Schwarzschild Radius

The radius where escape speed = the speed of light. 

\[ R_s = 2 \frac{GM}{c^2} \]

\[ R_s = 3 \times M \quad (R_s \text{ in km; } M \text{ in solar masses}) \]

A sphere of radius \( R_s \) around the black hole is called the **event horizon**.

<table>
<thead>
<tr>
<th>Object</th>
<th>Mass (solar)</th>
<th>Black Hole Event Horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star</td>
<td>10</td>
<td>30 km</td>
</tr>
<tr>
<td>Star</td>
<td>3</td>
<td>9 km</td>
</tr>
</tbody>
</table>
General Relativity: Orbits around BHs

**Schwarzschild BH:** an innermost stable orbit at $R_{ms} = 3R_s$

**KERR BH:** 1) presence of a static limit, inside of which one must co-rotate with the BH

2) The horizon moves further inward the faster the BH spins.

This implies $R_{ms}$ also move inward.

Efficiency: The amount of binding energy that is extracted from infalling matter goes up from $<0.06$ to $\sim 0.42 m(c^2)$
black holes – schwarzschild vs. kerr

Black Holes

Schwarzschild
\[ a = 0 \]

Kerr
\[ a = 1 \]
\[ F_{\text{rad}} < F_{\text{grav}} \]

\[
\sigma_T \frac{L}{4\pi r^2 c} < \frac{GM \cdot m_p}{r^2}
\]

\[
L < L_{\text{edd}} = \frac{4\pi c GM \cdot m_p}{\sigma_T} \approx 1.3 \times 10^{38} \left( \frac{M \cdot}{M_{\odot}} \right) \text{erg/s}
\]
If the disc radiates like a Blackbody

\[ L_E = T^4 4\pi r^2 \sigma_{\text{Stefan-Boltzmann}} \]

We assume as „r“ the last stable orbit around the black hole

\[ T = 2 \times 10^7 M^{-1/4} \text{K} \]

<table>
<thead>
<tr>
<th>Microquasar</th>
<th>AGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>M (solar masses)</td>
<td>T (K)</td>
</tr>
<tr>
<td>3</td>
<td>1.5 (10^7)</td>
</tr>
<tr>
<td>(10^9)</td>
<td>(10^5)</td>
</tr>
</tbody>
</table>
3.1 The Nature of the Compact Object

The most reliable method to determine the nature of the compact object is the study of the Doppler shift of absorption lines in the spectrum of its companion. The study of the changing radial velocity during the orbital motion is a technique that has been applied for more than one hundred years to measure the masses of stars in binary-systems. The same method is applied for systems like X-ray binaries, where one component is "invisible". In this case the variations of the radial velocity of the normal companion during its orbit are studied.

Figure 6: Amplitude of the radial velocity variations versus orbital phase (Filippenko et al. 1999: GRS 1009-45). Using the Doppler shift of spectral
Reverberation mapping from optical variability

- Broad emission line region: 0.01 - 1pc;
  Illuminated by the AGN's photoionizing continuum radiation and reprocess it into emission lines

\[ R_{BLR} \] estimated by the time delay that corresponds to the light travel time between the continuum source and the line-emitting gas: \[ R_{BLR} = c \Delta t \]
Reverberation mapping from optical variability

- Broad emission line region: 0.01 - 1pc; Illuminated by the AGN's photoionizing continuum radiation and reprocess it into emission lines
- $R_{BLR}$ estimated by the time delay that corresponds to the light travel time between the continuum source and the line-emitting gas: $R_{BLR} = c \Delta t$
- $V$ estimated by the FWHM of broad emission line
  
  \[ V = f \text{ FWHM}(H\beta), \quad f \sqrt{3/2} \text{ for random distribution of BLR clouds} \]

\[ M_\bullet \]
Central AGN Mass

Using $R_{\text{BLR}}$ the central mass is:

$$M = \frac{f R_{\text{BLR}} V^2}{G}$$

$V$ is the BLR clouds velocity (either from FWHM or $\sigma_{\text{LINE}}$)

$f$ is a dimensionless factor that depends on the geometry and kinematics of the BLR.
**Quiescent State:**
- Large transient radius;
- very low luminosity, \( L_x \sim 10^{30.5}\text{ to } 10^{33.5}\) erg/s;
- power law spectrum photon index \( \Gamma = 1.5\text{ to } 2.1 \);
- Jet is thought to be exist

**Hard State:**
- power law spectrum >80% (2-20keV)
- power law spectrum photon index \( \Gamma = 1.4\text{ to } 2.1 \)
- strong variability (QPO)
- strong radio emission (Jet exist)

