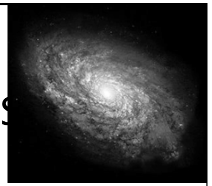
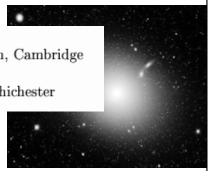
FORMATION AND EVOLUTION OF GALAXIES



Y4 tutorial

- Manifestations of "nuclear activity"
  - Nearby universe/low-luminosity AGN
  - QSO's and AGN in the high-z universe
- Ubiquitous super-massive black holes at galaxy centres
  - Our Milky Way and nearby Galaxies
  - High-z galaxies
- Cosmic Census of Accretion and Black Hole Growth
  - The Impact of BH Accretion on Galaxies



Literature:
"An Introduction to Active Galactic Nuclei", Bradley M. Peterson, Cambridge University Press, Cambridge
"Active Galactic Nuclei", Ian Robson, John Wiley & Sons, Chichester

Somak Raychaudhury

Size of a black hole

Schwarzschild radius

$$R_S = \frac{2GM}{c^2}$$

Mass	$R_S=3\left(\frac{M}{M_\oplus}\right)$ km	Innermost stable orbit=$3R_S$
1 Earth mass	2 cm	6 cm
1 Solar mass	3 km	9 km
10 Solar masses	30 km	90 km
1 million Solar masses	3 million km ~ 4 x	9 million km Solar radius!

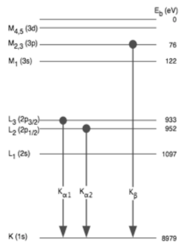
SMBHs exist in cores of all large galaxies

- Stellar kinematics in the core of the galaxy
- Optical spectra: the width of the spectral line from broad emission lines
- X-ray spectra: The iron Kα line is seen is clearly seen in some AGN spectra
- The bolometric luminosities of the central regions of some galaxies is much larger than the Eddington luminosity
- Variability in X-rays: Causality demands that the scale of variability corresponds to an upper limit to the light-travel time

The Fe Kα emission line

K-alpha emission lines result when an electron transitions to the innermost "K" shell (principal quantum number 1) from a 2p orbital of the "L" shell (with principal quantum number 2)

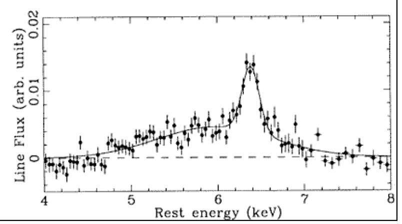
Same as Lyα in Hydrogen



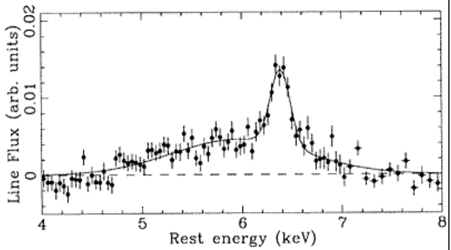
Moseley's Law:

Energy of K-alpha for $_{26}$Fe

$=10.2\,(Z-1)^2$ eV
$=10.2\,(26-1)^2$ eV
$= 6.38$ keV.

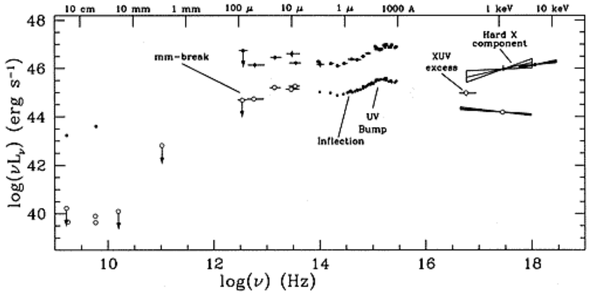


Broad red wing of Fe Kα emission
→ reflection of X-ray continuum off inner accretion disk



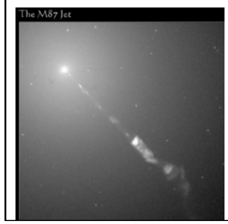
Nandra et al. ASCA composite for Seyfert 1s

Continuum Spectral energy distributions



Radio: Synchrotron (relativistic electrons in B-field)
Mm-1 micron: Dust emission
1 micron - .2 keV: Thermal emission from optically thick accretion disk
X-rays: Synchrotron, Inverse Compton, Hot corona + reflection

