What are quasars and active galaxies?

- Probably the same phenomena: a supermassive black hole at the nucleus of a galaxy. The differences come from:
  - how fast the black hole is fed
  - how much dust is near it
  - what angle we view it

The unified phenomena are termed "AGNs" for Active Galactic Nuclei.
TORUS (The Obscuration Required by Unified Schemes)
Quasars

Key points:

• Active Galactic Nuclei: powerful energy sources in nuclei of some galaxies

• Types: Seyferts, quasars, blazars and radio galaxies.

• Power source: accretion of matter onto a supermassive black hole.
Radio galaxies: main classes

Large radio galaxies with lobes are divided into two types called *Fanaroff-Riley (1974)* type I and II:

FRI: weaker radio sources that are bright in the center and fainter towards edge of lobes.

FRII: stronger radio sources that are brighter towards the limbs.

Luminosity transition around $L_{1.4\,\text{GHz}}=10^{25} \, \text{J/s/Hz}$
Example FRI and FRII morphologies:
Quasars resemble High Power (FR II) radio galaxies
More quasars

Quasar 3C334
VLA 6cm image (c) NRAO 1996

3C279 MERLIN 1.67GHz
More quasars

Vintage Quasar Model Gx3621...
$71.99
Used
eBay

Quasar Gx3604 Cassette Radio...
$67.46
Used
eBay

Vintage Quasar Gx-3611 Boombox...
$79.99
Used
eBay
Nearby Blazar 0706+591
Nearby Blazar 0706+591

0706+591

10 kpc
AGN classification

- Narrow Lines
- Broad Lines
- Synchrotron

**Radio-quiet**
- Type 2
  - Seyfert 2
  - Radio-quiet
  - Quasars

**Radio-loud**
- Type 1
  - Seyfert 1
  - Radio-loud
  - Blazars
- Type 0
  - Core-dominated
  - Quasars
  - HPQ, OVV
  - FSRQ

Luminosity
TORUS (The Obscuration Required by Unified Schemes)
Proposed by Rowan-Robinson in 1977, and became a popular model in the mid-80s.
Model for the central region: SMBH, surrounded by accretion disk containing infalling material. If conditions are right, the AGN may possess a magnetically confined jet (the source of radio emission).
Gas pressures and temps get very high in inner accretion disk – matter can be expelled away from disk in 2 jets.

Jets kept narrow by magnetic fields.
Support for unification:

Direct imaging of torus
Free-free absorption in 1946+708

Peck & Taylor (2001)
Spectral index map from 1.3/5 GHz VLBI observations

1946+708 Spectral Index

Relative Decl. (mas)

Relative R.A. (mas)

-1.5 -1 -0.5 0 0.5

SP INDEX

20 pc
Energy source

• AGN power output truly huge.

• Comes from release of potential energy as gas falls toward black hole.

\[ PE = -\frac{G m_{\text{gas}} M_{bh}}{r} \]

• Energy released when a particle falls toward a black hole is the difference between its potential energy when \( r = \infty \) and when \( r \rightarrow R_s \)

• Change in energy = \( -\frac{G m_{\text{gas}} M_{bh}}{\infty} + \frac{G m_{\text{gas}} M_{bh}}{r} \)
  \[ = 0 + \text{very large number!} \]
Energy source

\[ V_{esc} = \sqrt{\frac{2GM}{R}} \]

\[ P_e \cdot E = -\frac{GmM_{BH}}{\rho_0} + \frac{GMmM_{BH}}{r_g} \quad r_g = \frac{2GM}{c^2} \]

\[ K_E = P_e \cdot E = \frac{\frac{5mM_{BH}}{2GM}}{\frac{2GM}{c^2}} = \frac{1}{2} c^2 m_{gas} \quad E = mc^2 \]

\[ \frac{1}{2} mv^2 = P_e \cdot E = E = \frac{1}{2} m_{gas} c^2 \]

\[ E_S = \frac{1}{2} mc^2 \]

\[ L = \frac{1}{2} mc^2 \leq \epsilon \cdot mc^2 \]
Bondi Accretion

\[ v = \left( \frac{2GM}{R} \right)^{1/2} = c \left( \frac{R_g}{R} \right)^{1/2} \]

\[ L = 0.5 \ M \ c^2 \left( \frac{R_g}{R} \right) \]

\[ L = \varepsilon \ M \ c^2 \]

c = speed of light
\( v \) = velocity
\( R \) = object radius
\( R_g \) = gravitational radius
\( \varepsilon \) = efficiency

\[ \varepsilon = 3 \times 10^{-4} \] for a white dwarf, \( 0.15 \) for a neutron star
\( \varepsilon \) up to \( 0.5 \) for a rotating black hole

Compared to \( 7 \times 10^{-3} \) for hydrogen fusion, or \( 10^{-9} \) for chemical reactions

Accretion is a very efficient energy source
How much luminosity can an AGN make?

