Whittle : EXTRAGALACTIC ASTRONOMY

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15. ACTIVE GALAXIES & QUASARS

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Under Current Construction : last update April 6 2011

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(1) Introduction

(a) Operational Definition of AGN

- We now know that ~all galaxy bulges harbour **supermassive black holes** (SMBH) in their nuclei.
  Most are **quiet/silent** - starved of gas and detectable only via near-nuclear orbital dynamics
  A few are **accreting gas** which makes them visible through the release of potential energy.
  Such nuclei are called **Active Galactic Nuclei** (AGN) and their hosts are called **Active Galaxies**.

  One definition for AGN might therefore read:

  "A galaxy nucleus which shows evidence for accretion onto a supermassive black hole"

- First note what is **not** considered an AGN:

- Nuclear SMBHs are not sufficient to assign an AGN classification:
  e.g. M31 and M32 both have SMBH's but neither show signs activity (accretion power).
- Accreting **stellar mass** black holes are not AGN -- we need an SMBH located in a galaxy nucleus.
- The activity classification explicitly **excludes** stars or stellar life cycles
  Star formation, HII regions, Supernovae, etc may be present, but they do **not** constitute an AGN.
- Luminosity **isn't** part of the definition: activity can be **quite weak**
  For this reason, one often qualifies the power of the AGN, for example:
  "QSOs are powerful AGN"; "M81 contains a weak AGN"

- In practice, "evidence for accretion onto an SMBH" means one or more of the following:

- Emission lines with distinct ratios (defined in 3d below) [image].
  Often, these are strong & imply photoionizaton by a hard spectrum, rather than by a black body.
- Broad $H\alpha$ wings or profile ($\gtrsim$1000 km/s) - i.e. much more than typical galactic velocities. [image].
- Broad band unresolved continua, with comparable power in X-ray, UV, optical, IR
  In the optical, they often appear blue; overall, their continua are unlike starlight. [image]
- Variability of one or more parts of this continuum (or the emission lines)
  this points to a highly compact ($\lesssim$1pc) source of emission [image].

- Radio source, often bipolar & significantly more luminous than in normal galaxies
  this may also show jet-like morphology; steep spectrum jet & lobes; flat spectrum core [image].

(b) Reasons for Studying AGN

- The study of AGN started ~50 years ago and now comprises a major branch of astrophysics
  A number of factors make AGNs worthy of study:

- At their heart lie **giant black holes**, perhaps the most exotic astrophysical animal we know of.
  AGN give us observational access to these otherwise ellusive objects

- Almost by definition, physical processes near SMBHs are in the **relativistic regime**
  A host of interesting and extreme physical process occur.
  While often confusingly complex, they provide a **laboratory for studying high energy processes**.

- Black hole accretion is very efficient, making AGN amongst the **most luminous objects known**.
  e.g. for mass m in orbit at $R_S = 2GM/c^2$, we have $2KE \sim PE \sim GMm/R_S = ½mc^2$
  → typical accretion efficiencies are ~¼ mc^2
  this is huge compared to either fusion (~0.7%) or chemical ($\sim 10^{-6}$%) energy sources.
  Accreting just 1 $M_\odot\ yr^{-1}$ yields $\sim 10^{46}$ erg $s^{-1} \approx 4 \times 10^{12} L_\odot \approx 200\ L_*$ galaxies.

- In addition to photon luminosity, AGN can provide powerful collimated **mechanical** luminosity.
  The creation, propagation and interaction of these **jets** provide yet another important area of study.
  Of course, both accretion flows and jet flows are found in many astrophysical contexts
  → AGNs provide excellent windows on both these complex phenomena.

  High AGN luminosities yield other important opportunities:

- Luminous AGN can be seen to **enormous distances** (currently, z~7, lookback time ~95%)
  One can therefore study directly their cosmic evolution.
  They show **strong evolution**, with a "hey day" at z~2 (×1000 more common than today).
  This evolution is closely tied to **early galaxy construction** -- another topic of great importance.

- As distant beacons, their spectra provide **access to the intervening IGM**; for example:
  - the highest z QSOs probe the epoch of reionization,
  - the transparency of the Lyman continuum proves the IGM is highly ionized
  - the ISM in galaxy halos can be analysed throughout much of cosmic history
  - the disks of young spirals can also be studied.

- The accretion power ultimately emerges in essentially **all spectral wavebands**
  → AGN present observationally very rich targets
  → they feature in ~all new satellite & instrument observational programs.

- AGN influence **11 decades**, from accreting SMBH (~AUs) to jet powered radio lobes (~Mpc)
  Of these decades, ~half are observationally unresolvable.
  → AGN offer a wonderful window on a huge range of environments and physical processes.

- With this motivation, let's now begin to look at AGN in more detail
  As with all our other Topics, the treatment will be relatively broad and superficial.

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(2) Brief Historical Sketch

(a) Early Optical Spectroscopy

1909 : Fath used Lick's Crossley reflector to take spectra of "spiral nebulae"
motivation was to test their extragalactic nature: similar to stars, or MW gas clouds?
most had absorption lines (supports extragalactic); NGC 1068 also had **nebula-like emission lines**

1917-30 : Slipher, Hubble, Humason confirm Fath's observations & find other examples"

NGC 1275, NGC 4051, NGC 4151.

1943 : Carl **Seyfert** studied 6 of the 12 known examples in more detail. He found:

- Luminous semi-stellar nuclei [image]
- Nebular spectra of high ionization
- Emission lines broader than either the absorption lines, or HII regions from irregular galaxies
- Forbidden lines narrower than Hydrogen lines in some objects. [image]

Not much notice taken at the time.

1974 : Kahchikian & Weedman argue for Doppler origin for the line-widths; define Sy 1 & Sy 2.

(b) Early Radio Observations

1932 : Jansky discovers radio from the sun & MW

1944 : Reber maps sky @ 160 MHz (1.9 m) & sees peak in Cygnus (Cyg A)

Late 1940s : Post WWII groups @ Manchester; Cambridge (UK); & CSIRO (Australia)
simple interferometry (Michelson & cliff) gives positions & sizes (small) to $\lesssim$ few arcmin.
→ Virgo A = M87; Centaurus A = NGC 5128; Cygnus A = ?? [image]

Early 1950s : Baade & Minkowski identify Cyg A: "colliding galaxies" [image]
emission lines @ cz=16,830 km/s → high radio luminosity

Late 1950s : small double structures; v.high brightness temperatures.
Burbidge applies synchrotron theory → 10^{60} erg ~ $10^6\ M_\odot c^2$ stored energy.

1974 : Blandford & Rees provide "twin exhaust model" of jets to power the radio lobes.

(c) Quasar Discovery

1960 : Minkowski identifies 3C 295: faint galaxy @ z = 0.46 (huge!)
Sandage identifies 3C 48 : 16^m star + faint fuzz; strong UV & variable.
Greenstein's spectrum shows broad emission lines at odd wavelengths
Several other 3C "stars" identified : quasi-stellar radio sources, QSRS; QSS; quasars.

1963 : Hazard, Mackey & Shimmins observe lunar radio occulation of 3C 273
→ double source; sep 20" (A & B); B = optical star ($f_\nu \propto \nu^{0.0}$); A = faint jet ($f_\nu \propto \nu^{-0.9}$) [image]
Schmidt recognizes Hβ, Hγ, Hδ, Hϵ @ z=0.16 and can therefore identify MgII 2800.
Greenstein & Oke : confirm Hα in 3C 273 & identify MgII in 3C 48 @ z=0.37
Several papers in Nature:

→ they prefer cosmological redshift, but this means L(QSO) ~ 10-30 × L(giant elliptical)
→ suggest central mass $\gtrsim 10^9\ M_\odot$ provides the energy & confines the emission line gas

Mid 1960s : more redshifts @ z~1 (CIII] 1909; CIV 1550); 3C 9 Lyα z=2.012
Sandage finds radio quiet UV bright "QSOs"; estimates more common than radio loud
assuming cosmological z (see below) required **high energy sources**:
Suggestions: SN chain reaction; collisions in dense star clusters; supermassive stars.
Salpeter (1964) & Zeldovich (1964) independently suggest accretion onto supermassive black hole
Lynden-Bell (1969): developes accretion power; "dead" QSOs may inhabit all nearby galaxies.

(d) Redshift Controversy

- High measured z suggests very high luminosity

Rapid variability suggests very small source [image]
→ difficult to believe → perhaps z is **not** cosmological?

- Alternatives: local objects with high gravitational redshifts,
  objects with high Doppler velocities, ejected either from the MW or some nearby galaxy.

- Objections to both these, for example:
  difficult to explain same z for broad and narrow lines with gravitational redshift
  Very high energy for local ejection; why no blueshifts for non-local ejection?

- Evidence grows for cosmological redshift, for example:
  Cluster galaxies with same redshift as QSO
  Fuzz around some QSOs consistent with host galaxy; ultimately same z measured. [image]
  Highest Seyfert luminosities overlap lower QSO luminosities: **continuous population**
  Today, HST sees host galaxy whenever it "should". Note, it can be difficult to detect because:
    - QSOs nucleus often outshines surrounding galaxy
    - Rest frame UV of galaxy is much fainter than in the optical for nearby galaxies
    - Galaxy surface brightness drops as $(1+z)^4$, making detection difficult.

- Today, cosmological redshifts aren't in doubt, but it was important to check them thoroughly.

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(3) The AGN Paradigm

- Before encountering the zoo of AGN species, let's outline their basic anatomical components
  Note: not all of these components are apparent/present in any given AGN
  The length-scales below refer to a moderately luminous AGN: $L \sim 10^{45}$ erg s^{-1}, $M_{BH} \sim 10^{7.5} M_\odot$
  these lengths probably depend on luminosity: ×10 for QSOs; ×0.1 for weaker AGN.

