An introduction to Active Galactic Nuclei. 1.

Paolo Padovani, ESO, Germany

• The beginning
• AGN main properties
• The AGN zoo: radio-quiet and loud AGN, Unified Schemes, and relativistic beaming
• AGN masses and physical evolution

September 17, 2013
It all started fifty years ago ...

3C 273: A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

By Dr. M. SCHMIDT

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THE only objects seen on a 200-in. plate near the positions of the components of the radio source 3C 273 reported by Hazard, Mackay and Shimmins in the preceding article are a star of about thirteenth magnitude and a faint star or jet. The jet has a width of 1"-2" and extends away from the star in position angle 43°. It is not visible within 11" from the star and ends abruptly at 20" from the star. The position of the star, kindly furnished by Dr. T. A. Matthews, is B.A. 12h 38m 33.5s ± 0.04s, Decl. +2° 10' 42.0" ± 0.05° (1950), or 1° east of component B of the radio source. The end of the jet is 1" east of component B. The close correlation between the radio structure and the star with the jet is suggestive and intriguing.

Spectra of the star were taken with the prime-focus spectrograph at the 200-in. telescope with dispersions of 400 and 190 Å per mm. They show a number of broad emission features on a rather blue continuum. The most prominent features, which have widths around 40 Å, are, in order of strength, at 5868, 5892, 5902 Å. These and other weaker emission bands are listed in the first column of Table I. For these faint bands with widths of 100-200 Å, the total range of wave-length is indicated.

The only explanation found for the spectrum involves a considerable red-shift. A red-shift Δλ/λ of 0.168 allows identification of four emission bands as Balmer lines, as indicated in Table I. Their relative strengths agree with this explanation. Other identifications based on the above red-shift involve the Mg II lines around 2796 Å, thus far only found in emission in the solar chromosphere, and a forbidden line of [O III] at 5007 Å. On this basis another [O III] line is expected at 4959 Å with a strength one-third that of the line at 5007 Å. Its detectability in the spectrum would be marginal. A weak emission band suspected at 5785 Å, or 4927 Å reduced for red-shift, does not fit the wave-length. No explanation is offered for the three very wide emission bands.

It thus appears that six emission bands with widths around 50 Å can be explained with a red-shift of 0.158. The differences between the observed and the expected wave-lengths amount to 6 Å at most and can be entirely understood in terms of the uncertainty of the wave-lengths. The present explanation is supported by observations of the infra-red spectrum communicated by Oke in a following article, and by the spectrum of another star-like object associated with the radio source 3C 48 discussed by Greenstein and Matthews in another communication.

The unprecedented identification of the spectrum of an apparently stellar object in terms of a large red-shift suggests either of the two following explanations.

(1) The stellar object is a star with a large gravitational red-shift. Its radius would then be of the order of 10 km. Preliminary considerations show that it would be extremely difficult, if not impossible, to account for the occurrence of permitted lines and a forbidden line with the same red-shift, and with widths of only 1 or 2 per cent of the wave-length.

(2) The stellar object is the nuclear region of a galaxy with a cosmological red-shift of 0.158, corresponding to an apparent velocity of 47,400 km/sec. The distance would be around 500 megaparsecs, and the diameter of the nuclear region would have to be less than 1 kiloparsec. This nuclear region would be about 100 times brighter optically than the luminous galaxy itself. It would be identified with radio sources thus far. If the optical jet and component A of the radio source are associated with the galaxy, they would be at a distance of 50 kiloparsecs, implying a time-scale of 10¹⁰ years. The total energy radiated in the optical range of constant luminosity would be of the order of 10¹⁹ ergs.

Only the detection of an irrefutable proper motion or parallax would definitively establish 3C 273 as an object within our Galaxy. At the present time, however, the explanation in terms of an extragalactic origin seems most direct and least objectionable.

I thank Dr. T. A. Matthews, who directed my attention to the radio source, and Drs. Greenstein and Oke for valuable discussions.
It all started fifty years ago ...

