3

integration over the volume of the star

Detailed treatment in H. Bradt, *Astrophysical Processes*

A little degression: the virial theorem. III

$$d(PV) = PdV + VdP \rightarrow (PV)|_0^R = \int_{star} PdV + \int_{star} VdP$$

Integrate over the volume
of the star (R=radius of the star)

Left term of eq. =0 because:

$$V \rightarrow 0 \; at \; r = 0$$

$$P \rightarrow 0 \; at \; r = R$$

$$-3 \int_{star} PdV = U$$

$$P = \frac{2}{3} n \left(\frac{1}{2} m v^2\right)_{av} = \frac{2}{3} u_k$$

For a **perfect nonrelativistic gas**
u_k=kinetic energy density [J/m^3]

$$\int_{star} PdV = \int_{star} \frac{2}{3} u_k dV = \frac{2}{3} T$$

T=kineric energy

A little degression: the virial theorem. IV

$$-3\ \frac{2}{3}T = U \rightarrow -2T = U \rightarrow 2T + U = 0$$

In the case of a stable collection of particles (galaxies…)

$$2\sum_i \frac{1}{2}m_i v_i^2 - \sum_{pairs} \frac{Gm_i m_j}{r_{ij}} = 0$$

The accretion disc. II

$$L = \int_{R_{out}}^{R_{in}} dL = \frac{1}{2} G M \dot{M} [\frac{1}{r}]_{R_{out}}^{R_{in}} = \frac{1}{2} G M \dot{M} (\frac{1}{R_{in}} - \frac{1}{R_{out}}) \sim \frac{1}{2} \frac{G M \dot{M}}{R_{in}}$$

$$L = \frac{1}{2} \frac{G M \dot{M}}{R_{in}}$$

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

$$\eta = \frac{G M}{2 c^2 R_{in}}$$

Efficiency conversion factor
matter → energy

Schwarzschild BH: R_{in}=6 GM/c^2: $\eta = \frac{1}{12} \sim 0.08$ vs. ~0.007 for nuclear processes

↓

Radius of the **Innermost Circular stable orbit (ISCO)**, depending of BH kind (Schwarzschild vs. Kerr, i.e., static vs. maximally rotating disc, discussed later in the course)

Black holes: basics

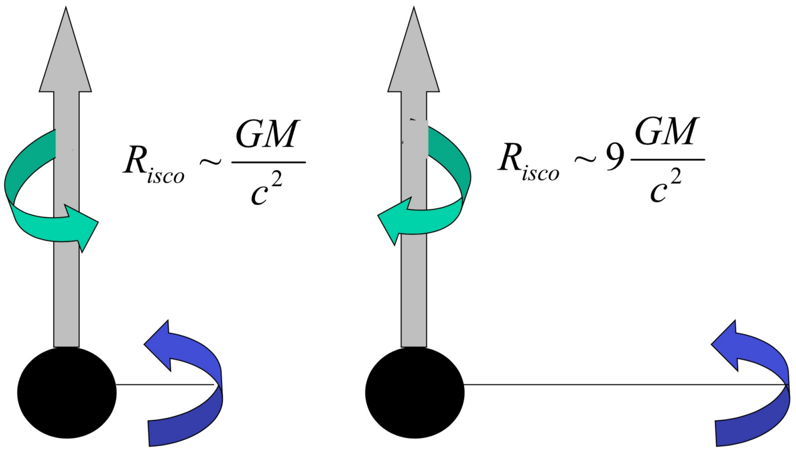
- ISCO depends on spin angular momentum $J = G\, M_{BH}\, a/c$ (a=dimensionless angular momentum)

- BHs are characterized completely by mass M_{BH} and spin parameter *a*, where a=[-1,1]

- a<0 means that the spin is in opposite sense wrt. the angular momentum of a test particle orbit (the orbit is prograde)

$$R_{ISCO} = z\frac{GM}{c^2}$$

$$\eta = 1 - [1 - \frac{2}{3z}]^{1/2}$$



Link between ISCO and radiative efficiency

	a	$z=r_{isco}/r_g$	η
maximal retrograde	-1.0	9.0	0.038
Non-rotating (Schwarzschild) BH	0	6.0	0.057
	0.1	5.67	0.061
	0.5	4.23	0.082
	0.9	2.32	0.156
Rapidly-rotating (Kerr) BH	0.998	1.24	0.321
maximal prograde	1.0	1.00	0.423