- A number of "global" figures help:

Figure 1:	sketch showing 5 nested scales for Seyferts
Figure 2:	single spatial axis with various ranges identified
Figure 3:	Blandford's comic-strip of 12 successive scales differing by a factor 10 in scale.
Figure 4:	Robson's version of Blandford's comic-strip
Figure 5:	size & waveband axes identifying various emission regions

- Summarizing these, from innermost to outermost scales, we have (plus/minus ½ decade):

Log r pc	Other	Region/Properties
-5	2 AU	$R_S = 2\ M_{BH,8}$ AU, last stable orbit is $3R_S$ ($M_{BH,8} = M_{BH}/10^8 M_\odot$)
-4	20 AU	relativistic accretion disk (AD); Fe Kα line; variable X-ray emission (mins-hours)
-3	200 AU	UV accretion disk; radiation supported AD;
-2	2000 AU	optical AD; Broad Line Region (BLR); $V \sim 10^4$ km s^{-1}; ~few light days.
-1	0.1 pc	compact, flat-spectrum radio core; VLBI jet; outer BLR
0	1 pc	star cusp with velocities affected by BH; dense gas may block some sight lines.
1	10 pc	Inner Narrow Line Region (NLR); $V \lesssim 10^3$ km s^{-1}; inner bulge.
2	100 pc	bulge; NLR; forbidden emission lines; warm dust; VLA jet.
3	1 kpc	inner disk; disk ISM; Extended-NLR; Bar & inflow; VLA jet.
4	10 kpc	host galaxy; distortions/merger?; ENLR; weak jets blocked.

5	100 kpc	near neighbors; tidal influences; powerful jets.
6	1 Mpc	jets terminate in IGM hotspots; may affect ICM in cluster.

- A related summary that considers causal processes goes like this:

- On large scales, galaxy disturbances/mergers are efficient at removing angular momentum from orbiting gas and this finds its way down to the nuclear regions, possibly with an associated starburst. Some of this gas may cool and form a dusty thick disk in the central 1-1000 pc. This gas can obscure our view of the central regions and, conversely, block the outgoing radiation from the AGN along certain directions.

- Ultimately, some of this gas finds its way into an inner accretion disk, whose Keplerian dynamics is dominated by the black hole. Here, magnetic fields create viscosity in the disk, which causes the gas to move inwards, releasing gravitational energy which heats the disk. The disk has a temperature gradient, and generates at least some of the optical/UV/X-ray continuum emission via thermal radiation at its surface. Also likely are non-thermal processes in a disk corona which add to the continuum. Ultimately, gas within a few R_S emits X-rays before crossing the horizon, adding to the mass and angular momentum of the black hole.

- It is in this innermost region that a jet is somehow generated moving out along the disk axis, probably via magnetic fields tied to the rotating disk. It is not known why this jet is sometimes very powerful (radio loud AGN), and sometimes much weaker (radio quiet AGN). The jets are born with bulk relativistic speeds, and contain magnetic fields and particles with random relativistic speeds -- hence these jets are visible mainly via synchrotron. The jets burrow out through the surrounding galaxy ISM with varying degrees of difficulty, entraining and disturbing the ISM en-route. The most powerful jets can escape the galaxy ISM altogether and traverse a Mpc before slamming into an outward moving "working surface" of IGM material.

- Returning to the central engine, the accretion process also yields a luminous source of X-ray, UV, and optical photons, with roughly power-law spectral shape. This radiation floods out into the galaxy, although some directions may be blocked by the denser ISM components. Whether or not we get a clear line of sight to the nucleus is thought to explain at least some of the observational variety of AGN.

- The UV-X-ray radiation is an effective ionizer. It first encounters gas clouds within the central few light days/weeks and the resulting line emission reveals cloud velocities $\sim 10^3$ - 10^4 km s^{-1} with gas densities $\sim 10^{10}$ cm^{-3}. This emission defines the so-called "Broad Line Region" (BLR). The BLR velocities are probably gravitational, while the origin of the BLR material is uncertain -- perhaps arising from an accretion disk wind.

- At larger distances, the ISM velocities and pressures both drop. By 10pc - 1kpc the ionized gas clouds yield velocities ~few $\times 10^2$ km s^{-1} -- roughly equal to typical bulge gravitational speeds -- and gas densities fall from $\sim 10^6$ to $\sim 10^2$ cm^{-3}. This emission defines the so-called "Narrow Line Region" (NLR). Depending on the geometry of the inner obscuration, the NLR may show bi-conical shape. If jets are blocked in this region, the gas often exhibits significantly higher disturbed velocities.

- Sometimes the jets and ionized gas can be seen to much larger radii, often in association with eachother. The most powerful jets can travel far from the galaxy and dump their energy in the IGM or, if the galaxy is in a cluster, in the ICM. In that case, large cavities in the X-ray emission can be seen surrounding the expanding radio source.

- With this outline now in place, we can move on to retrace the rather tangled web of historical discovery, which led to an equally tangled web of AGN taxonomy. Hopefully, if you keep the basic anatomy and physiology in mind, you'll be able to clearly navigate this more historical part.

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(4) AGN Taxonomy

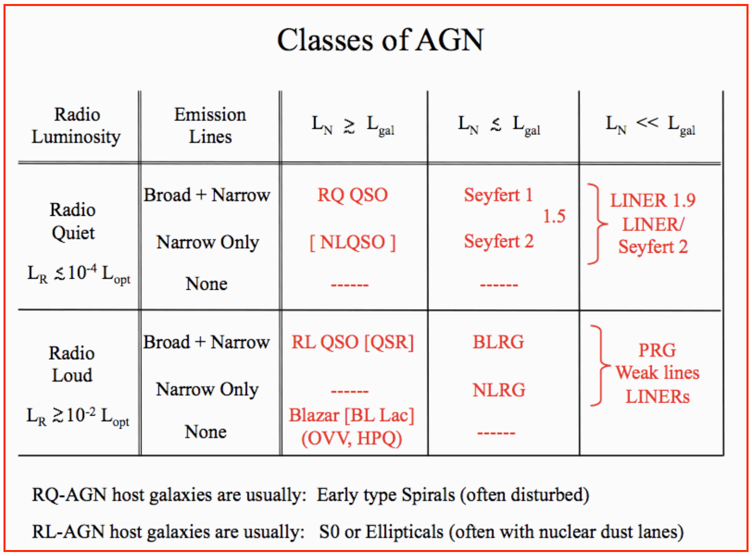
(a) Four Basic Criteria

- Over the years, many different categories of AGN have been identified, each with its own name.
In hindsight, this apparent diversity has three distinct components:
  - **Genuine** variation in one or more **key properties** of AGN
  - **Apparent** variation arising from our particular **viewing angle**
  - Variation which arises from observing the object at a **particular stage in its evolution**.

- There are (at least) **two** genuine ways in which AGN differ from eachother:
  - UV/opt/IR luminosity: This probably tracks the accretion rate and black hole mass.
    Three categories:
    Quasars ($L_{nuc} \gtrsim L_{gal}$);
    Strong AGN ($L_{nuc} \lesssim L_{gal}$);
    Weak AGN ($L_{nuc} << L_{gal}$).
  - Radio Luminosity: determined mainly by the jet power
    The cause of jet power isn't known : possibly black hole spin and/or disk temperature?
    Two categories:
    Radio Quiet ($L_R \lesssim 10^{-4} L_{opt}$)
    Radio Loud ($L_R \gtrsim 10^{-2} L_{opt}$)
- There are (at least) **two** differences which seem to depend on viewing angle [images]
  - Emission Line Shapes: do we get a clear view to the inner (BLR) region, or not.
    Two categories:
    Broad + Narrow lines (**can** see the BLR)
    Narrow lines only (**can't** see the BLR).
  - High variability & high polarization: this depends whether we look directly down a fast jet.
    Two categories:
    High variability & polarization (look down jet);
    Low variability & polarization (look at some other angle).

(b) Taxonomic Table

The following table loosely identifies a number of categories of AGN.



Classes of AGN

Radio Luminosity	Emission Lines	$L_N \gtrsim L_{gal}$	$L_N \lesssim L_{gal}$	$L_N << L_{gal}$
Radio Quiet $L_R \lesssim 10^{-4} L_{opt}$	Broad + Narrow	RQ QSO	Seyfert 1 1.5	LINER 1.9 LINER/ Seyfert 2
	Narrow Only	[NLQSO]	Seyfert 2	
	None	------	------	
Radio Loud $L_R \gtrsim 10^{-2} L_{opt}$	Broad + Narrow	RL QSO [QSR]	BLRG	PRG Weak lines LINERs
	Narrow Only	------	NLRG	
	None	Blazar [BL Lac] (OVV, HPQ)	------	

RQ-AGN host galaxies are usually: Early type Spirals (often disturbed)

RL-AGN host galaxies are usually: S0 or Ellipticals (often with nuclear dust lanes)

Here are some optical spectra of some of these classes: [image]

Let's define in observational terms some of the various classes;
(some names are not quite standard, but they will help clarify our discussion of unification)

Name	Radio	Observational Characteristics
Seyfert 1	RQ	moderate luminosity ($M_B > -23$); strong/visible blue optical continuum; host galaxy clearly visible; broad + narrow lines; narrow lines have high ionization; radio quiet
Seyfert		

Seyfert 2	RQ	as for Seyfert 1, but weaker/no blue optical continuum & only narrow lines visible
QSO	RQ	Radio quiet quasar; optically luminous ($M_B < -23$); host galaxy barely/not visible; strong optical continuum; broad + narrow lines of high ionization
QSO-2	RQ	same as QSO but missing broad lines; not many currently known (some are IRAS-QSOs)
LINER	RQ/L	Low Ionization Nuclear Emission Line Region; weak/no continuum; narrow lines of low ionization & moderate strength; sometimes weak broad Hα visible; can be either radio quiet or loud
BLRG	RL	Broad Line Radio Galaxy; similar to Seyfert 1 but radio loud
NLRG	RL	Narrow Line Radio Galaxy; similar to Seyfert 2 but radio loud
PRG-II	RL	Powerful Radio Galaxy of Fanaroff-Riley class II (edge brightened, powerful jet); unspecified optical spectrum (could be BLRG/NLRG/LINER)
RG-I	RL	Similar to PRG-II except lower radio luminosity & Fanaroff-Riley class I (edge darkened, lower power jet)
LD-QSR	RL	Lobe Dominated (steep spectrum) Radio Loud Quasar; usually FR-II radio morphology; optically similar to QSO
CD-QSR	RL	Core Dominated (flat spectrum) Radio Loud Quasar; optically similar to QSO
BL-Lac	RL	Strong featureless continuum, no/weak lines, little starlight; highly variable; high polarization; radio loud flat spectrum core
OVV-QSR	RL	Optically Violently Variable Quasar; similar to BL Lac but normal QSO spectrum

Notes addressing some details:

- Whether QSO-2s exist (optically luminous AGN with no visible BLR) isn't yet clear
  A few examples exist, but they seem to be rare.