3C 273: A STAR-LIKE OBJECT WITH LARGE RED-SHIFT
z = 0.158

Quasar = quasi-stellar radio source
It all started fifty years ago ...

with a redshift $\Delta \lambda / \lambda_0 = 0.243$; the line at $\lambda 5102$ as H with $\Delta \lambda / \lambda_0 = 0.244$; and the line at $\lambda 5260$ as $\lambda 4226$, Ca i, with $\Delta \lambda / \lambda_0 = 0.245$. A redshift of 0.244 is consistent with the brightness of the foreground galaxy, but the interpretation is not beyond doubt.

The emission line in the spectrum of the brightest cluster galaxy is undoubtedly to be interpreted as [O ii] $\lambda 3726/29$, the most common emission line in the spectra of galaxies. It is by far the strongest line in the spectrum of Cyg A; on a spectrogram on which it would appear as strong as here, none of the other lines would be observable. One might consider the possibility that the [O ii] line is hidden by the strongest night sky line [O i] $\lambda 5577$ and that the emission line is one of the fainter lines of the Cyg A spectrum—but such an interpretation can be ruled out because it would require the presence of additional lines with observable intensity. The measured wavelength of the emission line is $5447.8 \pm 0.9$; the stated error is the deviation of the two individual values from their mean. On the assumption that the unshifted wave length of the [O ii] blend has the value 3727.7 valid for low density (Seaton and Osterbrock 1957), the redshift is $\Delta \lambda / \lambda_0 = 0.4614 \pm 0.0002$.

Using multicolor photometric photometry, Baum has derived a redshift of 0.44 $\pm$ 0.03 for two galaxies that are probable members of the cluster. This establishes that the galaxy with the strong emission line is indeed a member of the cluster. It is not unusual that the brightest galaxy in a cluster is of outstanding brightness. If the analogy to Cyg A is complete, the galaxy should be double and therefore brighter than the single
Quasar luminosities

- 3C 273: $L_{\text{bol}} \approx 10^{47}$ erg/s $\approx 3 \times 10^{13} L_\odot \approx 1,000$ bright galaxies

Vestergaard 2009
Quasars belong to the Active Galactic Nuclei (AGN) class

AGN main characteristics include:

1. High powers: most powerful "non-explosive" sources in the Universe
   - Visible up to large distances: current record \( z = 7.1 \)

2. Small emitting regions:
   - \( \approx \) a few light days (1 light-day = \( 2.6 \times 10^{15} \) cm = 1 millipc);
   - Very large energy densities

3. Broad-band emission: from the radio- to the \( \Gamma \)-ray band

4. Strong evolution: higher powers in the past, with peak at \( z \approx 2 \)

AGN phenomenon relatively rare: it affects \( \approx 1\% \) of galaxies (at a given time)

Active Galactic Nuclei
Tavecchio et al. 2001
Hopkins et al. (2007)
NED
September 17, 2013
Active Galactic Nuclei

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Hopkins et al. (2007)
AGN energy source

• What could explain the enormous and concentrated powers of AGN?
• Consensus reached (after a while) on supermassive black holes
Gravitational power

\[ E_{\text{acc}} = \frac{GMm}{R} \quad L_{\text{acc}} = \frac{GMm}{R} = \frac{GMm}{kR_s} = \frac{GMm}{k2GM} = \frac{c^2}{2k} \dot{m} \]

\[ L_{\text{acc}} = \eta mc^2 \]

\( \eta = 0.06 \) non-rotating BH
\( \eta = 0.42 \) maximally rotating BH
c.f. \( \eta \approx 0.007 \) for Hydrogen burning

\[ \dot{m} \equiv 2 \left( \frac{L_{\text{bol}}}{10^{46}} \right) \frac{M_\odot}{\text{yr}} \left( \frac{\eta}{0.1} \right) \]

\[ L_{\text{Edd}} = 1.3 \times 10^{46} \left( \frac{M}{10^8 M_\odot} \right) \text{erg/s} \]

1. \( L \leq L_{\text{Edd}} \rightarrow \) gives lower limit to BH mass \(( M_{3C 273} > 8 \times 10^8 M_\odot )\)
2. \( L/L_{\text{Edd}} \) measures how close to maximum accretion a BH is
Gravitational power and the Sun

