Quasars: A Brief Introduction
& the Continuum

Martin Elvis
Harvard-Smithsonian Center for Astrophysics
Lecture 1
#25: What power quasars?

“The mightiest energy fountains in the universe probably get their power from matter plunging into whirling supermassive black holes. But the details of what drives their jets remain anybody’s guess.”

Quasars: A Quick History

- 1917: Slipher - broad em. Lines from NGC1068
- 1918: Curtis - optical jet from M87 nucleus
- 1943: Seyfert- extremely broad lines in ~6 galaxy nuclei
- 1953: radio sources found to be double (but unidentified)
- **1963**: huge redshift (0.158) of radio star 3C273
  - Implies huge luminosity
  - Variability of 3C48 implies small size
  - *Shock!* Is redshift really cosmological?

- 1963-2006:
  - Redshifts above 6
  - >100,000 quasars
  - Pan-chromatic mapping
  - Black hole masses
12,277 Papers on Quasars since 1963*

*ADS to 4/18/03, refereed only, search on abstract containing ‘quasar’ | ‘AGN’

1/day. Now 2 per day = 5% of all astronomy papers
Terminology: Taming the Zoo

• I will use “Quasar” for all types of ‘non-stellar’ activity in galaxy nuclei
  – Often reserved for high luminosity objects
  – Originally only for radio-loud (obsolete)

• AGN = Active Galactic Nucleus is a near synonym of quasar
  – type 1 = broad em. Lines; type 2 = narrow em. lines

• Blazar is used for quasars with a relativistic jet pointing at us

• Seyfert galaxy = lower luminosity AGN, radio-quiet.
  – Radio galaxy is radio-loud version

• There are many other terms in the literature. They are mostly not worth learning.
Why Study Quasars: 1. An Astronomer’s Answer

Quasars dominate the sky over wide ranges of the spectrum
2. An Astrophysicist’s Answer

Gravity powered, not fusion.

via Black Holes $10^6 - 10^9$ as massive as the Sun.
Gas heats up falling toward it, like a spacecraft on re-entry.
The power available from gravity for heating is all too obvious following the Columbia tragedy

Emit strongly from radio to $\gamma$-rays.
How do they do that?

Billions of times brighter than stars. Can outshine a whole galaxy

Make galaxy length jets
3. A Cosmologist’s Answer

Quasars know about their host galaxies:

*Galaxy mass and quasar black hole mass are tightly connected.* Maggorrian et al, Ferrarese & Merritt, Gephardt et al.

*How? Should be governed by different processes.* Requires *Feedback*

**Emit up to 1/5 of power in Universe:**

*Important input, may dominate in some places, times.*

**Already exist at t<1Gyr (z=6)**

FIRST survey discovery, Becker et al.

< 1 Gyr from reionization at z=11

special role in early Universe?

reionization, seeding galaxies...

element creation, star formation catalyst via dust creation?
4. A Physicist’s Answer

Eject bulk gas at 99.50% speed of light $\gamma=10$

similar to proton in Fermilab Tevatron 99.88%c

Impacts gas of intergalactic medium. -> what emerges?

Accelerates $e^{-}$ to $\gamma \sim 1000$ -> TeV photons

X-rays come from region of Strong Gravity seen in 6.4 keV 'Fe-K' (=Fe Lyman-\(\alpha\)) emission line?

# Quasars compared with Stars

<table>
<thead>
<tr>
<th>Property</th>
<th>Stars range value</th>
<th>Quasars range value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity range</td>
<td>$10^9$</td>
<td>$&gt;10^7$</td>
</tr>
<tr>
<td></td>
<td>$10^{-4} - 10^5$ L$_\odot$ (M8-O5)</td>
<td>$10^7$ - $10^{14}$ L$_\odot$</td>
</tr>
<tr>
<td>Mass range</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>0.05 - 50 M$_\odot$</td>
<td>$10^6 - 10^9$ M$_\odot$</td>
</tr>
<tr>
<td>Temperature range</td>
<td>10</td>
<td>~10?</td>
</tr>
<tr>
<td></td>
<td>3,000 K - 50,000 K</td>
<td>[big blue bump]</td>
</tr>
<tr>
<td>Lifetime</td>
<td>10,000</td>
<td>&lt;1000?</td>
</tr>
<tr>
<td></td>
<td>1 Myr - 10 Gyr</td>
<td>~10 Myr - 10? yr</td>
</tr>
<tr>
<td>Spectra</td>
<td>~ black body</td>
<td>~ power-law</td>
</tr>
</tbody>
</table>
Why Study Quasars?
Seven Quasar Mysteries