- The Seyfert 1 - 2 division is continuous; there are intermediates with weak BLRs
  In practice, four intermedate designations have been used: [image]
    - Seyfert 1.2 : [OIII]5007 / Hβ(broad) ~ 1
    - Seyfert 1.5 : [OIII]5007 / Hβ(broad) ~ 0.3
    - Seyfert 1.8 : Hβ(broad) just visible
    - Seyfert 1.9 : Hβ(broad) not visible, but Hα(broad) just visible

- Whether **all** Seyfert 2s have hidden BLRs is still unclear (some certainly do)
  There is likely to be an **intrinsic** range in BLR strength, possibly going down to zero.
  NLRs (ionized gas on kpc scales), on the other hand, seem to be ubiquitous.

- The physical nature of LINERs is still under review (see below, in 3d)
  There may be (at least) two types, "weak [OI]" and "strong [OI]" LINERs ([OI] λ6300).
  Weak [OI] LINERs may be powered/photoionized by stars (possibly post-AGB stars)
  Strong [OI] LINERs usually have weak broad Hα wings, suggesting a true AGN.
  In that case, low radiation parameter photoionization by an AGN matches the spectra well.

- The association of Elliptical/Spiral with radio loud/quiet is still uncertain.
  While this seems the case for intermediate/low AGN power, it is less clear for QSOs

(c) Mixed Classifications

- Galaxy nuclei can be both active **and** have star formation.

What we see (and classify) depends on the **relative strength** of these contributions

- strong activity can mask weak/moderate star formation
- comparable contributions can lead to **mixed classification**
- star formation can mask weak activity.

- Regarding mixed objects, there are two contexts worth mentioning.
  - At modest luminosity, emission line ratios can lie between those of AGN & HII region often the two components have different kinematics (line profiles; kpc-scale velocities)
  - At high luminosity, many luminous infra-red galaxies (e.g. ULIRGs) may hide a buried QSO. such objects may be evolving from merger/starburst, to blowout, to exposed QSO (Topic 7).

(d) Emission Line Classification

- Given the various possible types of galactic nuclei, is there a quick/easy way to tell them apart?
  → in most cases, the answer is **yes**, by using the **relative strengths of the narrow lines**

- Ultimately, different objects contain different sources of ionization with different spectral form. The resulting ionized regions have different structure and different emission line strengths. For example, here are four classes of emission line region:

Object	Ionizing source	Spectral form
PN	Post-AGB star	Black Body, T ~ 35,000K
HII region	OB stars	Black Body, T ~ 10,000K
Seyfert	strong AGN	Power Law, High U
LINER	weak AGN	Power Law, Low U

- Two important papers introduced **ratio-ratio** diagrams to separate these classes :
  → Baldwin, Phillips & Terlevich (1981 PASP 93, 5)
  → Veilleux & Osterbrock (1987 ApJS 63, 295)
  the diagrams use only strong lines, and have come to be known as BPT (or VO) diagrams.

  BPT use : [OIII]5007 / Hβ; [NII]6584 / Hα; [OIII]5007 / [OII]3727; [OIII]5007 / [OI]6300.
  VO use : [OIII]5007 / Hβ; [NII]6584 / Hα; [OI]6300 / Hα; [SII]6717+6731 / Hα

  Note that some BPT ratios need reddening correction while the VO ratios don't (being close in λ).

- Here's some example spectra and BPT diagrams [image]
  In general:
  - Seyferts have strong [OIII] / Hβ ; strong [NII] / Hα; strong [OI] / Hα i.e. a **wide range of ionization degree**
  - LINERs have lower ionization degree: weaker [OIII] / Hβ but strong [NII] / Hα & [OI] / Hα
  - HII regions have much weaker [OI] / Hα and somewhat weaker [NII] / Hα.

  Some comments:

  - HII regions lie along a sequence in metallicity : low Z have higher ionization. The sequence can reach [OIII] / Hβ ~ 10, so high [OIII]/Hβ is **not** unique to Seyferts.
  - AGNs are different because their ionizing spectra are **broad**, with a high energy component. Behind the fully ionized region lie large partially ionized regions kept hot by x-ray heating. It is in these regions that the [OI], [NII] and [SII] lines are generated efficiently.
  - One can think of the Seyfert/LINER group as a single sequence in **radiation parameter**, U. e.g. Seyferts: intense hard radiation field → LINERs: weak hard radiation field
  - Very high ionization lines can be unambiguous indicators of AGN: e.g. [NeV]3426, since $Ne^{3+} + h\nu \rightarrow Ne^{4+} + e^-$ requires 90 eV photons.
  - Some non-AGN emission regions can mimick LINER spectra :

  e.g. cooling flows; shocks in starburst driven winds; bulge ISM ioinzed by post-AGB stars.
  - Fast (500 km/s) shocks can also mimick Seyfert spectra, though no clear cases are known
  - Through the 1980s [OIII] line**width** was used in defining AGN (FWHM > 300 km/s)
    no more: FWHM tracks bulge mass; many AGN now known with FWHM < 300 km/s.

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(5) AGN Detection and Identification

- AGN, particularly luminous ones, are **rare** - how does one find them?
  → search for objects with, e.g., strong radio; UV; emission lines; X-ray.
  Since AGN differ in their properties,
    no method finds **all** AGN; and
    all samples are **biassed** to some degree.
  However, each selection strategy has led to a deeper understanding of the AGN phenomenon.

(a) Radio Surveys

Historically, most early AGNs were discovered from radio surveys at Cambridge & Parkes: e.g.

- 3C (1959) & 3CR (Revised; 1962) cover $\delta > -5^{\circ}$ with S > 9 Jy @ 178 MHz (328 sources)
    Note: 1 Jansky = 10^{-26} W m^{-2} Hz^{-1} = 10^{-23} erg s^{-1} cm^{-2} Hz^{-1}
    1C & 2C were found to be badly confusion limited, and are never referred to.
  4C (1965) had S > 2 Jy; PKS (1965) survey covered the southern sky @ 408 MHz.

- Optical IDs found ~75% radio galaxies ~25% QSOs;
  High-z (>2) AGN quite rare, but present; most have steep spectrum ($F_{\nu} \propto \nu^{-0.8}$)
  Until ~1970 it was thought **all** AGN were radio loud;
  Then optical surveys find many radio quiet AGN:
  Now think only 10% of AGN are radio loud

- Since these early surveys, there have been many others : e.g.
  - Green Bank: Northern sky with S > 0.8 Jy @ 1.4 & 5 GHz (1970s)
  - Parkes: Southern sky with S > 0.7 Jy @ 2.7 GHz (1970s)
  - FIRST: ~¼ full-sky @ 1.4 GHz & 5" beam (VLA-B) S > 1 mJy (~10^6 sources; 1990s)
  - NVSS: ~ 0.8 full-sky @ 1.4 GHz & 45" beam (VLA-C) S > 2 mJy (2×10^6 sources; 1990s)
  - 5C: ~15 areas of 10 deg^2 with S > 10 mJy @ 408 MHz & S > 2 mJy @ 1.4 GHz (1990s)
  - VLA: deep pencil beam surveys: 0.05 deg^2 with S > 15 μJy (early 1990s)

- In general, from these surveys one finds:
  - The highest flux sources are **all** powerful AGN.
  - The intermediate flux sources are also AGN but of lower luminosity
  - The fainter sources include many more normal or starburst galaxies
  - At lower frequency (100s MHz) one tends to find large steep spectrum AGN
  - At higher frequency (GHz) one tends to find compact flat spectrum AGN

(b) Optical Colors

(i) Single Color

- Bare AGN have much "broader" spectra than stars/galaxies → UV & IR excesses w.r.t. visible.
  In surveys for QSOs, we need to discriminate against **stars**
  From a U-B vs B-V color-color plot a good choice for QSOs is U-B < -0.4 [image]
  The main contaminants are hot sub-dwarfs & white dwarfs (O & B stars are too rare to matter).
  Here are two well known surveys that used this method:

- BQS : Palomar Bright Quasar Survey (early 1980s; Schmidt & Green).

Used Palomar 48" Schmidt to survey 11,000 $\deg^2$ to $m_B < 16^m$; select U-B < -0.44
1700 candidates, of which 114 (7%) are AGN (90 have $M_B < -23$, so are classified as QSOs).
These are often referred to as "PG quasars" (Palomar Green).

- Boyle; Shanks; Peterson (~1990) make a similar survey, but much deeper & smaller area
  Use UK 48" Schmidt with U & J plates for 7 5°×5° areas to $B_J < 21$; select U-B < -0.4
  Automated plate scanning finds 1400 UVX candidates; fiber spectroscopy identifies 420 QSOs.
  They estimate ~90-95% complete for 0.6 < z < 2.2
- The UVX selection method **breaks down** for QSOs with z above 2.2
  Why? Because Lyα enters the B filter, so U-B appears **red** → confuse with stars
  At even higher z, Lyα forest and LyC IGM absorption suppress both U & B → ~invisible
  Notice how N(z) for all known QSOs (c. 1993) closely reflects emission-line influence on color [image]
- However, at z > 4.2 the IGM absorption makes B-R much **redder** than ~all stars
  → The APM Survey: (Irwin; McMahon; Hazard; 1991) search 2000 $\deg^2$ for B_J-R > 3
  Proved to be quite efficient at finding very high-z QSOs.

(ii) Multi-color

- Not surprisingly, ambiguities in U-B for z > 2.2 are removed by including **additional colors**
  A number of such multi-color surveys have been done, especially aiming for high-z QSOs.
  Here are just four of them:
- UK Schmidt Survey: (Warren; Hewett; Osmer; 1991) take 6 bands: U,B_J,V,OR,R,I of 43 $\deg^2$
  Use the APM to scan the plates for stellar objects with $16 < m_{or} < 20$ → **5 colors**.
  Stars define a "tube" in 5-d space, while QSOs lie outside this space [image].
  Ultimately find 85 QSOs with z > 2.2.
- POSS II quasars: (Kennefick et al 1995) use g,r,i plates of 680 $\deg^2$
  look for Lyα in r giving very red g-r for 4.0 < z < 4.8
  find ~20 QSOs with z > 4 (needs updating)
- Sloan DSS QSOs: Stars define a locus in two color cubes: (u-g, g-r, r-i) and (g-r, r-i, i-z).
  QSOs are selected as 4σ away, and found in the FIRST radio survey.
  These QSOs are divided into low ($\lesssim 3$) and high ($\gtrsim 3$) redshift (see o-link).