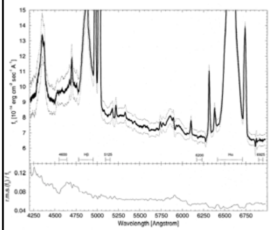
AGN Types
1) Radio Galaxies



- Radio emission comes from lobes 0.1-0.5Mpc
- Radiation is synchrotron emission
- $L_{radio} \sim 10^{8\text{-}10}\ L_o$
- Reside almost exclusively in massive galaxies
- Particle acceleration to $>10^{12}$ MeV

- **Note:** all ‘radio AGN’ show other signs of nuclear activity, but not all AGN have radio jets/lobes

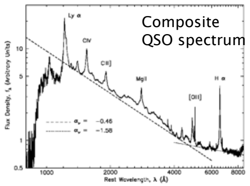
AGN Types
2) Seyfert galaxies



- Bright, unresolved nuclei 10^{45} erg/s
- Forbidden emission lines narrow (300km/s)
- Permitted emission lines (in Seyfert 1) broad: ~3000km/s
- Line ratios exclude photo-ionization by hot stars
- From Variability studies (light travel time continuum → broad lines:$R_{\text{broa-lines}}$ ~0.01-1pc

AGN Types: 3) luminous Quasars (QSO)

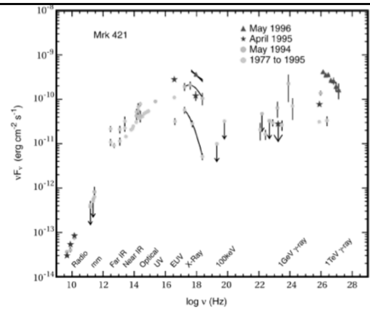
1963 M. Schmidt discovers that the radio source 3C273 can be identified with an optical point source (stellar) with a jet. The spectrum shows broad emission lines $H_{\beta,\gamma,\delta,...}$, MgII, OIII ... which are redshifted by $z = 0.158 \Rightarrow v_rad = 47400\frac{km}{s}$. So, the object was called a **QUAsi StellAr Radio source** → QUASAR.



- Bright, unresolved nuclei of galaxies, at 10^{48} erg/s they can outshine their host galaxy by x100
- Continuum: not black-body
- Broad lines: ~3000km/s
- Found at redshifts z~0...6.5, with a peak at z~2 → phenomenon more common in the past
- Phenomenon rare or common but short-lived phase:

$n_{galaxy} \sim 100 - 10.000\ n_{QSO}$

AGN Emission Across the Energy Spectrum



It turns out that to explain emission across such a vast range of energy, one needs a combination of:

- accretion disk (multiple black-bodies)
- Relativistic particle acceleration (including jets)
- Dust (at 50K), heated by the radiation from the accretion disk

Orientation effects (jets, relativistic beaming) must play role

What powers most AGN?

- From what region does the activity emerge?
- AGN vary at many wavelengths
- More rapid variability for more energetic variation
- Size < c x $t_{variability}$

radio/optical	$\Delta t_{obs} \simeq 10d$	$\Rightarrow$	$l_{emis} \simeq 0.01pc$
radio/optical	$\Delta t_{obs} \simeq 1d$	$\Rightarrow$	$l_{emis} \simeq 10^{-3}pc$
TeV	$\Delta t_{obs} \simeq 1h$	$\Rightarrow$	$l_{emis} \simeq 10^{-5}pc$

Possible Power Sources

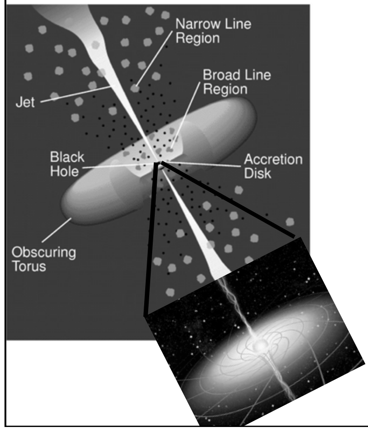
- Stars?

