2. Active Galaxies

- 2.1 Taxonomy
- 2.2 The mass of the central engine
- 2.3 Models of AGNs
- 2.4 Quasars as cosmological probes

Read JL chapter 3

Active galaxies: interface with JL

All of JL chapter 3 is examinable, except:

- 3.1 and 3.2 are (hopefully) a revision of earlier courses
- 3.4.4 An accretion disk should be basic stuff

Additional examinable notes will be provided on:

- Eddington limit will be derived
- Quasar luminosity function and evolution (log(N)-log(S) and V/V_{max} tests)

Definition of an active galaxy

- What is an active galaxy?
  - Radiation is not directly attributable to stars or dust
  - Usually very powerful: ~10^{11} L_{solar} in ~1AU
- What is an AGN?
  - Active Galactic Nucleus
  - Non-stellar radiation comes from small region
  - Is in the center of galaxy, if galaxy is seen
  - AGN used interchangably with "active galaxy"
- Role in galaxy formation unknown
  - Special type of galaxy? or short phase of every galaxy?
- Four main classes:
  - Seyfert galaxies, Quasars, Radio galaxies, Blazars

2.1 Taxonomy

List of topics and summary of properties:

- Seyfert galaxies
  - Galaxies with very bright nuclei
- Quasars
  - Point-like, extremely bright
- Radio galaxies
  - Radio lobes beyond galaxies (often in pairs)
- Blazars
  - Extremely variable

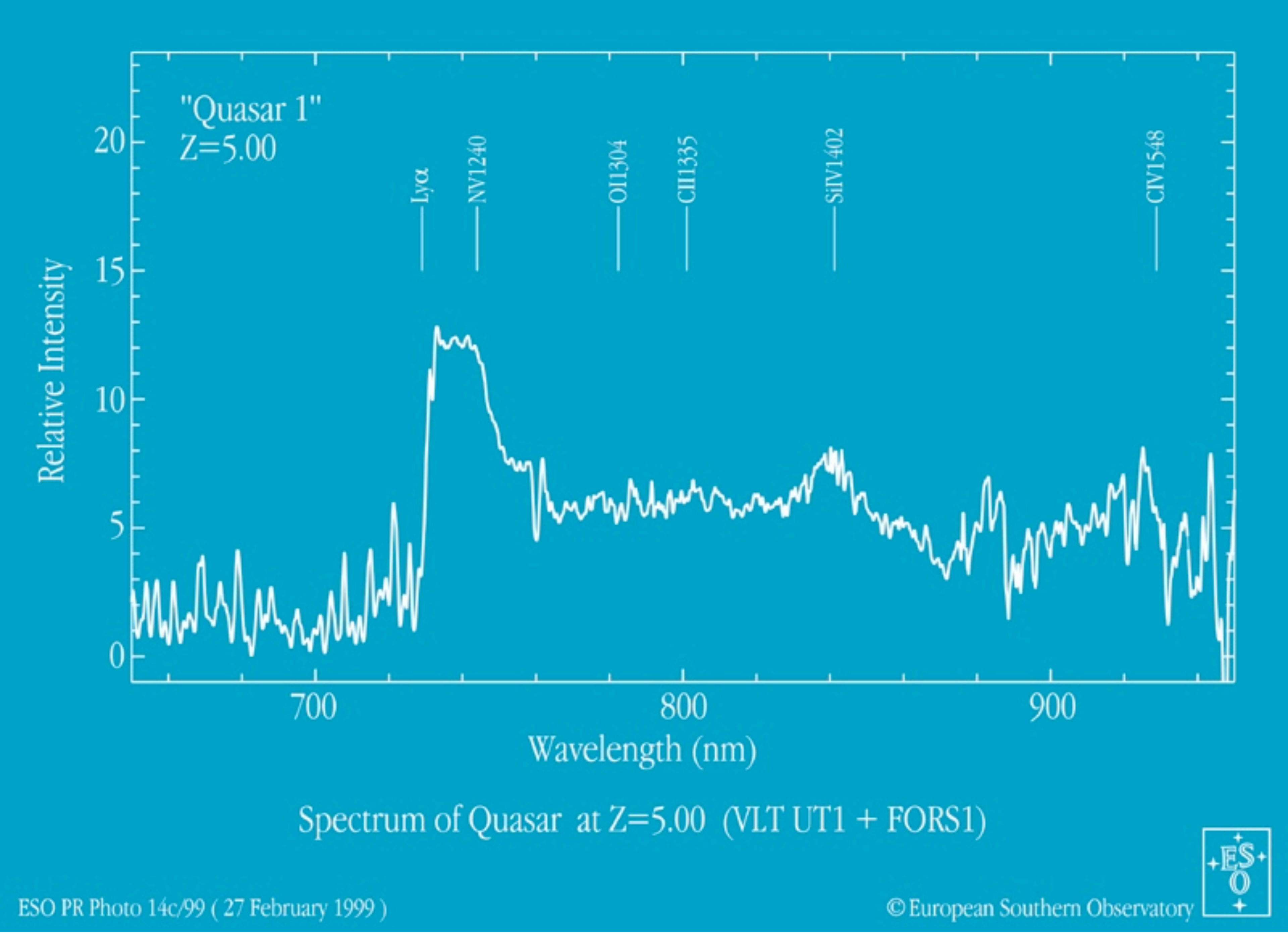
Read JL section 3.3 (pages 136 – 145)