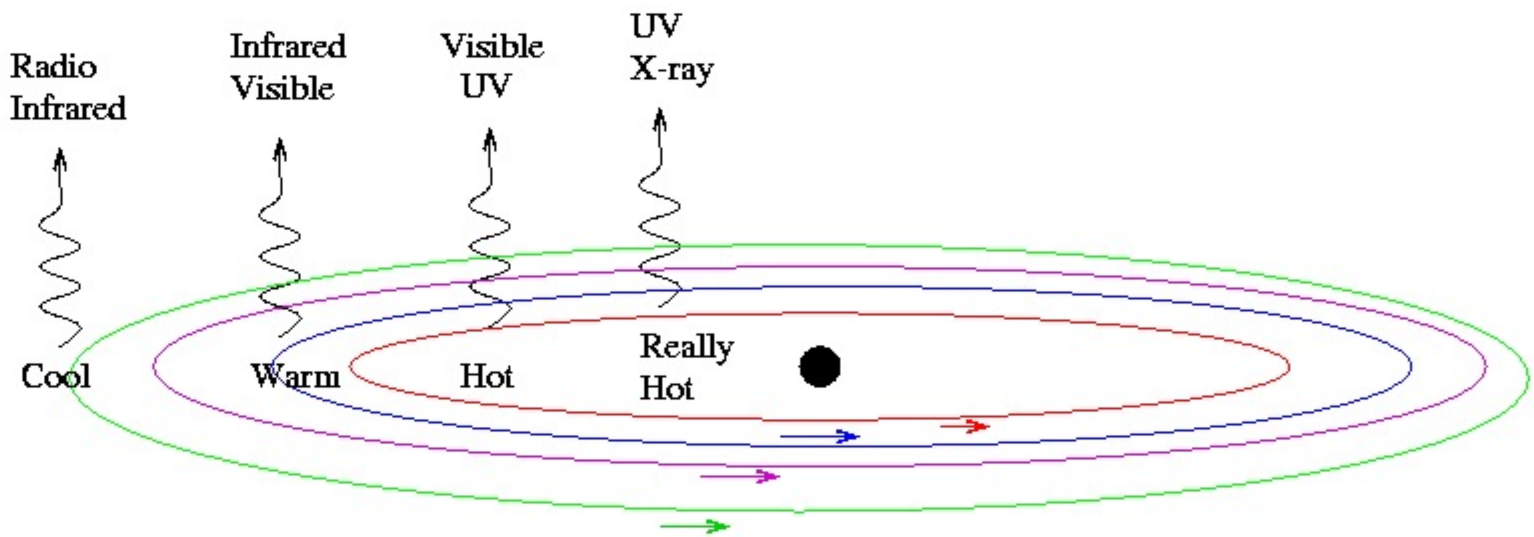
high η means less mass available for M_{BH} growth

η=radiative efficiency
J=angular momentum=IΩ, where Ω=angular velocity
J/M=specific angular momentum
j=a/M=dimensionless angular momentum per unit mass
a=dimensionless angular momentum (sign=direction of rotation)

"SPIN" of the BH

$$j = Jc / GM^2_{BH} = a / M_{BH} \rightarrow a = Jc / GM_{BH} = J / M_{BH} r_g c$$