Eddington 1920
Accretion spectrum

- Simple assumptions:
  ✓ matter and radiation in equilibrium: thermal radiation → black body emission
  ✓ most of the emission from deepest part of potential well → single blackbody radiating at T of innermost stable circular orbit (ISCO)
- Matter supposed to have some angular momentum: cannot fall radially → accretion disk

\[ L \approx 2\pi R_{ISCO}^2 \sigma T^4 \]

\[ L \approx \left(\frac{2\pi R_{ISCO}^2}{R_s^2}\right) \sigma T^4 R_s^2 \quad R_s^2 \propto M^2 \propto L_{Edd} \Rightarrow \]

\[ T \approx 10^6 \left(\frac{A_{rad}}{R_s^2}\right)^{-1/4} (L / 10^{46})^{-1/4} (L / L_{Edd})^{1/2} K \]

\[ T \approx 10^5 K \rightarrow \lambda_{peak} \approx 300 \text{ A} \]
Observed quasar spectra

Elvis et al. 1994
The AGN Zoo

AGN come in a large (and scary!) number of sub-classes:

Radio-quiet AGN

Type 1 & 2, QSO, QSO2, Seyfert 1, Seyfert 2, Seyfert 1.5, Seyfert 1.8, Seyfert 1.9, Narrow-line Seyfert 1, Liners

Radio-loud AGN

Type 1 & 2, blazars, flat- and steep-spectrum radio quasars, core-dominated, lobe-dominated, optically violent variable quasars, BL Lacertae objects (high-peaked, low-peaked, radio-selected, X-ray selected), high- and low-polarization quasars

Radio-galaxies: Fanaroff-Riley I & II, narrow-lined, broad-lined, high-excitation, low-excitation, GHz-peaked
The first quasars

quasar = quasi stellar radio source

3C 273

Tavecchio et al. 2001
The Existence of a Major New Constituent of the Universe: The Quasi-Stellar Galaxies

Allan Sandage
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
Received May 15, 1965

Abstract

Photometric, number count, and spectrographic evidence is presented to show that most of the blue, starlike objects fainter than $m_{pg} = 16^m$ found in color surveys of high-latitude fields are extragalactic and represent an entirely new class of objects. Members of the class called here quasi-stellar galaxies (QSG) resemble the quasi-stellar radio sources (QSS) in many optical properties, but they are radio-quiet. The QSG brighter than $m_{pg} = 19^m$ are $10^4$ times more numerous per square degree than the QSS that are brighter than 9 flux units. The surface density of QSG is about 4 objects per square degree to $m_{pg} = 19^m$.

The evidence is developed in three parts: (1) Photoelectric photometry shows that a fundamental change occurs in the color distribution of high-latitude blue objects at about $V = 14.5^m$. Brighter than this, the objects fall near the luminosity class V line of the $U - B, B - V$ diagram. Fainter than this, 80 per cent of the objects lie in the peculiar region known to be occupied by the quasi-stellar radio sources. (2) The observed integral-count-curve, $\log N(m)$, for objects in the Haro-Luyten catalogue undergoes a profound change of slope between $m_{pg} = 12^m$ and $m_{pg} = 15^m$, steepening and reaching a constant slope for $m_{pg}$ fainter than $16^m$. This magnitude interval is the same as that in which the color distribution changes, as discussed above. The slope fainter than $16^m$ is $d \log N(m)/dm = 0.383$. It is shown that this is the expected value from the theory of cosmological number counts for uniformly distributed objects with large redshifts. (3) Spectra of five of the faint blue objects are similar to spectra of quasi-stellar radio sources. Intense, sharp emission lines of forbidden [O III], [O II], and [Ne III], together with very broad (35 Å wide) lines of H$\beta$, H$\gamma$, H$\delta$, H$\alpha$, and [Ne V] are present in two of the five. Two broad emission lines are present in another at λ 3473 and λ 4279, identified as C IV (1550) and C III (1099). The other two objects have featureless spectra with only a blue continuum showing. The redshifts ($\Delta\lambda/\lambda_0$) for the three objects with lines are 0.0877, 0.1307, and 1.2410. The position of the objects in the redshift-apparent-magnitude diagram shows each of the three to be superluminous.