(c) Slitless Spectroscopy

- Since AGNs have distinctive optical spectra, is there a way to take spectra of **regions of the sky**?
  The answer is **yes!**, and the technique is called **slitless spectroscopy**
  The method is simple, and has a venerable history (1920s HD spectral types for ~10^5 stars):
  - Attach a large prism **in front of the entire telescope**
  - Use **Schmidt** telescopes + photographic plates → ~small-ish aperture + large field of view.
  - The prism apex angle is **small** ($\lesssim$ few degrees) → dispersions ~10^2-10^3 A/mm at the plate [image].

  Variations in the method use gratings/grisms/grenses, sometimes placed nearer the focal plane
  These also give zero-order images → helps measure positions; magnitudes; redshifts
  The plates contain thousands of small spectra, to be scrutinized by eye (or machine).
  For AGN: look for strong blue/UV continuum &/or emission lines (bright patches)
- Main limitations of slitless surveys are:
  - brighter limiting magnitude (since light is dispersed)
  - difficulty of completeness estimates, since detection depends on several factors
  - bias in favour of strong high equivalent width emission lines
  - there are barren redshift ranges with few lines (e.g. z~1, has only MgII 2800)
  - spectra may be overlapping in crowded (e.g. low b) fields.

(i) Markarian Survey

- 1967-1981: Byurakan Observatory (Armenia) 1.3m Schmidt surveyed 10,000 deg^2
  Look for **galaxies** $m_B \lesssim 15.5^m$ with strong UV continuum (term UVX = UV-excess).
  15 lists published containing 1500 "Markarian Galaxies"
  Follow-up spectroscopy (mainly by Osterbrock at Lick) found ~10% (~150) Seyferts
  Since all have strong UVX, Seyferts divide ~50/50 for types 1/2, with quite luminous Seyfert 2s.
  The other 90% are mainly starburst galaxies (strong blue/UV light from OB stars).

- These Markarian Seyferts were a primary target list for studies in the 1970s-80s.
  Their virtue is that they provide a sample of relatively nearby ($z \lesssim 0.05$) luminous Seyferts.

(ii) Other Slitless Surveys

- Since color searches for QSOs fail for $z \gtrsim 2$ (see above), slitless spectra can help.
  This is astrophysically important, to go beyond the "quasar era" at z ~ 2
  Look for **rest frame UV lines**: Lyα 1215; CIV 1550; CIII] 1909 (eg Lyα @ 5500A → z~3.5)

- LBQS : Large Bright Quasar Survey (1986 - 95; Foltz; Hewett; Chaffee).
  Use UK Schmidt & 2° prism & IIIaJ plates to survey 450 deg^2
  Select for blue continuum ($z < 2.2$) **or** spectral features ($z > 2.2$; limit z~3.4 @ 5400A from IIIaJ)
  Find ~1000 QSOs with $16 < B_J < 18.5$ and $0.2 < z < 3.4$
  Sample is ~complete in this brightness & redshift range → good for demographic studies.

- PTGS : Palomar Transit Grism Survey (mid-late 1990s; Schneider; Schmidt; Gunn).
  Use 200" & grism & CCDs in drift-scan mode; gives 4400 - 7500A for Lyα at $2.5 < z < 5$)
  Survey 62 deg^2 in six stripes → 90 QSOs with $2.75 < z < 4.75$
  → use to show **drop** in QSO co-moving space density at $z > 3$.

(d) Emission Lines

- The previous methods find **high levels of activity** which dominate the optical light.
  What about **weaker activity**? How does one hunt for that?
  One of the most sentitive diagnostics of activity are **emission line ratios**, for which one needs:
  → high S/N ratio spectroscopy of galaxy nuclei, through small apertures.
  A number of such surveys have been done, some with AGN detection as goal, some not.
  For well defined samples these give the most unbiassed window on AGN demographics

- There have been (at least) four spectroscopic surveys of the nuclei of nearby bright galaxies:
  - 1980 Heckman: 100 early type spirals & ellipticals (check) [image]
  - 1983 Keel : 100 spirals (check)
  - 1984 Stauffer : 80 Spirals (check)
  - 1985-95 Ho; Fillipenko; Sargent: 486 galaxies from the RSA ($B_T < 12.5$)

  To access weak emission lines, galaxy continuum spectra must often be subtracted (figs)
  Emission line ratios are used to establish nucleus type: Seyfert; HII region; LINER.

- From his survey, Heckman identified **LINERs** = Low Ionization Nuclear Emission Line Regions
  While unclear at the time, it is now thought that many of these are weakly active nuclei.

- Using the Palomar survey it is found that (see below for details):
  - ~86% of galaxy nuclei have detectable ($\gtrsim$1 A EW) emission lines
  - ~13% are dominated by Seyfert emission (cf. 2-5% in the Markarian lists)
  - ~30% are dominated by LINER emission
  - ~40% are dominated by HII emission

  → activity is **much more common** than originally thought, if one includes weak AGN.

- Recently, the Sloan & 2dF galaxy redshift surveys have found thousands of new AGN:
  These allow a much more definitive analysis of the demographics of galaxy nuclei.

(e) Infra-red

- As discussed in Topic 9.11bv, AGN tend to have "warmer" FIR colors than normal galaxies.
  Rather than peaking near 60μm (30K dust) they peak closer to 12-25μm (~100 - 300K)
  Moderate luminosity AGN can be selected quite efficiently in the IRAS color-color plot
  For example, de Grijp et al (1992) find .... TBD.

(f) X-ray & Gamma-ray

- X-ray emission is obviously an efficient diagnostic for AGNs, especially away from the MW plane
  Compared to other wavebands, X-ray surveys have lagged behind somewhat, but are catching up
  It is useful to divide X-rays into two bands : **soft** (0.2 - 2 keV) & **hard** (2 - 10 keV)
  Typical columns to galaxy nuclei may **absorb** soft, but not hard, X-rays
  → soft surveys may miss a significant fraction of the high-column AGN (e.g. Seyfert 2s).

- There are a number of X-ray surveys which are commonly referenced:
    - HEAO-1 all sky (8.2 Sr) 2-10 keV; $S > 3\times10^{-11}$ erg s^{-1} cm^{-2} (Piccinotti et al 1982)
      85 sources detected; ~60 extragalactic; ~30 clusters; ~30 AGN (Seyfert 1s)
    - EMSS (Einstein Extended Medium Sensitivity Survey; Gioia et al 1990)
      hunt in 1435 0.3-3.5 keV IPC fields for serendipitous sources
      Ultimately, ~800 deg^2; varying flux limits; 835 sources; 51% Seyferts & QSOs; 4.3% BL Lacs.
    - ROSAT Deep Survey (Hassinger et al 1993) of the "Lockman Hole" (low N_H) at 0.5 - 2 keV
      ~660 sources detected (+ "sky" fluctuations give information on fainter sources)
    - ROSAT all sky survey (TBD)
    - Chandra Deep Field (TBD)

- There has been one all sky gamma ray survey (Thompson et al 1995)
  EGRET on Compton-GRO found 130 sources with $S > 10^{-11}$ erg s^{-1} cm^{-2} at 30 - 3000 MeV;
  of these, 40% (~50) were AGN.

(g) Variability & Proper Motion

- It transpires that essentially **all AGN are variable**.
  → variability may provide a relatively **unbiassed** selection method.
  Also, of course, AGN should have zero proper motion (!)
  Hence, a combined criteria will eliminate most variable star contaminators
  This method will be used in the upcoming LSST, which should detect 10^7 AGN.

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(6) AGN Demographics

- Overall, how common are the various types of AGN?
  As with all astrophysical objects, it depends on **luminosity**: many more low luminosity AGN.
  Our ability to analyse AGN populations depends, to some extent, on the range in luminosity.

(a) Frequency of AGN in the Local Galaxy Population

- First consider the spectroscopic surveys of complete samples of nearby galaxies.
  The most recent (prior to SDSS) is the Palomar survey by Ho, Fillipenko & Sargent.
  → 486 galaxies of all Hubble types, brighter than $B_T = 12.5$, north of $\delta = -2^o$
  Of their sample, 86% have emission lines (EW(Hα) $\gtrsim$ 1A); (100% of the spirals)
  Expressed in terms of emission types:

    - 40% have **HII emission** regions due to star formation
    - 30% are **LINERs**
    - 13% are **Seyferts** (with #Sy1 ~ #Sy 2)

  Combining LINERs & Seyferts:

→ **43% of all local galaxies could be considered active** !
This is **much** more than originally thought (e.g. in the 1970s)

- This may, however, be an **overestimate**:
  → close examination of the LINERs suggests two types:
  - Strong [OI] LINERs ([OI]6300/H$\alpha \geq 0.1$) are probably genuine weak AGN
  - Weak [OI] LINERs ([OI]6300/H$\alpha \leq 0.1$) are probably photoionized by stars

  their ratio is ~2:1, making the **total fraction of AGN closer to ~30%** (check)
- A conservative estimate comes from the incidence of detectable **broad** Hα.
  - 40% of all Seyferts
  - 15% of all LINERs (xx% of strong [OI] LINERs; 0% of weak [OI] LINERs)

  → **10% of all galaxies have a broad H**α component
  This latter number is a strict lower bound to AGN frequency
- The high frequency of weak AGN is consistent with the widespread presence of nuclear SMBH.

(b) AGN Preference for Big Bulges

- The spectroscopic surveys also find a link between emission type & Hubble type.
  As seen in these histograms: [image]
  - HII emission tends to be in **late type Spirals**, including lower luminosity galaxies;
  - LINERs & Seyferts tend inhabit **early type Spirals**, & avoid low luminosity galaxies

  → Activity favours galaxies with relatively luminous bulges.
  Similarly, the most luminous early type galaxies ($M_B \lesssim -22$) are ~all active.