**SPL/Very High State/Intermediate State:**
- power law spectrum photon index \( \Gamma > 2.4 \)
- power law component >20% (2-20keV) and QPO
- power law component >50% (2-20keV) and no QPO
- radio flare at HS \( \rightarrow \) VHS

**High Soft State (Thermal Dominant State):**
- disk component >75% (2-20keV)
- no QPO or QPO is too weak to be detected
- very weak radio emission and no Jet exist
- power law spectrum photon index \( \Gamma = 2.1\text{ to } 4.8 \)
Advection-dominated accretion flow

ADAF

Shakura-Sunyaev disk

SSD

gracia et al., mnras 344, 468, 2003
Atoll and Z Sources -- CCD

~1% Eddington Accretion

Accretion rate direction

~Eddington Accretion

Figure 7: Left: X-ray color-color diagram of the atoll source 4U 1608–52. (Méndez et al. 1999) Right: X-ray hardness vs. intensity diagram of the Z source GX 340+0. (after Jonker et al. 1999c) Values of curve-length parameters $S_z$ and $S_\alpha$ and conventional branch names are indicated. Mass accretion rate is inferred to increase in the sense of increasing $S_\alpha$ and $S_z$. X-ray color is the log of a count rate ratio (3.5–6.4/2.0–3.5 and 9.7–16.0/6.4–9.7 keV for soft and hard color respectively); intensity is in the 2–16 keV band. kHz QPO detections are indicated with filled symbols.
**Figure 6.** Sketch of the disc–jet coupling in Z-type sources, which we believe to be the NS equivalents of the BHGRS 1915+105, constantly accreting at approximately Eddington rates and producing powerful jets associated with rapid state transitions. See Section 4.5 for a discussion.
Figure 4. Optically thin (i.e. spectral index $\alpha < 0$) radio spectra from several radio-bright X-ray binaries which were not in the Low/Hard X-ray state at the time of the observations, compared with the flat/inverted spectra of the seven sources in Figs 1 & 4 (for the transients, the later, i.e. most inverted, spectra are plotted). As well as the different spectral indices (the optically thin sources all have $-1 \leq \alpha \leq -0.2$, the source in the Low/Hard state all have $0.0 \leq \alpha \leq 0.6$), note also the much wider range of fluxes observed from optically thin emission.
Synchrotron spectra

- Importantly, then, the medium becomes optically thick. It can be shown that, regardless of the energy spectrum of the electrons, the specific intensity in the optically thick region \( \propto \nu^{5/2} \). We thus observe a steep, rising spectrum at low \( \nu \).

- Since the emission is from a non-thermal population, this optically thick component of the spectrum differs from the \( \nu^2 \) behaviour of the Rayleigh-Jeans law.

The production of synchrotron radiation is indicative of the presence of violent particle acceleration + B fields. It is seen within the Galaxy, and also in supernova remnants, pulsars, external AGN, radio sources, gamma-ray bursts etc.
Relativistic Jets

Relativistic jets known for many years in AGN
Spectacular examples seen recently in XRBs: Microquasars

\[ \Phi_0 = \frac{\theta \sin \theta}{1 - \beta \cos \theta} \]
Active Galaxies

But a small fraction of galaxies are different; they are much brighter and produce more long- and short-wavelength emission. They are called active galaxies.
• Blazars
  - BL Lacs
  - OVV