The space density of the quasi-stellar galaxies is estimated to be about $5 \times 10^{-8} \text{ QSG/cm}^2$, which is to be compared with the space density of normal galaxies of about $1 \times 10^{-78} \text{ galaxies/cm}^2$. The ratio, per unit volume, of QSG to QSS is estimated to be 500, which gives a lifetime of the QSG phase as $5 \times 10^8$ years if the lifetime of the radio source is $10^8$ years.

The objects would seem to be of major importance in the solution of the cosmological problem. They can be found at great distances because of their high luminosity. QSG at $B = 22^m$ are estimated to have a mean redshift of $\Delta\lambda/\lambda_0 \approx 5$ for a model universe of $q_0 = +1$. At these redshifts, we are sampling the universe in depth to 0.63 of the distance to the horizon (for $q_0 = +1$), and are looking back in time more than 0.9 of the way to the “creation event” in an evolutionary model. Study of the $m, z$- and log $N(m)$-curves using the QSG should eventually provide a crucial test of various cosmological models. But even more important, comparative study of the quasi-stellar galaxies and the intimately connected quasi-stellar radio sources is expected to shed light on the evolutionary processes of the violent events that characterize the two classes.
The radio-quiet – radio-loud dichotomy

Only applies to quasars!

Radio-loud $\Rightarrow R > 10$

\[ R = \frac{f_j}{f_B} \]
Radio quiet AGN

\[ \log P_r (5 \text{ GHz}) [\text{W Hz}^{-1}] \]

\[ \log L_{\text{opt}} (\text{V band}) [\text{erg s}^{-1} \text{ Hz}^{-1}] \]

\( \sim 1,000 \times \)
The radio-quiet – radio-loud distinction

- **Radio-loud AGN:** most energy non-thermal: powerful relativistic jets (can also have a thermal component [accretion disk])
- **Radio-quiet AGN:** jets not present or insignificant w.r.t total energy budget → thermal energy dominates
NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT†

ABSTRACT

Spectrograms of dispersion 37–200 Å/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from $\lambda$ 3727 to $\lambda$ 6711 found in planetary nebulae like NGC 1068 appear in the spectra of the two brightest spirals observed: NGC 1068 and NGC 4151.

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

The observed relative intensities of the emission lines exhibit large variations from nebula to nebula. Profiles of the emission lines show that all the lines are broadened, presumably by Doppler motion, by amounts varying up to 6000 km/sec for the total width of the hydrogen lines in NGC 4151 and NGC 7469. The hydrogen lines in NGC 4151 have relatively narrow cores with wide wings, 7800 km/sec in total breadth. Similar wings are found for the Balmer lines in NGC 7469. The lines of the other ions show no evidence of wide wings. Some of the lines exhibit strong asymmetries, usually in the sense that the violet side of the line is stronger than the red.

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

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

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

Many of the spectra of extragalactic nebulae obtained at the Mount Wilson and Lick observatories show one or more emission lines in addition to the usual absorption spectra. In particular, N. U. Mayall finds that 50 per cent of his spectra of spirals show the [O II] doublet $\lambda$ 3727 in emission either in the nuclear region or in the arms. However, only a very small proportion of extragalactic nebulae show spectra having many high-excitation emission lines localized in the nuclei. These emission features are similar to those found in planetary nebulae and are superposed on the characteristic solar-type absorption spectra. Twelve nebulae are now known which probably belong to this unusual class of objects. Most of them are intermediate-type spirals with ill-defined amorphous arms, their most consistent characteristic being an exceedingly luminous stellar or semistar nucleus which contains a relatively large percentage of the total light of the system. Plate I shows a photograph of NGC 4151, a typical example of this type of nebula.

Probably the easiest spectrographic observation of a member of this unusual class of objects was that of NGC 1068 by E. A. Fath, in which he found five emission and two absorption lines. In 1917, V. M. Slipher found hydrogen lines and the nebular lines N1 and N2 bright in the nucleus of NGC 5236. Shortly afterwards, Slipher made the discovery that the emission lines in NGC 1068 were not monochromatic images of the slit but were small “discs.” These findings were confirmed by Campbell and Moore.

* Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington, No. 671.
† Fellow of the National Research Council.
2 NGC 1068, 1275, 2782, 3077, 4227, 3516, 4051, 4151, 4258, 5548, 6814, and 7469.