(c) Higher Luminosities

- A very rough census of the **local** populations might go like this:
  (Note: 1 Gpc^3 ≡ sphere radius 620 Mpc ≡ out to z ~ 0.20h ≡ 2 Gyr lookback time)

Type	# Gpc^{-3}
Galaxies (excl. dwarfs)	10^8
Luminous Spirals	10^7
Weak AGN	$10^{6.5}$
Markarian Seyferts	10^5
Radio Galaxies	1000
Radio Quiet QSOs	100
Radio Loud QSRs	1

Clearly, **powerful AGN are locally very rare** (e.g. nearest QSR = 3C273 @ 480h^{-1} Mpc)
At redshift ~2 (10 Gyr ago), luminous AGN were much more common, by ~×1000 (see sec 16)

- More precise discriptions are **local AGN luminosity functions**
  These are usually defined for a given band (radio; optical; X-ray; rarely bolometric)
  It is often necessary to combine different samples (e.g. faint & bright), and
  correct for various types of bias (see Topic4.4)

  Here is one version of the optical luminosity function $\Phi(L,z=0)$: [image]
  Of course, it is the change of Φ with redshift that that helps define AGN evolution (sec 16)
- An alternative demographic is the **number of AGN per square degree of sky** (~5 full moons)
  This depends on AGN brightness & waveband, and in part measures a survey's relative efficiency.

Here is N(<B) deg^{-2} for QSOs, divided into $z < 2.2$ and $z > 2.2$ [image]
For example, above 21^m in B, there are ~30 QSOs with $z < 2.2$ and ~8 with $z > 2.2$
@ 22.5^m those numbers are 130 & 30, while @ 16^m there is ~1 QSO per constellation (10° square).
@ 13^m we have one QSO in the whole sky: it is 3C 273.

- Comparing with the other two bands at their approximate current limits :
  In X-rays, the ROSAT/EMSS survey finds ~100 AGN deg^{-2} above 10^{-14} erg/s/cm^2 (0.3-3.5 keV)
  In radio, one finds ~25 deg^{-2} at 5 GHz above 1 mJy (where most sources are still AGN)
  While many of the X-ray sources will also be optical QSOs, the radio sources will not.
  Surveys in the three main wavebands yield comparable numbers of AGN at their current limits

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(7) AGN Unified Schemes

- The huge diversity of AGN can be greatly simplified by first recognizing two **intrinsic** differences:
  - a continuous range of **luminosity**, from very weak to exceedingly powerful
  - a clear division into **radio loud** ($L_{GHz}/L_{opt} \sim 10^{-2}$) and **radio quiet** ($L_{GHz}/L_{opt} \sim 10^{-4}$)

- Can we gain further simplification by asking how **appearance** changes with **viewing angle**?
  The answer is **yes**...., to some extent.
  Below we identify various AGN pairings which may differ only by viewing angle
  Since viewing angle is essentially arbitrary, this **"Unifies"** the types involved

- Please note: **no-one** is suggesting that **all AGN are identical !**
  Just that there may not be quite as many sub-types as originally thought.

(a) Two Different Angle-Dependent Phenomena

- It is important to realise that there are **two different phenomena** invoked in unification schemes [image]

(i) Angle Dependent Obscuration

- Near nuclear regions may have dense gas which blocks some lines of sight into/out of the nucleus.
  → the ionizing radiation field may not emerge isotropically
  → we may or may not see the active nucleus.

- What we can/can't see depends on the location and opacity of the obscuring material
  Perhaps surprisingly, dense **molecular gas & dust** is often found in active nuclei
  It is thought that this dense phase provides the necessary UV-optical opacity

- The obscuring region is thought to lie somewhere **between the BLR and NLR** : 1 - few pc out.
  Its geometry is uncertain, though it is often assumed to be in a thick disk/torus
  This naturally yields an axis, possibly aligned with the inner AGN axis.
  There may, of course, be other obscuring material further out, e.g. within nuclear dust lanes

- In the simplest case, three components are **unaffected** by the obscuring region
  - Narrow Line Emission -- which originates outside the obscuring region
  - Hard X-rays -- which penetrate the region
  - Far IR -- which also penetrates the region (though probably not Near-IR or Mid-IR)

  → we expect these to be emitted **isotropically**
  AGN selected using these properties should yield **unbiassed** samples with regards orientation
  Such samples are important in exploring the Unified schemes.

(ii) Doppler Boosting of a Relativistic Jet

- Radio loud AGN are thought to have a relativistic jet.
  Emission from this jet will be **Doppler boosted** by the bulk flow in the forward direction.
  Depending on your viewing angle, you may see this emission brighter/unchanged/dimmer

- Boosting the jet base can increases the prominance of the flat spectrum core &/or VLBI jet
  Further out, the more extended (VLA, steeper spectrum) jet may also be boosted/suppressed

- However, the outermost (steep spectrum) radio lobes are **not** boosted (they move too slowly)
  Their emission is therefore thought to be **isotropic**
  → samples selcted by this extended flux should be **orientation independent**.

- Obviously, Doppler boosting is only invoked for unification within radio loud AGN

  Note: Doppler boosting should not be confused with two typographically related terms:

  - Doppler bootsing -- a very fast style of tap dancing
  - Doppler boosing -- drinking so fast you turn blue

(b) Seyfert 2s / Seyfert 1s

- This provides, perhaps, the clearest example of unification :
  → at least some Seyfert 2s are in fact Seyfert 1s seen from the "wrong" direction.

- The model invokes angle dependent obscuration: a ~pc scale (equatorial) dense region
  This region blocks the nuclear radiation, which enters the NLR/ENLR **anisotropically**
  For Seyfert 2s, it is argued, we are in the blocked (equatorial) sight line
  There are a number of (~independent) lines of evidence for this scenario:

(i) NLR/ENLR shapes

- NLR/ENLR shapes are studied by imaging AGN using narrow filters centered on emission lines.
  In fact, dividing the [OIII]5007 image by the Hα image reveals just the high ionization gas
  Here are some examples, most taken using HST [image]

- For Seyfert 2s the emission regions are very often elongated, a number having **(bi-)conical shape**
  Conversely, Seyfert 1s show such geometry much less frequently
  This is exactly what you expect for an equatorially blocked ionizing radiation field.

- One needs to be careful: bipolar radio (weak) jets are often associated with NLR emission
  → the ionizing radiation field is best probed using **ENLR** emission, beyond the radio source

- When cone geometry is observed, the cone opening angles are ~40-80°
  → ~25% of the sky witnesses the central source
  this is consistent with the ratio of Sy1/Sy2 in orientation independent samples (see below)

(ii) NLR vs nuclear luminosity comparison

- Our model assumes that, for Seyfert 2s, the NLR sees a much brighter nucleus than we do.
  → the NLR should be **more** luminous than we would guess from our view of the nucleus

- How do we estimate the (ionizing) luminosity **entering** the NLR ? **By using Hβ**
  → one ionizing photon makes one recombination which makes $\alpha_{H\beta} / \alpha_B = 0.118$ Hβ photons.
  (the α's are recombination coefficients)
  So, if Q_{ion} ionizing photons emerge isotropically from the nucleus, & a fraction C_i enter the NLR:
  → $L_{H\beta} = C_i\, Q_{ion} \times 0.118 \times 4.08 \times 10^{-12} = 5.11 \times 10^{-13}\, C_{ion}\, Q_{ion}$ erg s^{-1}

- Let's model the central source as a power law: $L_\nu \propto \nu^{-\alpha}$, or equivalently $L_\lambda = L_{\lambda ref}\, (\lambda/\lambda_{ref})^{\alpha-2}$
  where $L_{\lambda ref}$ is the luminosity in erg s^{-1} A^{-1} at a reference wavelength λ_{ref}
  Choosing $\lambda_{ref} = 912$A and integrating from 912 to ∞
  → the total number of ionizing photons is $Q_{ion} = 4.18\times 10^{13} \times (L_{\lambda 912} / \alpha)$
  Hence, we expect $L_{H\beta} = 21.4 \times C_i \times (L_{\lambda 912} / \alpha)$ erg s^{-1}

- Is this in fact what we find?

The comparison is tricky for a couple of reasons:
  The UV continuum is not easily accessible.
  The optical continuum is confused by starlight, especially in Seyfert 2s.
  C_i, the NLR covering factor, is uncertain: maybe ~25% from cone angle? (but not > 1 !)
The few UV observations available suggest: Seyfert 1s obey the relation while Seyfert 2s do not.

- Extrapolating the continuum into the optical, we have: $L_{\lambda 4800} = L_{\lambda 912}$ $(4800/912)^{\alpha-2}$
  → the Hβ **equivalent width**: EW(Hβ) = $L_{H\beta} / L_{\lambda 4800} = 21.3 \times 5.3^{2-\alpha} \times C_i$ Angstrom
  → EW(Hβ) $\approx 113\ C_i$ Ang. ($\alpha \approx 1$; and EW is w.r.t. the **non-stellar** optical continuum)
  This is, in fact, true for the BLR emission in Seyfert 1s, but is **too low** for Seyfert 2s
  → since C_i cannot be > 1, we conclude we **don't see the nuclear continuum** in Seyfert 2s.

- An alternative estimate of the total nuclear UV output is the reprocessed FIR emission:
  → $L_{UV} \approx L_{FIR} \approx 4\pi d^2 \times 1.8 \times 10^{-11}\ [13.5S_{12} + 5.2S_{25} + 2.6S_{60} + S_{100}]$ erg s^{-1} (Topic 11.2)
  As before, the IRAS luminosities imply much larger UV luminosities than we in fact see.

(iii) Q(nuc) from ENLR Radiation Parameter

- A similar analysis uses ENLR emission lines to estimate the UV flux impinging on it.
  The [SII]6717/6731 line ratio gives the electron/gas density in the ENLR
  other lines (eg [OIII]5007/[OII]3727 vs [OIII]5007/Hβ) give the radiation parameter, U,
  where $U = Q_{ion} / (4\pi R^2\ c\ n_e)$, and R is the separation between ENLR and the nucleus:
  → knowing R and n_e, we find Q_{ion}, which can be compared with the **observed** nuclear UV flux.
  → Again, it is clear we do **not** see the full UV radiation field in Seyfert 2s.

- The virtue of this analysis is that it is independent of covering factor
  The drawback is that it uses a (potentially uncertain) link between line ratios and ionizing flux.

(iv) Periscopic (Polarization) View of the Nucleus

- This is the most impressive demonstration that some Seyfert 2s hide a Seyfert 1 nucleus.
  light emerging along the polar axis can be scattered into our line of sight
  if we could see just the scattered light, we would be looking down the polar axis, like a periscope.
  Since scattering introduces linear polarization (E vector perp to radial vector):
  → do **spectropolarimetry** and extract just the polarized (scattered) light.