"Stratified" emission in the accretion disc

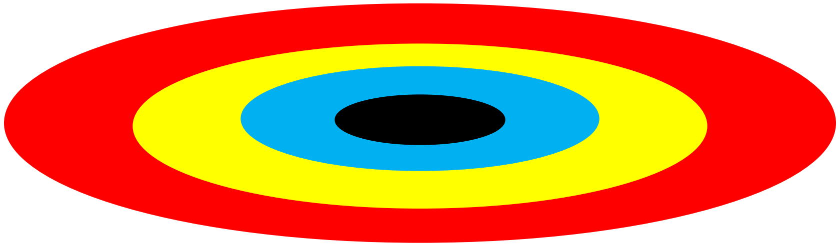


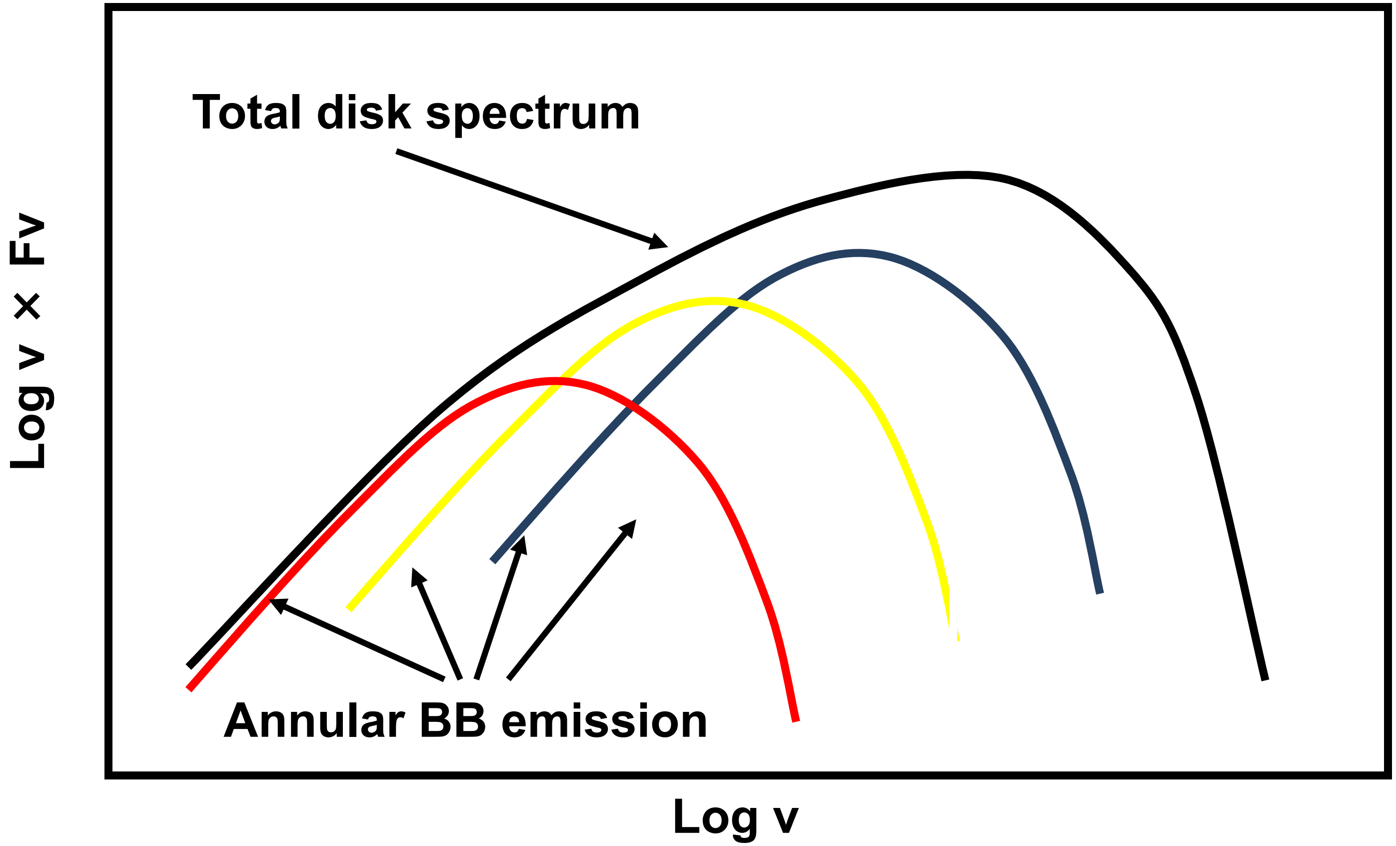
- Friction between adjacent layers which converts gravitational potential energy of the accreting matter into radiation
- Gas in differential rotation, **viscosity transports angular momentum outward, while matter is driven inward**
- Multi-color blackbody (MCD) emission=BB from layer at different temperatures

Multi-color blackbody

M_{BH}=10 $M_{\odot}$: 1 keV, 10^7 K
M_{BH}=10^8 $M_{\odot}$: 10 eV, 10^5 K

Why?