20
Why the Seyfert 1 – Seyfert 2 distinction?

Narrow lines:
FWHM < 1,000 km/s
The importance of orientation

NGC 1068, Antonucci & Miller (1985)
The importance of orientation

NGC 1068, Antonucci & Miller (1985)

Nagao et al. 2004
FIG. 5.—Cutaway drawing of a continuum source and broad-line clouds surrounded by a geometrically and optically thick disk. Only photons traveling out along the polar directions can scatter into the line of sight. We would observe a high polarization in the plane perpendicular to the symmetry axis, which we presume to be the radio structure axis.
The “torus” opening angle

- The fraction of Sey 1’s depends on the “torus” half opening angle $\theta$; extreme cases:
  - $\theta = 0^\circ \rightarrow$ no Sey 1’s (covering fraction = 100%)
  - $\theta = 90^\circ \rightarrow$ all Sey 1’s (no torus)

- $\theta$ estimated from the observed fraction of Seyfert 1’s: 
  $1 - \cos \theta = \frac{N_{Sey1}^\theta}{N_{Sey1} + N_{Sey2}}$

- Tricky $\rightarrow$ selection needs to be done on isotropic properties

- Sey 1’s fraction $\approx 30 \% - 50\% \rightarrow \theta \approx 45^\circ - 60^\circ$
Radio galaxies and radio quasars

Barthel (1989)
\( \Gamma = (1 - \beta^2)^{-1/2} \) (Lorentz factor), \( \beta = v/c \)
\( \delta = 1/[(\Gamma(1 - \beta \cos \theta))] \) (Doppler factor)

\( \nu_{\text{obs}} = \delta \nu_{\text{em}} + \frac{I_{\nu}}{\nu^3} \) relativistic invariant \( \rightarrow \)

\( L_{\text{obs}} = \delta^3 L_{\text{em}} \) (but energy is conserved); \( L_{\text{obs}} = \delta^{p+\alpha} L_{\text{em}} \), \( p \sim 2 - 3 \)

- Strong evidence that jets are relativistic (\( v \sim c \)):
  1. Superluminal motion
  2. Synchrotron self–Compton emission (Marscher et al. 1979)
Superluminal motion

\[ t_A - t_B = t (1 - v/c \cos \theta) \]

\[ v_{\text{app}} = \frac{\Delta r}{t_A - t_B} = \frac{v \sin \theta}{(1 - v/c \cos \theta)} \]

\[ \theta \approx \frac{1}{\Gamma} \]

For \( v \geq 0.7c \), \( v_{\text{app}} > c \) for some \( \theta \)

e.g., \( v = 0.95c, \theta = 18^\circ \), \( v_{\text{app}} \sim 3c \)

\[ \Gamma > \left[ \left( \frac{v_{\text{app}}}{c} \right)^2 + 1 \right]^{1/2} \]

If \( v_{\text{app}} = 5c \) \( \rightarrow \Gamma > 5.1, \ v > 0.98 \ c \)

Rees (1966)
Superluminal motion

\[ v \approx v \cos \theta \]

\[ v \approx v \sin \theta \]

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\[ \theta \approx \frac{1}{\Gamma} \]

\[ \beta_{app} = \frac{v_{app}}{c} \]

(Urry & Padovani 1995)
Superluminal motion

3C 279
Superluminal Motion

$V_{app} \sim 5c$

(Wehrle et al. 2001)
Superluminal motion

Lister et al. (2009)
In practice in radio sources:

- $f_{\text{X-ray}}$ is predicted from $f_{\text{radio}}$ using the SSC formalism.
- $f_{\text{X-ray}}$ is compared to observed values.
- Turns out that $f_{\text{X-ray, predicted}} \gg f_{\text{X-ray, observed}}$.
- Simplest explanation: assumption of isotropic emission in radio band is wrong $\Rightarrow$ energy density much smaller than we think ($L_{\text{obs}} = \delta^3 L_{\text{em}}$); lower limit on Doppler factor $\delta$. 