- Famous example: NGC 1068, a classic Seyfert 2:
  The spectrum of polarized light shows a Seyfert 1 spectrum! [image]
  A centro-symmetric polarization pattern pinpoints the location of the hidden AGN
  The amount of polarization is **independent of wavelength** :
  → scattered by **free electrons** (Thomson cross-section independent of λ in optical & UV).

  In NGC 1068 there is a **second** mirror located ~300pc out: an HII region containing **dust**
  This also yields a Seyfert 1 spectrum in polarized light, but with slight differences:

  it rises strongly into the blue, confirming dust as the scatterer
  the broad Hβ profile is slightly **narrower** & **blueshifted** by ~400 km/s w.r.t. the first mirror
  → the electrons have $T \sim 3\times10^5$ K which adds thermal broadening to the first mirror
  → the electrons in the first mirror are outflowing in a 400 km/s wind.

- So far ~half the Seyfert 2s studied show broad Hβ in polarized light
  The fraction could increase with better data (difficult work, often only ~1-few% net polarization).
  Still unclear whether there are any pure Seyfert 2s with **no** BLR or strong blue nucleus

- In general, polarization angles in Seyfert 2s are **perpendicular** to their radio axes.
  → consistent with radiation emerging along radio axis, some of which is scattered.
  → obscuration & black hole (jet) axes may be the same.
  → supports obscuration as thick equatorial disk, aligned with inner accretion disk.

(v) Nuclear Absorption: X-ray spectra

- Is there any **direct** evidence for a near-nuclear obscuring region?
In fact there is, and it comes from the X-ray spectra of Seyfert 1s and Seyfert 2s
Recall that with columns $\gtrsim 10^{22}$ cm^{-2} soft X-rays (0.2-4 keV) suffer significant absorption
Seyfert 2s tend to have X-ray spectra with soft absorption, while Seyfert 1s don't.
The derived columns are large: 10^{22} - 10^{24} cm^{-2} corresponding to $A_V \sim 5 - 500$.

- Hard X-rays (2-10 keV) lie above the photoelectric edges, and aren't absorbed at these columns
Do the hard X-ray spectra of Seyfert 2s resemble those of Seyfert 1s ?
Yes, they have the same slope and their luminosities approach those of Seyfert 1s
Also L(hard X)/L(UV-opt) is **high** in Seyfert 2s, because we aren't seeing the UV-opt emission.

- A couple of interesting details:
  - The soft X-rays are often thought to be **scattered**; showing strong FeKα periscopically
  - In NGC 1068 the column is ~10^{25} and even the hard X-rays are blocked (Thomson thick)
    → it is anomalously week in both soft and hard X-rays
    → it shows no soft absorption
    → it is thought to be **all** scattered
    → at 1% scattering efficiency, we recover a Seyfert 1 luminosity ~10^{44} erg s^{-1}

- AGN samples selected by hard X-rays are thought to be ~unbiased w.r.t. orientation

(vi) Nuclear Absorption: Molecular Masers

- Conditions for Masers: long low v path through dense gas exposed to strong pumping radiation
These conditions are met in many AGN nuclei; the most famous is NGC 4258 [Topic 14.4e]
The path lengths will be at their largest for **edge on** dense gas disks.

- Surveys of Seyferts find many H_2O masers, but only Seyfert 2s
→ consisent with expectations for obscuring tori
Unfortunately, few/none have the clean geometry of NGC 4248 allowing a BH mass determination.

(vii) Opening Angle

- A further check of the anisotropic absorption picture is the following:
Cone angles seen in ENLR's (~40-60°) predict relative numbers of Sy2 to Sy1 of ~2 to 1
Is this true for orientation independent samples?

- Broadly speaking, yes, though reliable samples are hard to come by.
  - Selected by Far-IR, gives #Sy2/#Sy1 ~ 2 (Kinney et al 1996 check)
  - Selected by [OIII]5007, gives #Sy2/#Sy1 ~ 5 (Salzer 1989)
  - Selected by host galaxy (ie spectroscopic surveys), gives #Sy2/#Sy1 ~ 1 (Ho et al)

  One concludes that the opening angle is significant, though perhaps less than 50% of the sky.

- Can this estimate be repeated at QSO luminosities? Not really, finding QSO-2s is very difficult.
It isn't yet clear whether the apparent lack of QSO-2s is because the opening angle widens to ~4π
or because obscured QSOs would fail to be found in, e.g., color & slitless surveys
FIR surveys **do** find buried AGN, though often the story is muddled by strong star formation.

(viii) Do All Seyfert 2s have Seyfert 1 Nuclei?

- The ease of detecting a hidden broad line region depends on the overall luminosity of the Seyfert 2.
It is therefore difficult to tell whether the ~50% of Seyfert 2s that fail to show hidden BLRs really don't have them.
→ It is not known whether AGN exist with no BLR.

(c) NLRGs / BLRGs

- Many of the approaches given above also apply to the NLRG / BLRG objects.
Usually, however, these objects are fainter and more distant and the results are less clearcut.

Here are examples of seeing hidden BLRs in two NLRGs: [image]

(d) Radio Loud: PRG-II / LD-QSR / CD-QSR

First recall there are two types of radio AGN: FR-I and FR-II [image]
To some extent, the unification schemes apply to these types differently.

- It is thought that **orientation** plays a role in unifying radio galaxies and QSRs: [images]
- It is thought that **beaming** plays a role in unifying core and lobe dominated QSRs.

(e) RG-I / BL-Lacs : straight down the beam

-

(f) Intrinsic Differences: Luminosity & Radio Loudness

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(8) Accretion Power

- The combination of high luminosity and variability places strong limits on AGN energy sources
  → they must be very compact and very efficient
- Hoyle & Fowler (1963) first recognized that **gravitational collapse** might power AGN engines.
  Zeldovich and, separately, Salpter (1964) proposed **accretion onto a massive black hole**
  This became **"the AGN paradigm"**, especially after a nice paper by Lynden-Bell (1974).
- Real accretion is likely to be complex and time varying, with many associated physical processes.
  Our discussion will be somewhat idealized -- but it provides a likely overall framework.
- There are a few inter-related themes:
  - A natural **maximum accretion rate** limits AGN luminosity and black hole growth rate
  - Even a little angular momentum will ensure the accreting gas forms an **accretion disk**
  - **Turbulent viscosity** allows gas to lose angular momentum, spiral in, & release energy.
  - Black hole spin sets the disk's **inner radius** which in turn sets the disk's net luminosity.
  - Finally, it seems that initial ("seed") black holes will inevitably form in galaxy nuclei.

(a) The Eddington Luminosity & Growth Rate

- Like people, black holes cannot gulp down food with arbitrary speed.
  One limitation, which primarily applies to spherical accretion, is due to Eddington (date).
- There is a feedback valve which regulates the accretion flow.
  → accretion luminosity generates an outward radiation pressure on the surrounding matter
  → this counters the inward gravitational force.
  → if the two are equal, the accretion flow is shut down
- The standard (oversimplified) scenario considers spherical accretion:
  A radiation field of energy flux F (erg s^{-1} cm^{-2}) has momentum flux (ie pressure) F/c
  [note units of F/c: erg $cm^{-3} \equiv$ energy density (U_{rad}) $\equiv$ pressure (P_{rad})]
  For a single electron, the outward radiation force is:
  $$F_{rad} = \sigma_T F/c = \sigma_T L/4\pi r^2 c$$
  where $\sigma_T = 6.65 \times 10^{-25}$ cm^{-2} is the Thomson cross section (~independent of E up to ~½MeV)
- The electrons are strongly tied to the protons, on which gravity principally acts:

$F_{grav} = GMm_p/r^2$

Hence the limiting **Eddington luminosity**, below which gravity "wins" (ie $F_{grav} = F_{rad}$) is:

$$L_{Edd} = (4\pi G c m_p)/\sigma_T \times M \;=\; 1.26 \times 10^{38}\, M/M_\odot \text{ erg s}^{-1} \;=\; 3.28 \times 10^4\, M/M_\odot\, L_\odot$$

→ Spherically accreting black holes of mass M cannot have luminosities **above** L_{Edd}

→ Conversely, accretion powered QSOs **demand** massive (~10^8 $M_\odot$) central objects

- We may tie this to a maximum (Eddington) accretion rate via the accretion efficiency, η
  A source with efficiency η radiating at L_{Edd}, accretes matter at a rate:
  $(dM/dt)_{Edd} = \eta^{-1} L_{Edd}/c^2 \;=\; 1.4 \times 10^{26}\, \eta_{0.1}^{-1} M_8 \text{ gm s}^{-1} \;=\; 2.2\, \eta_{0.1}^{-1} M_8\;\; M_\odot \text{ yr}^{-1}$

- Do black holes accrete at these maximum rates ?
  Estimates of M_{BH} typically find **sub-Eddington** luminosities: $L \approx 0.1\, L_{Edd}$

- The accretion rate provides a framework for studying **black hole growth times**
  Allowing for sub-Eddington accretion rates, L/L_{Edd}, we have:
  $dM_{BH}/dt = 2.2\, \eta_{0.1}^{-1} (L/L_{Edd}) \times 10^{-8} M_8\;\; M_\odot \text{ yr}^{-1}$
  yielding exponential growth with e-folding growth times:
  $t_{growth} \approx\; 4.5 \times 10^7\, \eta_{0.1}\, (L_{Edd}/L)$ yr

  Thus, growth from ~10^3 to 10^8 $M_\odot$ is ~10 e-foldings
  → 0.5 - 5 Gyr for $L/L_{Edd} = 1 - 0.1$ which seems reasonable for most AGN

- Some high-z high luminosity QSOs may demand **super-Eddington** accretion
  This is not too problematic.
  - Radiate above L_{Edd} by breaking spherical symmetry: equatorial accretion & polar emission.
  - Accrete above Mdot_{Edd}: optically thick flow traps radiation which is also swallowed.