$N_\star = 3 \cdot 10^8$ O stars $\quad n_\star = \frac{N_\star}{\frac{4\pi}{3}[\frac{l}{2}]^3} \geq 2 \cdot 10^{14} pc^{-3}$

- AGN do not show stellar spectra
- → **No!**

- Supernovae?
- $L_{supernova}$~10^9 L_* → every QSO has 10^4 SN at any point in time
- → **No!**

The (Now) Standard Picture:
AGN are Powered by Accretion onto Black Holes



- **What are black holes?**
  - **GR analog to point masses**
  - **Two numbers to characterize them**
    - **Mass M_{BH}**
    - **Spin (or not)**
  - **"Size of the black hole" Schwarzschild Radius**

$$R_S = \frac{2GM_{BH}}{c^2}$$

$\frac{M}{M_\odot}$	R_S
10^6	$10^{-7}pc$
10^8	$10^{-5}pc$
10^9	$30^{-4}pc$

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Energetics of accretion onto a black hole

- As material moves to the black hole, its potential energy is converted into kinetic energy.
- If that kinetic energy is converted into thermal energy (dissipation) then it will be radiated away

$$\boxed{L_{Acc} \simeq \frac{1}{16}\dot{m}c^2} \quad 1g \rightarrow 10^6\ kWh$$

efficiency of hydrogen burning is:

$$\boxed{L_{H-burn} \simeq 0.007\dot{m}c^2}$$

- Such luminous accretion of an ionized plasma has a natural upper limit, the Eddington limit:
  - Gravitational pull on proton > radiation pressure on electron (Thompson cross section)

$$L_{Edd} = \frac{4\pi c G M_{BH} m_p}{\sigma_{Te^-}}$$

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Energetics of accretion onto a black hole

$$\boxed{L_{Edd} = 1.3 \cdot 10^{38} \frac{M_{BH}}{M_\odot}\left[\frac{erg}{s}\right]}$$

This implies

$$M_{BH} \geq 10^7 M_\odot$$

for Seyfert galaxies, and

$$M_{BH} \simeq 10^9 M_\odot$$

for quasars. Using

$$L_{Acc} \simeq \frac{1}{16}\dot{m}c^2 = L_{Edd}$$

yields the corresponding maximum accretion rate:

$$\dot{m}_{Edd} \simeq 5 \cdot 10^{-10} \frac{M_{BH}}{M_\odot}\left[\frac{M_\odot}{yrs}\right]$$

NB:

In an accretion disk it is assumed that the conversion of energies E_{pot} → $E_{thermal}$ (→ $E_{radiation}$ black body) happens locally and much faster than the inflow

→ gravitational energy is instantly exploited.

This need not be the case. There is an old-puzzle why some galaxy centres are so 'dark', despite the presence of BHs and gas at galaxy centres (e.g. Galactic centre)

→ 'advection dominated' accretion (ADAF) ← no radiation

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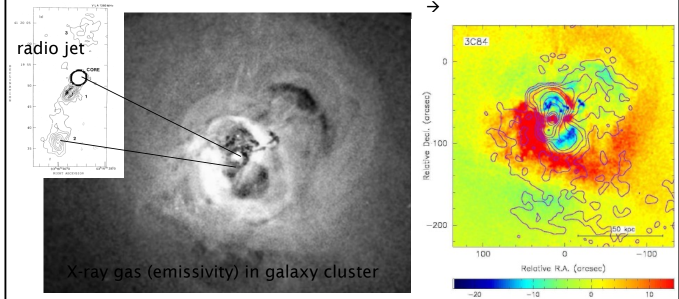
The Impact of AGNs on their Host Galaxies
Case study: radio AGN in the Perseus cluster

(e.g. Fabian et al 2003)

r
→



Radio-mode feed-back (e.g. Croton et al 2006)

- only effective in (massive) halos that have 'hot' X-ray atmosphere
- energetic feed-back that requires no star-formation itself
- Efficiency increases with M_{BH} →? only effective after the BH has grown?

→ explanation of why massive galaxies no longer form stars?

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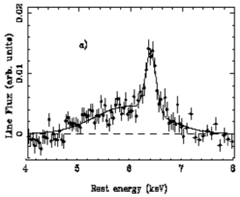
Proving the Existence of Black Holes and Measuring their Masses

- X-ray spectroscopy of AGN reveals an Fe K-line (transition in tighly bound electrons of Iron). Its rest-energy is 6.7KeV
- profiles, offset to the red → gravitational redshift!