$$e^- + \gamma_{\text{low-energy}} \rightarrow \gamma_{\text{high-energy}}$$
Relativistic Beaming: evidence and effects

\[ \Gamma = (1 - \beta^2)^{-1/2} \]
\[ \delta = 1/[\Gamma(1 - \Gamma \cos \theta)] \] (Doppler factor)
\[ \nu_{\text{obs}} = \delta \nu \] (observed frequency)
\[ L_{\text{obs}} = \delta^3 L_{\text{em}} \] (observed luminosity)

• Strong evidence that jets are relativistic \( (v \sim c) \):
  1. Superluminal motion
  2. Synchrotron self-Compton emission \( (\text{Marscher et al. 1979}) \)
  3. Powerful and variable \( \gamma \)-ray emission \( (\text{Maraschi et al. 1992}) \)

\[ \text{X-ray flux too large if isotropic emission} \]
\[ \text{high } L/R \text{ ratios, } \gamma \text{-rays would annihilate with X-rays through photon-photon collision if isotropic emission} \]

• Large Doppler factors \( \rightarrow \) large speeds + small angles

• Amplification: small \( \theta, \delta \sim 2\Gamma \rightarrow \Gamma = 10, \delta \sim 20, L_{\text{obs}} \sim 400 - 8,000 L_{\text{em}}; \Gamma = 30, \delta \sim 60, L_{\text{obs}} \sim 4,000 - 200,000 L_{\text{em}} \)
Blazar Properties
BL Lacs and Flat-Spectrum Radio Quasars

- Smooth, broad, non-thermal continuum (radio to $\gamma$-rays)
- Compact, strong radio sources
- Rapid variability (high $\Delta L/\Delta t$), high and variable polariz. ($P_{\text{opt}} > 3\%$)
- Strong indications of “relativistic beaming” (e.g., superluminal motion): “fast” jets forming a small angle with the line of sight

Sites of very high energy phenomena:
$E_{\text{max}} \sim 20$ TeV ($5 \times 10^{27}$ Hz) and $v_{\text{max}} \sim 0.9998c$

Nature’s free accelerators
Jet
Black Hole
Obscuring Torus

blazars

broad line sources (Type 1)
narrow line sources (Type 2)

Narrow Line Region
Broad Line Region
Accretion Disk

Urry & Padovani (1995)
The AGN Zoo: Unified Schemes

Type 2                           Type 1
≈ 40° – 90°                      ≈ 15° – 40° < 15°

Radio-loud
high-excit. RG¹/FRII² → SSRQ³ → FSRQ⁴  \{\text{blazars}\}
low-excit. RG¹/FRI                BL Lacs
≈ 45° – 90°                      < 45°

Radio-quiet
Seyfert 2                         Seyfert 1
QSO 2                             QSO

\text{edge-on} \quad \text{face-on}

\text{decreasing angle to the line of sight}

¹ radio galaxies
² Fanaroff–Riley
³ steep-spectrum radio quasars (also LPQs, lobe-dominated)
⁴ flat-spectrum radio quasars (also HPQs, core-dominated, OVVs, …)
The full AGN variety can be explained by only three (four?) parameters:

- angle; *Seyfert 1 – 2, radio quasars – radio galaxies, etc.*
- presence (or lack of) jets; *radio-loud – radio-quiet*
- accretion rate: \( \frac{L}{L_{\text{Edd}}} < 0.01 \) \( \rightarrow \) no broad line region or obscuring torus
- power (?): opening angle might depend on it
The full AGN variety can be explained by only three (four?) parameters:

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Trump et al. 2011
Simpson 2005
Bianchi et al. 2012

broad-lined AGN
narrow-lined AGN

Fraction of AGNs vs. \( \log \left( \frac{L_1}{L_{\text{Edd}}} \right) \)

Type 1 fraction
Type 1 fraction 0.5
Type 1 fraction 1

Models given in Gilli et al. [136]
The full AGN variety can be explained by only three (four?) parameters:

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- Presence (or lack of) jets; radio-loud – radio-quiet
- Accretion rate: \( L/L_{\text{Edd}} < 0.01 \) \( \Rightarrow \) no broad line region or obscuring torus
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Figure 8: Fraction of type 2 AGN as a function of X-ray luminosity (from Hasinger [132]). The solid symbols show hard X-ray selected AGN (blue and black symbols illustrate different sub-samples in terms of redshift completeness). The red dotted symbols show optically selected AGN (from Simpson [128]). The magenta line shows the type 2 fraction inferred from the dust covering factor obtained through near/mid-IR observations (from Maiolino et al. [133], note that these include also Compton-thick AGN, which are not present in X-ray samples). The green dotted line shows the expected fraction of Compton-thin type 2 AGN according to the X-ray background synthesis models given in Gilli et al. [136]).
AGN masses