(b) Thin Accretion Disks

(c) Accretion Efficiency: The Inner Radius

- Because the gravitational potential is so steep at small r, most energy is released in the inner disk.
  For this reason, the location of the innermost radius of the disk is crucially important
  For finite sized central objects, this is usually the object's surface radius
  For black holes, the inner disk radius depends on the black hole's **spin** (it is NOT just the horizon)

(i) Newtonian Point Mass Potential

- First consider a Newtonian point mass potential:
  Let's define the **gravitational radius**: $r_g = GM/c^2$ = distance where $PE_{grav} = -mc^2$ = -(rest mass)
  → one would need a total conversion of rest mass to energy to escape → not possible.
  → r_g is **very small**: $r_g = 1.5$ km $M/M_\odot = 1.0$ AU $M/10^8 M_\odot = 5$ mm M/M_E

- Escape velocity $v_{esc} = \surd(2GM/r)$ → $v_{esc} = c$ at a radius of $2GM/c^2 = 2r_g$
  Michel (1750) recognizes this as an important radius: light can't escape from inside $2r_g$
  By 1920s, this re-emerges as an **event horizon** for Schwarzchild black holes: $r_s = 2r_g$.

- Consider planar orbits in this Newtonian potential. (c.f. discussion in Topic 6.3c)
  The radial acceleration equation is (centrifugal - gravity):

$$\boxed{\ddot{r} \;=\; r\,\dot{\phi}^2 - \frac{\partial \Phi}{\partial r} \;=\; \frac{v_\perp^2}{r} - \frac{GM}{r^2}} \qquad (15.1)$$

Using the angular momentum per unit mass, $h = \mathbf{r} \times \mathbf{v} = r\, v_\perp$, we can rewrite this as:

$$\boxed{\ddot{r} \;=\; \frac{\partial\,\Phi_{\text{eff}}}{\partial\,r} \quad \text{where} \quad \Phi_{\text{eff}}(r) \;=\; \Phi(r) + \frac{h^2}{2r^2} \;=\; -\,\frac{GM}{r} + \frac{h^2}{2r^2}} \tag{15.2}$$

The **effective potential**, Φ_{eff}, allows us to describe the radial motion in 1-D form [image]

- For Newtonian, $\Phi_{N,eff}$ is zero at large r, slowly drops to a minimum before rising steeply at small r
  Stable circular orbits are found at the minimum in Φ_{eff} (lowest energy for given h)
  The inner steep term imposes an unsurmountable **angular momentum (or centrifugal) barrier**
  Only when h=0 (a radial orbit) can the trajectory strike the origin.

- Anticipating the relativistic regime, let's re-express 15.2:
  - include rest mass, so at large r the potential energy per unit mass → c^2 (not zero)
  - divide by c^2 to scale all energies relative to rest mass
  - express angular momenta relative to $r_g c$, using $H = h/r_g c$ per unit mass

$$\boxed{\frac{\Phi_{\text{N,eff}}(r)}{c^2} \;=\; 1 \,-\, \frac{GM}{c^2 r} \,+\, \frac{h^2}{2c^2 r^2} \;=\; 1 \,-\, \frac{r_g}{r} \,+\, \frac{H^2 r_g^2}{2r^2}} \tag{15.3}$$

We are now ready to compare this with the effective potential for black holes.

(ii) Schwarzchild (Non-Rotating) Potential

- Schwarzchild (1916) derived the metric for the space-time surrounding a point mass:

$$\boxed{ds^2 \;=\; A\,c^2 dt^2 - A^{-1} dr^2 + r^2 (d\theta^2 + sin^2\theta d\phi^2)\;,\;\; A \;=\; \left(1 - \frac{2r_g}{r}\right)} \tag{15.4}$$

Notice the discontinuity at $r = 2r_g$, and sign change of A when $r < 2r_g$
This radius is called the **Schwarzchild radius**: $r_S = 2r_g$
It marks an **event horizon**: inside r_S all light cones point **inwards** → a "boundary of no return"

- The relativistic effective potential per unit mass is given by:

$$\boxed{\frac{\Phi_{\text{S,eff}}(r)}{c^2} \;=\; 1 \,-\, \frac{r_g}{r} \,+\, \frac{H^2 r_g^2}{2r^2} \,-\, \frac{H^2 r_g^3}{r^3}} \tag{15.5}$$

- Comparing $\Phi_{S,eff}$ with $\Phi_{N,eff}$ we notice several important differences: [see image]
  - The $-(r_g/r)^3$ term ensures an inner turnover → the central AM barrier is **finite**
    → below a certain peri-center distance an orbit is pulled in.
  - For $H^2 > 12$, $\Phi_{S,eff}$ has a **minimum** just like $\Phi_{N,eff}$, allowing stable circular orbits
    → their radii are: $r_{co} = ½r_g\,[H^2 + \surd(H^4 - 12H^2)]$
  - For nearly circular orbits, the radial oscillation frequency is: $\kappa^2 = (d^2\Phi_{eff}/dr^2)_{r_{co}}$ [Topic 6.3c]
    Unlike the Newtonian case, this does **not** equal the orbital frequency
    → the orbits **do not close**, but instead **precess**
    → this is the origin of the famous precession of the perihelion of Mercury's orbit.
  - For $H^2 < 12$, there are **no minima or maxima**, so no persistent orbits exist
    → at $H_{crit} = 2\surd3$, the last circular orbit has radius $r_{lco} = ½r_g H^2 = 6r_g = 3r_S$
    → circular orbits with $r < 3r_S$ simply don't exist, they quickly spiral inwards.

- In an astrophysical context, gas enters the black hole via an accretion disk
  Viscous forces cause gas to slowly migrate to smaller circular orbits, releasing energy on the way

Finally, at $r = 3r_S$ the gas plunges into the black hole **without** dissipation of much further energy.
→ the binding energy **at $3r_S$** defines the total net accretion efficiency (**not** at r_S)
→ inserting $r = 3r_S$ and $H = 2\sqrt{3}$ into 14.5 gives $\Phi_{S,eff}/c^2 = 0.943$
→ the amount lost is: $\Phi_{S,eff}(\infty) - \Phi_{S,eff}(3r_S) = (1.0 - 0.943)c^2 = 0.057c^2$
→ simple accretion onto a Schwarzchild black hole is **~5.7% efficient**.
(The simple Newtonian estimate at $3r_S$ is ½ $GM/3r_s$ = 8.3%)

(iii) Rotating Black Holes

- Perhaps surprisingly, black holes can have **angular momentum**: investigated by Kerr (1963)
  In this case the metric shows "frame dragging" → a "whirlpool" of space
  → retrograde pointing rockets must fire to keep "stationary" as seen from afar

- In addition to the horizon, there is a new "surface": the **stationary limit**
  Inside the stationary limit even light cannot move in a retrograde direction ("flow" of space > c)
  The surface has an oblate axisymmetric shape:
  $r_{sl} = r_g \times [1 + \sqrt{(1 - a^2\cos^2\theta)}]$ [image]
  where a measures the BH AM per unit mass: $a = (J_{BH}/M_{BH})/(cr_g)$ scaled w.r.t. $c\, r_g$
  (note: a is sometimes defined as a length (Peacock) or mass (Krolik); here it is dimensionless)

- Meanwhile, the true horizon shrinks from the Schwarzchild value of $2r_g$ to:
  $r_h = r_g \times [1 + \sqrt{(1 - a^2)}]$
  Note that r_h is spherical, and meets r_{sl} at the poles.

- Plots of $\Phi_{K,eff}$ (not shown) for a rotating BH are similar to those of the Schwarzchild case:
  → circular orbits are allowed down to a last minimum radius, r_{lco}
  → as AM increases, r_{lco} **decreases** (increases for retrograde).
  There is a hard upper limit to AM: $a = 1$, for which $r_{lco} = r_g$ ($9\, r_g$ for retrograde)
  Inserting $a = 1$ and $r = r_g$ into $\Phi_{K,eff}$ yields a binding energy of 42% mc^2
  (the simple Newtonian efficiency is ½GM/r_g = 50%)
  In reality, optimum conditions can only create a = 0.998, which drops the yield to ~30%.

  Thus, the range a = 0 → 0.998 yields accretion efficiencies 6 - 30%
  Hence, the often used value, $\eta \approx 10\%$

- These efficiencies can yield enormous luminosities with only modest accretion rates:
  consider: $1\ M_\odot\ yr^{-1} = 2 \times 10^{33} / 3.17 \times 10^7 = 6.3 \times 10^{25}$ gm s^{-1} (M_E every 2 minutes)
  giving: $5.7 \times 10^{45}\ \eta_{0.1}\ M/M_\odot\ yr^{-1}$ erg s^{-1} ($\approx 1.4 \times 10^{12}\ L_\odot \approx 100\ L_*$ galaxies)
  → easily enough to power QSOs.

  Whether black holes can actually gorge themselves so fast is discussed below.

(d) Feeding the Disk

(i) Nuclear ISM

- TBD

(ii) Tidally Disrupted Stars

- Black hole sizes grow in proportion to their mass: $r_h \propto M_{BH}$
  This is unusual : constant density solids have $r \propto M^{1/3}$, degenerate matter has $r \propto M^{-1/3}$
  → black holes get "bigger" quickly

- Their mean density **drops**: $<\rho_{BH}> \equiv M / (4/3\pi r_h^3) \approx 1.7\ M_8^{-2}$ gm cm^{-3} (Schwarzchild hole).
  Obviously, for 1-few $M_\odot$ the mean density is huge, but SMBH are about like water !

- Tidal stretching forces behave in a similar way:
  Newtonian analysis: $T = dF/dr = 2GM/r^3 \approx 10^{-6} M_8^{-2}$ N m^{-1} at the horizon
  Again, for 1-few $M_\odot$, T ~ few million tons per meter; while for an SMBH it is imperceptible
  → you could happily fall into an SMBH and survive much of the journey to the singularity.

- Of more astrophysical interest: are stars tidally destroyed **before** or **after** entering the horizon?
  Before: the material will enter the accretion disk and liberate energy on the way in
  After: the star is already lost and its infall goes essentially unnoticed.

- The Roche criteria for tidal breakup of a self-gravitating object is discussed in Topic 12.3bi
  Breakup occurs if the mean density within the orbit is greater than the mean density of the orbiter
  Now, the mean black hole density within r_h is $1.7 \rightarrow 14\ M_8^{-2}$ gm cm^{-3} (Schwarzchild → Kerr).
  Whereas A0 → M0 main sequence stars have $<\rho> \approx 0.2 \rightarrow 2\ \rho_\odot \approx 0.3 \rightarrow 3$ gm cm^{-3}
  → Black holes with $M \gtrsim$ few × 10^8 will start swallowing main sequence stars whole.