1. Enormous luminosities from tiny regions
   • Fusion power is inadequate

2. Spectra that are nothing like starlight
   • Similar power/decade from Far-IR to X-ray

3. Accelerate material to high velocities
   • \( V \sim c \)

4. Linear symmetry
   • ‘spherical cow’ models not much use

5. Far less common now than in the past
   • Evolution. Not a steady state universe

6. Most are not radio sources ‘radio-quiet’
   • Though first discovered in radio

7. Most are hidden optical sources
   • Obscured by dust and gas

Annalisa Celotti, Tiziana Venturi, Günther Hasinger
Lecture 1: The Quasar Continuum

• The central problem:
  – Luminosities of a Galaxy from a Solar System sized region
  – Requires high efficiency of rest mass to luminosity conversion, $\varepsilon >> 1\%$ of fusion
  – Black holes Lynden-Bell 1969

• Plan:
  1. Description of radio to X-ray continuum; range of properties
  2. Likely mechanisms for each part; questions
  3. How we can make progress
     – Industrial methods
     – Physical correlations
Quasars SEDs are interesting because...

- **Black hole growth** occurs mostly during ‘active’ quasar phase.
- Black Hole and Galaxy mass are correlated: \( M-\sigma_v \) relation
- Quasars contribute a **substantial fraction of the luminosity of the Universe**: \( 5\%-25\% \, L_{\text{universe}} \) Fabian & Iwasawa 1999, Yu & Tremaine 2002, Elvis, Risaliti & Zamorani 2002…
- Quasars form **the X-ray background**
- May determine **Black hole Spin**
- High **Black hole accretion efficiency**
  - Soltan argument + \( L_{\text{acc}}(\text{Universe}) \)

And, of course…

- **#25: What power quasars?**
  - Physics of accretion (disks)
  - vs. BH mass, acc. Rate
Quasar Continuum: A Field Guide

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Quasar ‘Spectral Energy Distribution’ (SED)

Quasar Continuum: A Field Guide

Quasar ‘Spectral Energy Distribution’ (SED)

Quasar Continuum: A Field Guide

Quasar ‘Spectral Energy Distribution’ (SED)

**Quasar Continuum Variability**

- Typical variability:
  - X-ray: factor 2 in ~months
  - Optical: slightly larger amplitude
    - Starlight/non-blue-bump dilution
    - Small emission region
    - correlated on ~1yr timescale
    - Disk instability? Local $m_{\text{dot}}$ variations?
- Smaller, slower at high L


Diversity of X-ray to Radio SEDs of Quasars

SED spread: No theory, no correlations

Two primary sources of continuum in Quasars

1. accretion disk

2. relativistic jet
   Rees 1967 [PhD], Blandford & Rees 1974
Big Blue Bump = Accretion Disk?

• Broader than a black body
  – Even reaches soft X-ray?
• Dominates luminosity
  – By factor few, usually
  – => primary radiation
• Universal
  – Though sometimes reddened, or dominated by jet.
• Weak redshift or luminosity changes
• Variable
  – no color dependence (when host is removed)
  – Factor 2 in months (Seyferts)
  – Less, slower at high L
• Accretion disk?
  – Roughly right shape
  – Ly-edge, polarization Kinney et al
• Underlying power-law?
Big Blue Bump: long wavelength slope


Power-law continua have intrinsic spread

FUSE + HST spectra

Accretion disk models

Reddened continua are curved

Power-law continua have intrinsic spread

$\sigma \sim 0.2$
Big Blue Bump: break at 1100Å

- Broader than a black body

Big Blue Bump: Connection to soft X-ray?

- Broader than a black body
  - Even reaches soft X-ray?
- Dominates luminosity
  - By factor few, usually
  - => primary radiation
- Universal
  - Though sometimes reddened, or dominated by jet.
- Weak redshift or luminosity changes
- Variable
  - no color dependence (when host is removed)
  - Factor 2 in months (Seyferts)
  - Less, slower at high L
- Accretion disk?
  - Roughly right shape?
  - Or is a power-law closer?


Big Blue Bump: Scaling with Luminosity?

- $T_{\text{max}}$ scales with $M^{1/4}$ and $m_{\text{dot}}$ Frank, King & Raine 2000; Lawrence 2005 MNRAS, 363, 57
- $X$


Radio = synchrotron = jet

- **Synchrotron:**
  - Polarized
  - Variable
  - Power-law

- **Relativistic particles**

- **Jet?**
  - Clearly true in Blazars
  - Less obvious in radio-quiet quasars, Seyferts

- **X-rays in radio-loud quasars = Comptonized synchrotron?**
Infrared = dust, but where?