• Estimated through the virial theorem applied to the broad line clouds
  \[ \langle T \rangle = -\langle U \rangle/2 : mv^2/2 = GmM/2r \rightarrow M = rv^2/G \]
• Two parameters needed:
  ✓ velocity \( \rightarrow \) from Doppler line broadening
  ✓ distance \( \rightarrow \) through “reverberation mapping”
• Bound motion required: \( rv^2=\text{const} \rightarrow v \propto r^{-1/2} \propto T^{-1/2} \)

\[
M = f \frac{rv^2}{G}
\]

• Mass range: \( 10^6 - 10^9 \) Mo
• Almost always \( L \lesssim L_{\text{Edd}} \)
Estimated through the virial theorem applied to the broad line clouds:

\[ <T> = \frac{-<U>}{2} = \frac{mv^2}{2} = \frac{GmM}{2r} \]

\[ M = \frac{rv^2}{G} \]

Two parameters needed:
- Velocity \(v\) from Doppler line broadening
- Distance \(r\) through "reverberation mapping"

Bound motion required:

\[ rv^2 = \text{const} \]

Mass range: \(10^6 - 10^9\) Mo

Almost always \(L \approx L_{\text{Edd}}\)

P. Padovani – Black Holes at all scales

AGN masses

(Peterson 2001)
Estimated through the virial theorem applied to the broad line clouds:

\[ \langle T \rangle = -\langle U \rangle /2 = \frac{G m M}{2r} \]

\[ M = \frac{r v^2}{G} \]

Two parameters needed:
- velocity from Doppler line broadening
- distance through "reverberation mapping"

Bound motion required:
\[ r v^2 = \text{const} \]
\[ v = \sqrt{\text{const} \cdot \frac{1}{r}} \]

Mass range: \( 10^6 \) – \( 10^9 \) Mo

Almost always \( L \ll L_{\text{Edd}} \)

AGN masses

Peterson 2001

Bentz et al. 2010
41 local AGN
(z ≤ 0.158)

$R_{\text{BLR}} \propto L^{\frac{1}{2}}$

$\alpha = 0.533^{+0.035}_{-0.033}$

$\sigma = 0.19^{+0.02}_{-0.02}$ dex

Bentz et al. 2013
AGN physical evolution. 1.

\[ M = \int \dot{m} \, dt + M_i = \frac{(1-\eta)}{\eta c^2} \int L(t) \, dt + M_i \]

\[ M \approx 1.6 \times 10^9 \frac{(L_{bol} / 10^{46}) (\Delta T / \text{Gyr})}{(\eta / 0.1)} M_\odot + M_i \quad (L = \text{const.}) \]

3C273 \quad M \approx 10^9 M_\odot \quad \& \quad L_{bol} \approx 10^{47} \text{ erg/s} \quad \rightarrow \Delta T < 6 \times 10^7 \text{ yr}

- Large AGN samples indicate activity times 
  \approx a \text{ few } \% \text{ of the Hubble time (Cavaliere \& Padovani 1989)}
\[ \rho(M_{\text{AGN}}) \approx 10^{12} \text{ Mo/Gpc}^3 \]

\[ \rho(M_{\text{acc}}) \approx 2 \times 10^{14} \text{ Mo/Gpc}^3 \]

Marconi et al. 2004
Things to remember

• AGN are powered by black holes
• Accretion power peaks in the UV band
• The radio-loud – radio-quiet AGN distinction reflects different ratios of jet (non-thermal)/disk (thermal) power
• The profusion of AGN classes is an illusion (mostly) due to the non-spherically symmetric inner structure of AGN
• Know your AGN classes (please!!!)
• Jets in blazars are moving close to c and to the line of sight (relativistic beaming)
• AGN have been active only for a small fraction of the life of the Universe
• Most bright galaxies have been through an AGN phase