  However, giant stars are 10 - 100 times $R_\odot$, with $<\rho> \sim 10^{-4} - 10^{-5}\ \rho_\odot$
  → Giant stars, while much rarer, are essentially always disrupted

(e) Extracting Rotational Energy?

- Previous estimates of engine efficiency, η, express this relative to the infalling mass.
  One factor which limits η is the final KE of the accreted mass: it is lost to the black hole.
  Is there a way to recover any of this energy, perhaps by "slowing" down the hole?

- First let's see how much energy is actually available.
  The mass/energy of a rotating hole is in two forms: rotational energy & irreducible mass
  For a maximal Kerr hole (a = 1) it is found that $M_{irr} = M_{BH} / \sqrt{2} \approx 0.71\ M_{BH}$
  Hence, the total available for extraction is 29% of M_{BH}: a significant amount!

- A purely dynamical process was suggested by Penrose (1969)
  Between r_h and r_{sl} lies the **ergosphere**: "ergo" = work/energy
  Within this region, imagine throwing an object "upstream" in a retrograde direction
  → space pushes everything prograde: the object falls in & you recoil and escape
  → you slowed the BH (a bit) and extracted some of its rotational energy!
  Unfortunately, the high "throw speed" required by this process is unlikely to occur naturally.

- An MHD process was suggested by Blandford & Znajek (1977)
  TBD

(f) Inevitability of Black Hole Formation

Since QSOs were common at z~2-4, supermassive black holes must form quite quickly.
There is currently much work on how this might have occurred, with no clear consensus.
Perhaps the first stars die to form the first black holes, which then grow by accretion?
Perhaps large gas clouds collapsed directly to form massive black holes?

Here is a famous figure by Martin Rees that shows many paths to forming Massive Black Holes: [image]

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(9) Continuum SEDs

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(10) Emission Line and Ionized Cloud Physics

Ionizing radiation from the central engine enters surrounding gas and ionizes it.
There are a number of simple phenomena related to this ionized gas worth discussing.

Recall, there are two emission regions in our standard picture: the BLR and the NLR [image]
How do we find out the properties of the gas in these regions?

(a) Simple Density Limits for the NLR and BLR

There are two kinds of emission lines:

- **Recombination lines** (e.g. Balmer H lines).
  These transitions are electric dipole, so occur easily,
  → they have very short lifetimes, and are called "**permitted**" transitions.

- **Collisionally excited lines**: ground state often split by small energies $\Delta E \sim kT$
  → thermal collisions can populate these low lying levels.
  De-excitation occurs either by <u>collisions</u> or <u>radiatively</u> & which dominates depends on which occurs fastest.

  Often, the radiative lifetimes are **long**, because the transitions are "**forbidden**"
  (only occur via electric quadrupole or magnetic dipole transitions).
  → tend to be suppressed at high densities, when collision times are fast.

  At the **critical density**, the radiative and collisional rates are equal.
  In gas with density above the critical density, the line is not strongly produced (collisionally suppressed).

  Here are some (Log) critical densities, in cm^{-3}, for some important emission lines:

C III] 1909	9.0	[Fe VIII] 5159.0	6.5
[O II] 3726.1	3.5	[N II] 5754.6	7.5
[O II] 3728.8	2.8	[O I] 6300.3	6.3
[Ne III] 3868.8	7.0	[Fe X] 6374.6	9.7
[Ne III] 3967.5	7.0	[N II] 6583.4	4.9
[O III] 4363.2	7.5	[S II] 6716.4	3.2
[O III] 5006.9	5.8	[S II] 6730.8	3.6

- We can use these to get rough estimates of the gas density in the NLR and BLR:

	NLR	BLR	
Forbidden Lines:	yes	no	e.g. [OIII] 5007 ($N_{cr} \sim 10^6$)
Semi-forbidden Lines:	yes	yes	e.g. CIII] 1909 ($N_{cr} \sim 10^9$)
Permitted Lines:	yes	yes	e.g. Hα, Hβ
→ density n_e cm^{-3}	$\lesssim 10^{4-6}$	$\gtrsim 10^{7.5}$	(absence of, e.g., [OIII] 4363)
		$\lesssim 10^9$	(presence of [CIII 1909)

Of course, a **range** of densities is likely present in both regions.
→ In fact, other evidence suggests at least some BLR gas has $n_e \sim 10^{11}$.

(b) Properties of a Homogeneous Gas at Single n_e and T_e

- Temperature sensitive line ratios have two upper levels with $\Delta E \gtrsim kT$

→ collisional excitation favors the lower level by $\exp(-\Delta E / kT)$
→ the line from this level is relatively stronger at lower temperature.

A good example is [OIII] 5007 / 4363 [image]

- Density sensitive line ratios have two upper levels with $\Delta E \lesssim kT$

→ collisional excitation gives equal populations

However the line strengths differ due to their different critical densities.

A good example is [SII] 6717 / 6731 [image]

- Of course, in detail, the line ratios are functions of both temperature **and** density [image]

One can then use various line ratios to hunt for a single combination of n_e and T_e [image]
This is only justified for a single emission region with uniform properties (**not**, usually, an entire NLR).

(c) The Structure of Ionized Clouds

- The NLR and BLR are thought to contain **clouds** that are photoionized by the central UV-X-ray source.

The clouds are **optically thick** to the ionizing Lyman continuum.
→ This leads to a layered cloud structure:
highly ionized front; decreasing ionization into the cloud; neutral/low ionization back [image].

- For a black body spectrum, ionization degree ~uniform up to Stromgren depth, then neutral.

For a power-law (AGN) spectrum, wide range of ionization & extended partially ionized region.
→ wide range of excitation (e.g. [OIII] **and** [OI] lines strong). [image]

- There is a long history of computing the structure and emergent spectrum from photoionized gas clouds.

The most widely used code is "CLOUDY", written by Gary Ferland [o-link1 and o-link2]
[Here is a nice vignette of its 1978 origins at the IoA Cambridge].

(d) The Radiation Parameter

- The most important parameter governing the emission from photoionized gas is the **radiation parameter**.

It is defined by the ratio of ionizing photon density to electron (gas) density at the front of the cloud:

$$\boxed{U = \frac{n_{ion}}{n_e} = \frac{Q_{ion}}{4\pi R^2\ c\ n_e} = \frac{F_{ion}}{h\nu_{ion}\ c\ n_e} = \frac{L_{ion}}{4\pi R^2 h\nu_{ion}\ c\ n_e}} \qquad (15.6)$$

where, more precisely, $Q_{ion} = \int L_\nu / h\nu \ d\nu$ from the Lyman limit to infinity.

- Basically, higher U gives more highly ionized gas, for the obvious reason:

greater photon density causes higher rates of ionization
greater electron density causes higher rates of recombination

→ Their ratio sets the equilibrium ionization degree.

- The emitted spectrum from a single cloud changes with U as you'd expect:

High U → stronger high ionization lines (e.g. [OIII], CIV etc)
Low U → stronger low ionization lines (e.g. [OI], [SII] etc)

Here are some calculated line strengths for a sequence of models with different U: [image]

(e) Calculating Simple Region Properties

Some simple relations yield estimates for some emission region properties
The examples used here are for a typical BLR.

(i) Mass of Ionized Gas

- Simple recombination physics gives the luminosity of $H\beta$:

$$\boxed{L_{H\beta} \simeq n_e\ n_p\ \alpha_{H\beta}\ h\nu_{H\beta}\ V_{gas}} \qquad (15.7)$$

where $\alpha_{H\beta} = 3.0 \times 10^{-14}$ cm^3 s^{-1} is the recombination coefficient for $H\beta$ (at T = 10^4K).
This gives V_{gas} (ionized gas volume) using measured values for $H\beta$ luminosity and gas density ($n_e \approx n_p$).

- This now gives the mass of ionized gas: $M_{gas} \approx V_{gas}\, n_p\, m_p$.
  This gives ~1 $M_\odot$ for the BLR and ~ 10^6 $M_\odot$ for the NLR

(ii) Region Size

Line ratios yield an estimate for the radiation parameter, U (see section 10d above).
Knowing U, Q_{ion}, and n_e now gives R, the distance from the ionizing source to the line emitting gas.

Using $n_e \sim 10^{9.5}$ for the BLR gives R ~ 0.1 - 1pc and $n_e \sim 10^5$ for the NLR gives R ~ 100 - 1000pc
[Note: this BLR size is **larger** than from time delay analysis -- see below, section 11.?]

(iii) Filling Factor of Ionized Gas

The filling factor for the ionized gas is defined to be V_{gas} / V_{region}
Typical values suggest the filling factors are **small** ~ 10^{-4}
→ The regions contain relatively small **clouds**, within an intercloud medium.

(iv) Cloud Size

- A simple estimate for the depth of the ionized region is given by the **Stromgren Depth**, d_S
  Balancing the total ionizations with total recombinations, per unit area, we have: [image]

$$\boxed{d_S\, n_e\, n_p\, \alpha_H = \frac{Q_{ion}}{4\pi R^2} = \frac{L_{ion}}{h\nu_{ion}\, 4\pi R^2}} \tag{15.8}$$

This yields relatively small clouds: ~10^{12} and 10^{14} cm for the BLR and NLR respectively.

- What about the more neutral region behind the Stromgren depth?
  In AGN BLR clouds, this is partially ionized by X-rays and heated by photo-ejected electrons
  Matching line ratios yields a **total** column density ~ 10^{22-23} cm^{-2}
  → Using a cloud density then yields cloud diameter ~10^{13-14} cm for the BLR (~ 1 AU).
  These are **small** compared to the region size, confirming the low filling factor.

(v) Cloud Numbers

Taking the volume of ionized gas to be ~d_S^3, we have for the number of clouds:
$N_{cl} \approx V_{gas} / d_S^3 \approx 10^{10}$
This is only a rough estimate because we've ignored the neutral material.

But the overall conclusion is: a region sparsely filled with many optically thick line emitting clouds.

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(11) The Broad Line Region

See Peterson Review: here

High density and anisotropic cloud emission: o-link

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(12) The Narrow Line Region

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(13) Intrinsic Absorption Lines

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(14) AGN Radio Properties : Cores, Jets, Lobes

Compilation of double radio sources by Leahy & Bridle is here: [o-link]

Paper on collimation in M87 is here

More high res (7mm VLBA) on nearby RGs is here

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(15) AGN Host Galaxies and Environment

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(16) AGN Evolution

include source counts; V/Vmax (Krolik ch 3)

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