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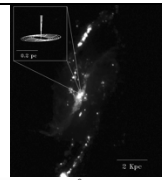
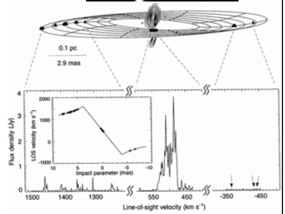
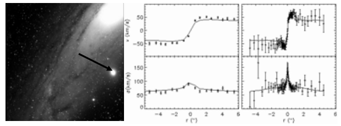
In nearby galaxies: masses from resolved kinematics



- NGC4258 appears to have a central disk of molecular gas → water maser lines → high-resolution measurements are possible.
- → $M_{dark\ object}$?=? $M_{BH} = 4\times10^7\ M_o$
- Density > $10^{10}\ M_o/pc^3$



- Note: also "inactive" nearby nuclei (e.g. M32) show kinematics that require a supermassive dark object/black hole to be explained
- → are black holes ubiquitous?



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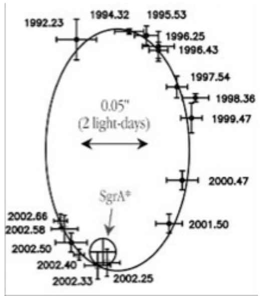
S2: star with orbital period 15.2 yr



- For S2, Eccentricity =0.87
- Perigalacticon distance = 120 AU
  $r_p = 120 \times 1.5 \times 10^8$ km

$$a = \frac{r_p}{1-e} = 1.4\times10^{14}\ \mathrm{m}$$

- From Kepler 3,

$$\frac{4\pi^2 a^3}{GP^2} \simeq 7\times10^{36}\ \mathrm{kg} = 3.5\times10^6\ M_\odot.$$

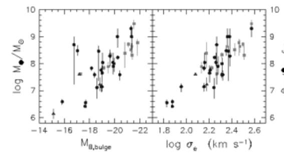
- Schwarzschild radius=

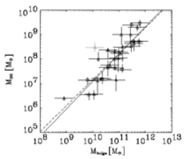
$$R_S = \frac{2GM_{BH}}{c^2} = 4.2\times10^{-7}\ \mathrm{pc} = 0.08\ \mathrm{AU} = 15 R_\odot.$$

Black Hole Masses and Host Galaxy Properties

- Spatially resolved spectroscopy with the Hubble Space Telescope (HST) has been key to measuring black hole masses in nearby galaxies
- Gebhardt et al 1999; Ferrarese and Merritt 1999:
  -

σ_e





Haering and Rix, 2004

Note: $R_{schw}(10^7 M_0)=10^{12}$ cm ←→ $R_{bulge} = 10^{22}$cm

Nature and origin of this relation are not (yet) known

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BH Mass estimates in high-z objects

(only in accreting object)

Three approaches:

1) Eddington-limit arguments:

$$\boxed{L \le L_{Eddington} \Rightarrow M > M_{min}(L_{Eddington})}$$

2) Reverberation mapping (Kaspi et al 2000)

$$\boxed{M_{BH} \sim \sigma_{BLR}^2 \times (t_{lag} \times c) \quad \rightarrow}$$

3) Photo-ionization models

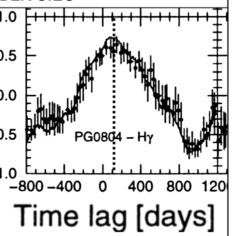
- continuum emission lines form?
- Calibrate from method 2)

$$\log M_{BH}(H_\beta,\ \text{rms or S-E}) = \log\left\{\left[\frac{\text{FWHM(C IV)}}{1000\ \text{km s}^{-1}}\right]^2 \left[\frac{\lambda L_\lambda(1350\ \text{Å})}{10^{44}\ \text{ergs s}^{-1}}\right]^{0.7}\right\} + 6.2 \pm 0.03(\pm 0.45)\ .$$

Time lag of variations in

Continuum (accr. Disk) and Hγ (BLR)

→ BLR size



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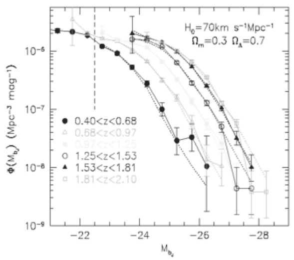
Cosmic Evolution of the AGN Activity

- Describe the distribution of accretion luminosities at different cosmic epochs by the "quasar-luminosity-function" at different redshifts



2DF Survey: Croom et al 2004

Abundance of luminous QSOs has decreased by 2 orders of magnitude since early epochs!

(e.g. SDSS Richards et al 2006)