- Dust:
  - Inflection point at 1µm: maximum dust temperature
  - Reverberation gives sublimation distance
  - Irregular SED - multiple temperatures components

- Dust properties:
  - Equilibrium temperature:
    \[ R = 1.3L_{UV,46}^{3/2}T_{1500pc}^{-2.8} \]
  - \( T_{max} \approx 1800 \text{ K for C grains} \)
  - \( T_{min} \): \( \nu^3 \) drop off at \( \sim 100 \mu m \)

- Molecular torus? Wind? ISM?

- Alternatives to dust:
  - Non-thermal (synchrotron? free-free) baseline

See also:

See also:
- Elvis et al., 1994, ApJS,
Hard X-ray: Comptonized disk radiation?

- Intrinsic properties
  - $\Gamma=2$, High E cut-off $\sim 100$keV
  - Rapid, large amplitude variability
- Origin: hot atmosphere (‘corona’ at $10^{12}$K) above accretion disk is natural
  - Lightman-Eardley instability
  - Will Comptonize disk opt/UV to X-rays: low y parameter - copies original spectrum
  - Why are Narrow Line Seyfert 1s steeper?
- Alternative: Jet
  - possibly base of jet
    - Variability requires small size, but need not be central

Ipser & Price, 1983
Spread of Quasar SEDs - Why?

- Narrow Line Seyfert 1s (NLSy1s):
  - FWHM(H\(\beta\)) < 2000 km/s c.f. ~5000 typical
  - steep, highly variable X-rays
  - high \(m_\text{dot}\)? c.f. X-ray binaries
  - weak FeII, strong [OIII] ‘eigenvector 1’

- Radio-loud:
  - also have flat X-ray - 2nd component
  - Radio-silent - exist, little studied

- IR quiet:
  - Little known, but exist

- X-ray loudness:
  - Range of 100

  - Obscuration?
  - Intrinsically faint?
  - Highly variable


Kellerman et al. 1989 AJ, 98, 1195; also SDSS (Ivezic?)
Quasars SEDs need Many Telescopes

Electromagnetic Spectrum

- Gamma rays
- X-rays
- Ultraviolet
- Visible
- Near infrared
- Shortwave infrared
- Middle infrared
- Thermal infrared
- Microwave
- Radio waves

10^15 range of wavelength in astronomy

Whipple 10 meter Observatory

Compton gamma-ray Observatory

Chandra

Hubble

MMT

Sub-millimeter array

VLA

Source: Christopherson (2000) Geosystems
Complications

- **Survey Properties:**
  - Selection biases
    - UV selection finds no red quasars!
    - fake redshift-luminosity correlations, due to narrow flux ranges
    - emission lines in bands
    - redshifting of bands,
  - Small samples
- **Quasar Properties:**
  - Obscuration by dust & gas
  - Variability
  - Host galaxy contamination
    - starlight (Magorrian relation)
    - dust (IR)
  - Extended AGN emission
    - radio lobes, jets
    - opt/X-ray photoionization nebulae

Quasar SEDs Today

• After a decade, Atlas from Einstein/IUE era is still state of the art: Elvis et al. 1994
  C.f. Downsizing

• Primitive:
  – Small sample: 29 radio-quiet, 18 radio-loud
  – Low z: 0.05 - 0.9
  – Low S/N: in X-ray, UV, FIR
  – Biased:
    • toward X-ray loud
      – small $\alpha_{\text{ox}}$ for Einstein detection
    • toward UV bright
      – (U-B) selection of PG RQQ

• Artisanal - pointed one-at-a-time
  not the way to go

Future: Mass-produced SEDs - COSMOS

- Industrial: ~1000 SEDs at once
  - Wide range of $z$, $\alpha_{Ox}$, $L$
  - High S/N
- Easily detect most AGN at all wavelengths: X-ray-UV-midIR-radio
- $\rightarrow$ Sensitive to deviant SEDs
- ACS i-band imaging gives host galaxy subtraction
  - Important at all $L$, given Magorrian $M_{bulge}-M_{BH}$ relation
Future: Physically based models

- Black hole mass measurements revolutionizing the field
  - STIS rotation curves
  - Reverberation BELR mapping
- secondary methods reach high z
- Have \((M, \dot{m})\) for large samples
- Can relate continuum to underlying physics at last
- **But:** - no inclination Core/lobe ratio, VLBI, Xray
  - assumed efficiency