• Quasars
  - Radio Loud
  - Radio Quiet

• Radio
  - Narrow Line
  - Broad Line

• Seyfert
  - Type 1
  - Type 2
AGN Unified Scenario

- Supermassive black hole
- Thin accretion disk – emission peaks in UV, optically thick
- Disk corona – produces X-ray/hard X-ray emission, optically thin
- Dusty torus – essentially outer part of accretion disk, optically thick, produces IR emission
- High-velocity clouds – located near BH, produce broad optical emission lines, electron density above $10^7$ cm$^{-3}$ (due to lack of forbidden lines), ionized by disk/corona
- Low-velocity clouds – located near/outside of torus, produce narrow optical emission lines which are collisionally excited, have a range of ionization levels, filling factor is small $\sim 10^{-3}$, material seems to be mainly outflowing
- Relativistic jets and radio lobes – extend parsecs to 100s kpc, detected up to X-rays, contain highly energetic particles
<table>
<thead>
<tr>
<th>Object</th>
<th>Found in which type of galaxy</th>
<th>Strength of radio emission</th>
<th>Type of emission lines in spectrum</th>
<th>Luminosity (watts)</th>
<th>Luminosity (Milky Way Galaxy = 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blazar</td>
<td>Elliptical</td>
<td>Strong</td>
<td>Weak (compared to synchrotron emission)</td>
<td>$10^{38}$ to $10^{42}$</td>
<td>10 to $10^5$</td>
</tr>
<tr>
<td>Radio-loud quasar</td>
<td>Elliptical</td>
<td>Strong</td>
<td>Broad</td>
<td>$10^{38}$ to $10^{42}$</td>
<td>10 to $10^5$</td>
</tr>
<tr>
<td>Radio galaxy</td>
<td>Elliptical</td>
<td>Strong</td>
<td>Narrow</td>
<td>$10^{36}$ to $10^{38}$</td>
<td>0.1 to 10</td>
</tr>
<tr>
<td>Radio-quiet quasar</td>
<td>Spiral or elliptical</td>
<td>Weak</td>
<td>Broad</td>
<td>$10^{38}$ to $10^{42}$</td>
<td>10 to $10^5$</td>
</tr>
<tr>
<td>Seyfert 1</td>
<td>Spiral</td>
<td>Weak</td>
<td>Broad</td>
<td>$10^{36}$ to $10^{38}$</td>
<td>0.1 to 10</td>
</tr>
<tr>
<td>Seyfert 2</td>
<td>Spiral</td>
<td>Weak</td>
<td>Narrow</td>
<td>$10^{36}$ to $10^{38}$</td>
<td>0.1 to 10</td>
</tr>
</tbody>
</table>
Seyfert galaxies were first identified by Carl Seyfert in 1943.

He defined this class based on observational characteristics:

Almost all the luminosity comes from a **small (unresolved) region** at the center of the galaxy – the **galactic nucleus**.

Nuclei have $M_B > -23$ (arbitrary dividing line between quasars/seyferts)

---

**Note:** Quasar 3C 273, located in the Virgo constellation, is one of the closest with a redshift, $z$, of 0.158.[2] = 2.44 Giga light years. It is also one of the most luminous quasars known, with an absolute magnitude of **-26.7**
Optical View:

Type I AGN:

Q2130-431

Type II AGN:

Q2125-431

[Fig. from Hawkins 2004]
Type 1 Seyfert galaxies have both narrow and broadened optical spectral emission lines. The broad lines imply gas velocities of 1000 - 5000 km/s very close to the nucleus.

Seyfert type 2 galaxies have narrow emission lines only (but still wider than emission lines in normal galaxies) implying gas velocities of ~ 500-1000 km/s. These narrow lines are due to low density gas clouds at larger distances (than the broad line clouds) from the nucleus.
Active Galactic Nuclei (AGN)
In some Type 2 Seyfert galaxies, the broad component can be observed in polarized light.

Seyfert galaxies were subdivided into types 1 and 2 20 years ago (Khachikian & Weedman 1974), a classification scheme that has served astronomers well in attempting to determine the nature of these galaxies. The original classification into two types was based almost entirely on the relative widths of the strong emission lines. In the Seyfert 1 galaxies, the permitted lines have strong components with widths on the order of 10,000 km s\(^{-1}\); they also may have weaker components with widths on the order of 500 km s\(^{-1}\), as do the forbidden emission lines (such as [O III]). Both permitted and forbidden lines have similar widths of 500 km s\(^{-1}\) in Seyfert 2 galaxies. Intermediate Seyfert classifications ranging from 1.2 to 1.9 have been proposed over the years based on the relative strengths of the broad and narrow components of the permitted lines (e.g., Osterbrock & Koski 1976; Osterbrock 1981; Cohen 1983). Some Seyfert galaxies have changed their classifications on time scales of weeks to months, usually within the various intermediate Seyfert classifications (e.g., Cohen et al. 1986).

It was long believed that the nuclei of Seyfert 2 galaxies have radio sources that are systematically more powerful and larger than those in Seyfert 1 galaxies, with Seyfert 1.2 through 1.9 galaxies being intermediate in radio properties (de Bruyn & Wilson 1978; Meurs 1982; Meurs & Wilson 1984; Ulvestad & Wilson 1984a, b; Ulvestad 1986). Edelson & Miller (1985) noted, however, that the Seyfert 1 galaxies are similar for an optically limited sample, although he had insufficient resolution to separate nuclear and disk radio emission. Ulvestad & Wilson (1989) showed that the apparently higher nuclear radio luminosity and size of the Seyfert 2 galaxies might be accounted for by selection effects; when the weaker Seyferts (mostly Seyfert 2 galaxies) found in surveys of nearby galaxies are included and radio-source sizes are compared at equivalent dynamic ranges, the differences in radio powers and sizes are no longer statistically significant. A contemporaneous study by Giuricin et al. (1990), based on a sample of bright, spectroscopically selected Seyferts, also concluded that the radio sources in the different Seyfert types are not significantly different. A recent summary of the radio properties of Seyfert galaxies can be found in Wilson (1991).