Temperature T(r) in the AD and its dependences.I

$$L = \frac{1}{2}\frac{GM\dot{M}}{R}$$

Half of the E_{grav} is radiated

$$L = 2\pi R^2 \sigma_{SB} T^4$$

πR^2=area of the disc (× 2: both surfaces)
$\sigma_{SB} T^4$: flux passing through the surface

Stefan-Boltzmann law

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

Proper treatment

$$R_{in} \approx R_S = 2GM/c^2$$

$$R >> R_{in} \rightarrow 1-(R_{in}/R)^{1/2} \approx 1$$

$$R^{-3/4} = (R/R_S)^{-3/4} \times (2GM/c^2)^{-3/4}$$

$$T(R) = \left(\frac{3c^6}{64\pi\sigma_{SB}G^2}\right)^{1/4} \mathrm{M}^{-1/2}\ \dot{M}^{1/4} \left(\frac{R}{R_S}\right)^{-3/4}$$

see also Done (2010, arXiv:1008:2287); Peterson (2008)

Temperature in the AD and its dependences.II

$$T=\left(\frac{3GM\dot{M}}{8\pi\sigma_{SB}}\right)^{1/4}\left(\frac{R}{R_S}\right)^{-3/4}\left(\frac{2GM}{c^2}\right)^{-3/4}=$$

$$=\left(\frac{3G}{8\pi\sigma_{SB}}\right)^{1/4}M^{1/4}\dot{M}^{1/4}\left(\frac{R}{R_S}\right)^{-3/4}\left(\frac{c^2}{2G}\right)^{3/4}M^{-3/4}=$$

$$=\left(\frac{3GG^{-3}c^6}{8\pi\sigma_{SB}2^3}\right)^{1/4}M^{-1/2}\dot{M}^{1/4}\left(\frac{R}{R_S}\right)^{-3/4}=$$

$$=\left(\frac{3G^2c^6}{8\pi\sigma_{SB}2^3}\right)^{1/4}M^{-1/2}\dot{M}^{1/4}\left(\frac{R}{R_S}\right)^{-3/4}=$$

$$=\left(\frac{3c^6}{64\pi\sigma_{SB}G^2}\right)^{1/4}M^{-1/2}\dot{M}^{1/4}\left(\frac{R}{R_S}\right)^{-3/4}$$

Temperature in the AD and its dependences.III

$$\dot{M}_{\rm Edd} = 2.2 M_8/\eta_{0.1} \quad [M_{\rm sun}/{\rm yr}]$$

+

$$T = {\rm cons} \times M^{-1/2}\, \dot{M}^{1/4} \left(\frac{R}{R_S}\right)^{-3/4}$$

$M^{-1/2}$ $\eta=0.1$ $M_{dot}^{1/4}=(M_{dot,Edd} \times M_{dot}/M_{dot,Edd})^{1/4}$

$$T(R) = {\rm cost} \times (10^8 M_8 M_{\rm sun})^{-1/2} (2.2 M_8)^{1/4} \left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\right)^{1/4} \left(\frac{R}{R_S}\right)^{-3/4}$$

$$T(R) \approx 2.1 \times 10^5\ M_8^{-1/4}\ (\dot{M}/\dot{M}_{\rm Edd})^{1/4}\ ({\rm R/R_S})^{-3/4}\ {\rm K}$$

$$\propto M^{-1/4}\ (\dot{M}/\dot{M}_{\rm Edd})^{1/4}$$

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

$T_{BB}(R) \propto M^{-1/4}$: thermal (disk) emission mostly emitting in UV for AGN (*big blue bump*), in soft X-rays in BHBs