The Eddington luminosity is the maximum possible luminosity that can be radiated without blowing away the accreting gas (via radiation pressure).

\[ L_{\text{edd}} = 3 \times 10^4 \left( \frac{M}{M_{\text{sun}}} \right) L_{\text{sun}} \]

\( M = \text{black hole mass} \)

Worksheet 11
Worksheet 11 solution

a) \[ \text{L}_{\text{ell}} = 3 \times 10^7 \cdot 10^9 \text{ cm} \]
   \[ = 3 \times 10^{13} \text{ cm} = E \cdot mc^2 \]

b) \[ 3 \times 10^{13} \text{ cm} = \frac{1}{2} mc^2 \]

c) \[ \dot{m} = \frac{g}{c^2} \cdot 3 \times 10^{13} \text{ cm} = \frac{6 \times 10^{13} \text{ cm} \cdot 3.8 \times 10^{26} \text{ kg}}{140 \times (3 \times 10^8 \text{ m/s})^2} \]
   \[ = 2.56 \times 10^{-23} \text{ kg/s} = \frac{1 \text{ MeV}}{1 \text{ GeV}} \]
   \[ = 1.28 \times 10^{-27} \text{ kg/s} = \frac{3.1 \text{ eV}}{1 \text{ eV}} \]
   \[ = 4 \mu \text{C} / \mu \text{r} \]
Spectral Energy Distributions (SEDs) for AGN

$L_{\text{IR}}$ contains up to 1/3 of the bolometric luminosity $L_{\text{bol}}$

$L_{\text{BBB}}$ contains a large fraction of $L_{\text{bol}}$ as well

IR bump due to dust reradiation

BBB due to blackbody emission from accretion disk
M87

Abdo et al. (2009)
The accretion disk around a black hole in NGC 4261
Faraday Rotation

\[ \psi = \psi_0 + RM \lambda^2 \]

\[ RM = 812 \int_0^{n_e B_\parallel} dl \text{ radians/m}^2 \]

Polarized Source
Superluminal radio jets

• Surprise: when the VLA and the VLBA were used to look right down the AGN nuclei in radio galaxies, the material looked as though it was moving many times faster than the speed of light.

• Astronomers realized that this apparent "superluminal" speed is an optical illusion of looking at jets moving just under the speed of light.
3C 279
Superluminal Motion

1992.0

1993.0

1994.0

1995.0

5 milliarcseconds
EXAMPLE 2
Superluminal motion

Pearson et al. 1981

c constant expansion observed at
rate = Δθ/year = 0.76 ± 0.04 mas/year
z = 0.158 so D = 940 Mpc
assuming H₀ = 50 km sec⁻¹ Mpc⁻¹.
1 mas = 10⁻³ arcsec = 4.85 x 10⁻⁹ radians
d = DΔθ so the apparent transverse velocity, or rate = d/year
    = 10 lt-years/year
    = 10 c [!!]
An Explanation of Superluminal Motion

An object moving almost directly toward the Earth at a high speed (but slower than light) can appear to be going faster than light. (a) If a blob of material ejected from a quasar moves at five-sixths of the speed of light, it covers the 5 light-years from point A to point B in six years. In the case shown here, it moves 4 light-years toward the Earth and 3 light-years in a transverse direction. The light emitted by the blob at A reaches us in 2000. The light emitted by the blob at B reaches us in 2002. The light left the blob at B six years later than the light from A but had four fewer light-years to travel to reach us. (b) From Earth we can see only the blob’s transverse motion across the sky, as in Figure 27-18. It appears that the blob has traveled 3 light-years in just two years, so its apparent speed is \( \frac{3}{2} \) of the speed of light, or 1.5 times \( c \).

\[
\beta_{\text{app}} = \frac{\beta \sin(\theta)}{1 - \beta \cos(\theta)}
\]
Apparent Velocity as a function of angle

\[ \gamma = \text{Lorentz Factor} \]
Why are AGN interesting?
a) For studying black hole physics
b) Studying high energy physics
c) Background sources on cosmological scales
   a) Lyman alpha forest in optical spectra (absorbing gas in walls? IGM information)
   b) Gravitationally lensed by clusters, can get Hubble constant from time delay
c) background radiation to detect absorption lines in host galaxies at large redshifts

d) produce cosmic background radiation, e.g. X-ray wavelengths

d) Use radio cores as cosmic reference points for fixed coordinate systems

e) History of the Milky Way: have all galaxies been an AGN at some point? Are they still?
Questions

• How do supermassive black holes form?
  – formation and growth of supermassive black holes are tightly coupled to
    the formation of the bulge of a galaxy.

• How are they fueled?
  – Galaxy interactions might dump gas into the nuclear region
  – Stellar bars might be able to funnel gas into the nucleus from the disk
  – Cannibalism of a gas-rich dwarf?

• Do most galaxies have supermassive black holes?
  – Probably, growing amount of dynamical evidence for the presence of
    massive black holes in many nearby, but otherwise "inactive" galaxy
    nuclei (including our own Galaxy)

• Where are all the dead quasars lurking?
  – There were many more AGNs in the distant past, but few today
High Redshift Quasars

- Radio Selected
- Optically Selected
- Sloan Digital Sky Survey

Maximum Known Quasar Redshift vs Date of Publication

- 3C 9
- 3C 147
- 3C 1116+12
- 3C 25.05
- 3C 273
- 3C 295
- RD J0301
- PC 0910+5625
- PC 1158+4635
- PC 1247+3406
Indications of rapid increase of H I Opacity at z ~ 4
Detection of Gunn-Peterson Troughs in $z \sim 6$ Quasars in 2001

Becker et al (2001)
Rapid increase in H I Opacity at $z \sim 6$

Gravitational Lensing of Quasars

Optical with Hubble Space Telescope

Radio with VLA
Myers et al. 1999
What we have Learned

• The number density of quasars drops dramatically at $z > 3$
• Billion solar mass black holes can form within a billion years of the big bang
• The Epoch of Reionization (EoR) ends around $6 < z < 8$ after which the Universe is fully ionized (again)