Antonucci (1983) noted that the Seyfert 1 galaxies tend to have optical continuum polarization parallel to their radio major axes, while Seyfert 2 galaxies have perpendicular polarization. This has been interpreted as a difference between thin and thick scattering disks (Antonucci 1984). However, the remarkable result that NGC 1068, the archetypal Seyfert 2 galaxy, shows very broad permitted line emission in polarized light (Antonucci & Miller 1985) indicates that at least some of the difference between Seyfert 1 and Seyfert 2 galaxies might be merely an orientation effect; a similar suggestion, based on x-ray properties of the galaxies, was made by...
Radio Galaxies

• Emit most of their energy at radio wavelengths
• Emission lines from many ionization states
• Nucleus does not dominate galaxy’s emission
• Host galaxies are Elliptical/S0

Radio morphology first classified by Fanaroff & Riley (1974)

• FR I: less luminous, 2-sided jets brightest closest to core and dominate over radio lobes
• FR II: more luminous, edge-brightened radio lobes dominate over 1-sided jet (due to Doppler boosting of approaching jet and deboosting of receding jet)

Spectroscopic classification of radio galaxies

• NLRGs (Narrow line ...): like Seyfert 2s; FR I or II
• BLRGs (Broad line ...): like Seyfert 1s; FR II only
FRI/FRII Radio Morphology Classification

Fanaroff-Riley Class I

Edge-darkened

$P_{178\text{MHz}} < 5 \times 10^{25} \text{ W Hz}^{-1}$

All FRIs classified as WLRG

Fanaroff-Riley Class II

Edge-brightened

$P_{178\text{MHz}} > 5 \times 10^{25} \text{ W Hz}^{-1}$

FRIIs mainly classified as NLRG/BLRG/RLQ

**Faranoff-Riley Typ I (FR I)**

$L_\nu(1.4\text{GHz}) < 10^{32} \text{ erg/s/Hz}$

**Faranoff-Riley Typ II (FR II)**

$L_\nu(1.4\text{GHz}) > 10^{32} \text{ erg/s/Hz}$
On **small scales** (< 15 kpc): 3 types of sources

**Compact, Flat Spectrum (CFS)**
- usually < 1”, physically small < 10 pc
- $f_{\nu} \sim \nu^{-\alpha}$, $\alpha \sim 0 – 0.3$
- variable, polarized, superluminal on VLBI scales

**Compact, steep spectrum (CSS)**
- $\alpha = 0.7 – 1.2$
- sizes 1-20 kpc (within host galaxy)
- peak at < 500 MHz
- (limited by Ionospheric cutoff is at 10 MHz)
- 30% of cm-selected radio sources

**GigaHertz Peaked Spectrum (GPS)**
- radio spectrum peaks at 500 MHz to 10 GHz
- sizes < 1 kpc (within NLR)
- not very polarized
- $\alpha \sim 0.77$ for $E>E(\text{peak})$
- 10% of cm-selected radio sources
Quasars

• First discovered in the 1960s.
• Detected radio sources with optical counterparts appearing as unresolved point sources.
• Unknown optical emission lines.
• Maartin Schmidt was the first to recognize that these lines were normal Hydrogen lines seen at much higher redshifts than any previously observed galaxies.

\[
D = 660 \text{ Mpc (2.2 billion light years)} \text{ for 3C273}
\]

\[
1340 \text{ Mpc (4.4 billion light years)} \text{ for 3C 48}
\]

\[
L = 2 \times 10^{13} \ L_{\text{sun}} \text{ for 3C273.}
\]

• Within ~2 years, quasars were discovered with: \(z > 2 \) and \( L \approx 10^{14} \ L_{\text{sun}}\)

• Most distant QSO discovered today - \( z = 6.42 \)

About 10% of all quasars are strong sources of radio emission and are therefore called “radio-loud”; the remaining 90% are “radio-quiet”
To be seen at such large distances, quasars must be very luminous, typically about 1000 times brighter than an ordinary galaxy.
Quasar Red Shifts

Spectrum of imaginary quasar not receding from our galaxy

- B2 1128+31: $z = 0.178$
- PKS 1217+02: $z = 0.240$
- 4C 73.18: $z = 0.302$
- B2 1208+32A: $z = 0.389$

Wavelength (nanometers)
This quasar has such a large redshift \((z = 3.773)\) that these ultraviolet hydrogen emission lines have been shifted to visible wavelengths.
<table>
<thead>
<tr>
<th>Redshift</th>
<th>Recessional velocity</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$v/c$</td>
<td>(Mpc)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>0.095</td>
<td>394</td>
</tr>
<tr>
<td>0.2</td>
<td>0.180</td>
<td>739</td>
</tr>
<tr>
<td>0.3</td>
<td>0.257</td>
<td>1040</td>
</tr>
<tr>
<td>0.4</td>
<td>0.324</td>
<td>1310</td>
</tr>
<tr>
<td>0.5</td>
<td>0.385</td>
<td>1540</td>
</tr>
<tr>
<td>0.75</td>
<td>0.508</td>
<td>2010</td>
</tr>
<tr>
<td>1</td>
<td>0.600</td>
<td>2370</td>
</tr>
<tr>
<td>1.5</td>
<td>0.724</td>
<td>2860</td>
</tr>
<tr>
<td>2</td>
<td>0.800</td>
<td>3170</td>
</tr>
<tr>
<td>3</td>
<td>0.882</td>
<td>3520</td>
</tr>
<tr>
<td>4</td>
<td>0.923</td>
<td>3710</td>
</tr>
<tr>
<td>5</td>
<td>0.946</td>
<td>3830</td>
</tr>
<tr>
<td>10</td>
<td>0.984</td>
<td>4040</td>
</tr>
<tr>
<td>Infinite</td>
<td>1</td>
<td>4190</td>
</tr>
</tbody>
</table>

This table assumes a Hubble constant $H_0 = 71 \text{ km/s/Mpc}$, a matter density parameter $\Omega_m = 0.27$, and a dark energy density parameter $\Omega_\Lambda = 0.73$ (see Chapter 28). The distance in light-years is equal to the light travel time in years.
Quasar density peaks at $z \sim 2$
$\sim 3$ billion after the Big bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start

Galaxies and Quasars begin to form
The Reionization starts

The Cosmic Renaissance
The Dark Ages end

Reionization complete, the Universe becomes transparent again

Galaxies evolve

The Solar System forms

Today: Astronomers figure it all out!
Only a few % of galaxies contain AGN.

Radio galaxies have powerful radio emission—usually found in ellipticals.

<table>
<thead>
<tr>
<th>Type</th>
<th>Radio Galaxy</th>
<th>Seyfert Galaxy</th>
<th>Quasar</th>
<th>Blazar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Examples</td>
<td>M87, Cygnus A</td>
<td>NGC4151</td>
<td>3C273</td>
<td>BL Lac, 3C279</td>
</tr>
<tr>
<td>Galaxy Type</td>
<td>Elliptical, irregular</td>
<td>Spiral</td>
<td>Irregular</td>
<td>Elliptical?</td>
</tr>
<tr>
<td>Luminosity (Solar units)</td>
<td>$10^6 - 10^8$</td>
<td>$10^8 - 10^{11}$</td>
<td>$10^{11} - 10^{14}$</td>
<td>$10^{11} - 10^{14}$</td>
</tr>
</tbody>
</table>

- RG $10^3 - 10^4$ erg/s
- Quasars $10^{44} - 10^{47}$ erg/s
* 'Blazars' (BL Lac objects and OVV quasars). These classes are distinguished by **rapidly variable**, polarized optical, radio and X-ray emission. BL Lac objects show no optical emission lines, broad or narrow, so that their redshifts can only be determined from features in the spectra of their host galaxies.

OVV quasars **behave more like standard radio-loud quasars** with the addition of a rapidly variable component.

In both classes of source, the variable emission is believed to originate in a relativistic jet oriented close to the line of sight. Relativistic effects amplify both the luminosity of the jet and the amplitude of variability.
BL Lacs – A Pure Jet Spectrum

- BL Lacs are thought to be beamed FRI radio galaxies (low power!)
- In BL Lacs the emission is dominated by the jet due to relativistic beaming.
- But there is also no evidence for any disk spectrum.
- The jet spectrum resembles a "camel's back."
- Radio – optical – X-rays: synchrotron from jet
- X-ray – TeV: inverse Compton from inner jet