Seyfert Galaxies

- Galaxies with very bright nuclei
  - Nuclei are unresolved in optical
  - Almost all are spiral galaxies
  - Variable over time
- Excess radiation in far ir and other bands
- Type 1 Seyferts: Two sets of emission lines
  - "Narrow lines": Widths ~400 km s^{-1}. Mostly forbidden
    - NB. this is wide cf typical HII region
  - "Broad lines": Widths ~10 000 km s^{-1}. All permitted lines.
- Type 2 Seyferts: Only narrow lines, no broad lines.
- Type 1.5 Seyferts: somewhere in between

Quasars

- Point-like, extremely bright
  - in both radio and optical
  - Quasi-stellar radio source/object -> quasar
  - Many are variable on times of months or days
- Spectral excesses in IR and other λ s
- Faint host galaxies ("quasar fuzz")
- Strong broad lines, weaker narrow lines
  - Strong Lyman-α
- Radio loud quasars: strong in radio
  - ~10% of quasars
  - many have jet(s)



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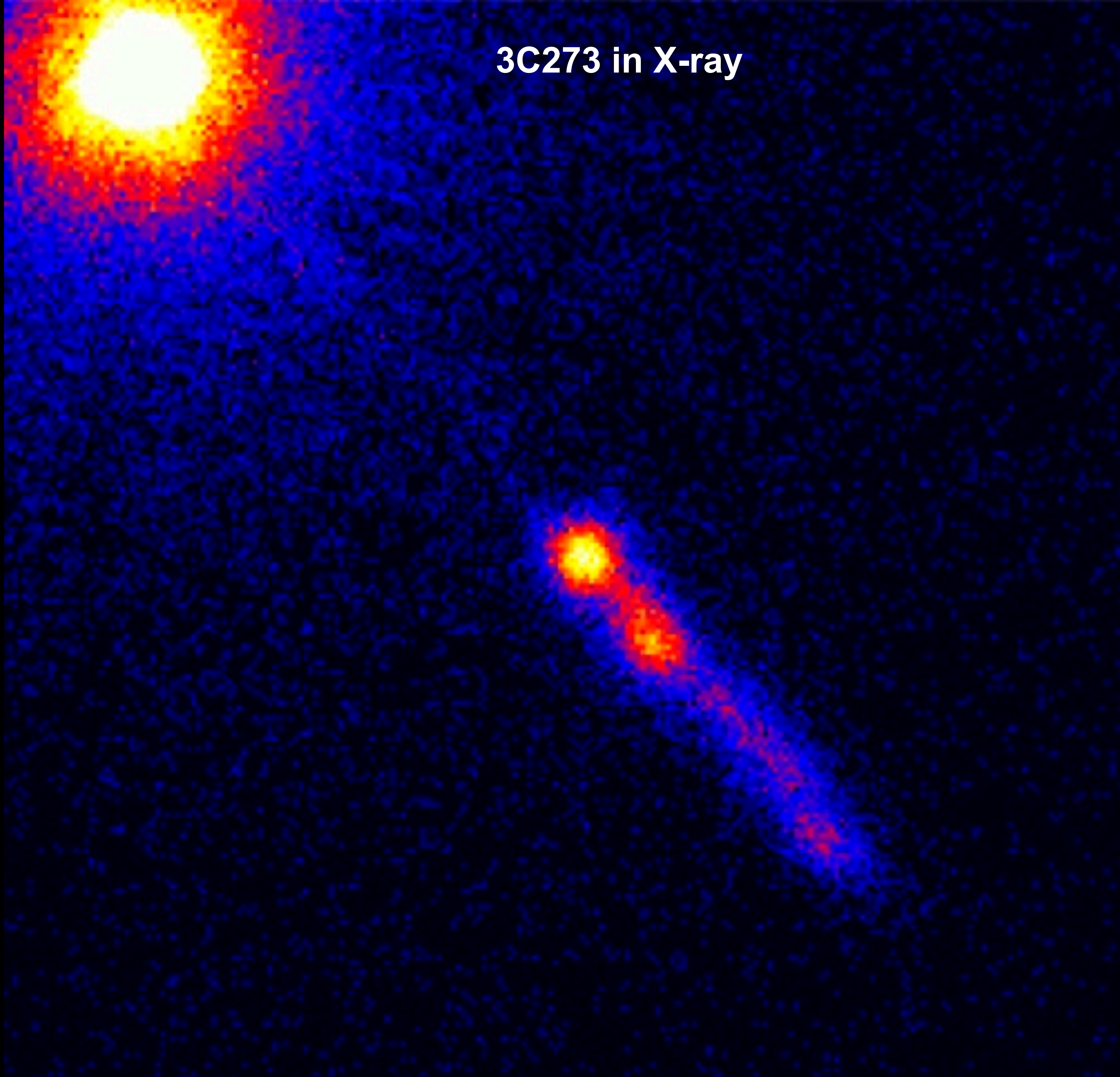


NASA/CXC/SAO/H.Marshall et al.
http://chandra.harvard.edu/photo/2000/0131/

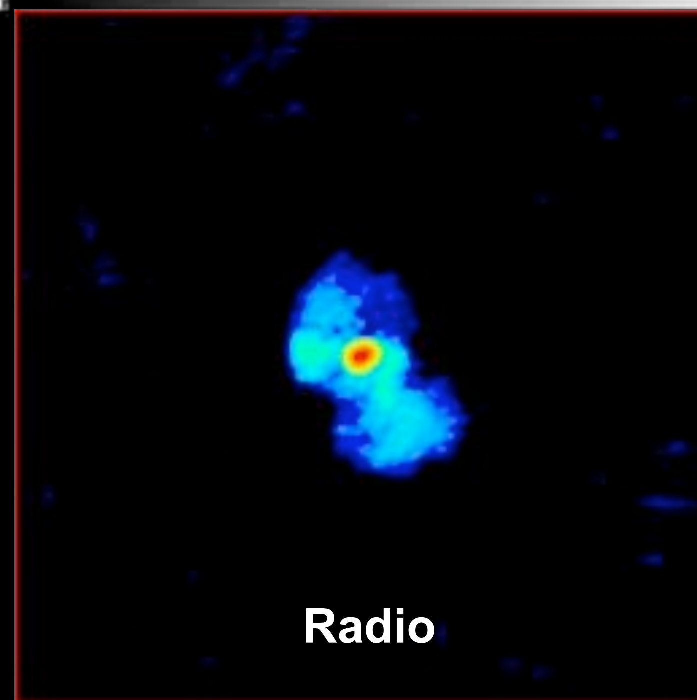
Radio galaxies

- The majority of known radio objects
- Pairs of bright lobes
  - fed by narrow jets from faint core
- Two types:
  - Broad-line radio galaxy (BLRG)
  - Narrow-line radio galaxy (NLRG)
- Often in elliptical galaxies
  - these often have dust lanes

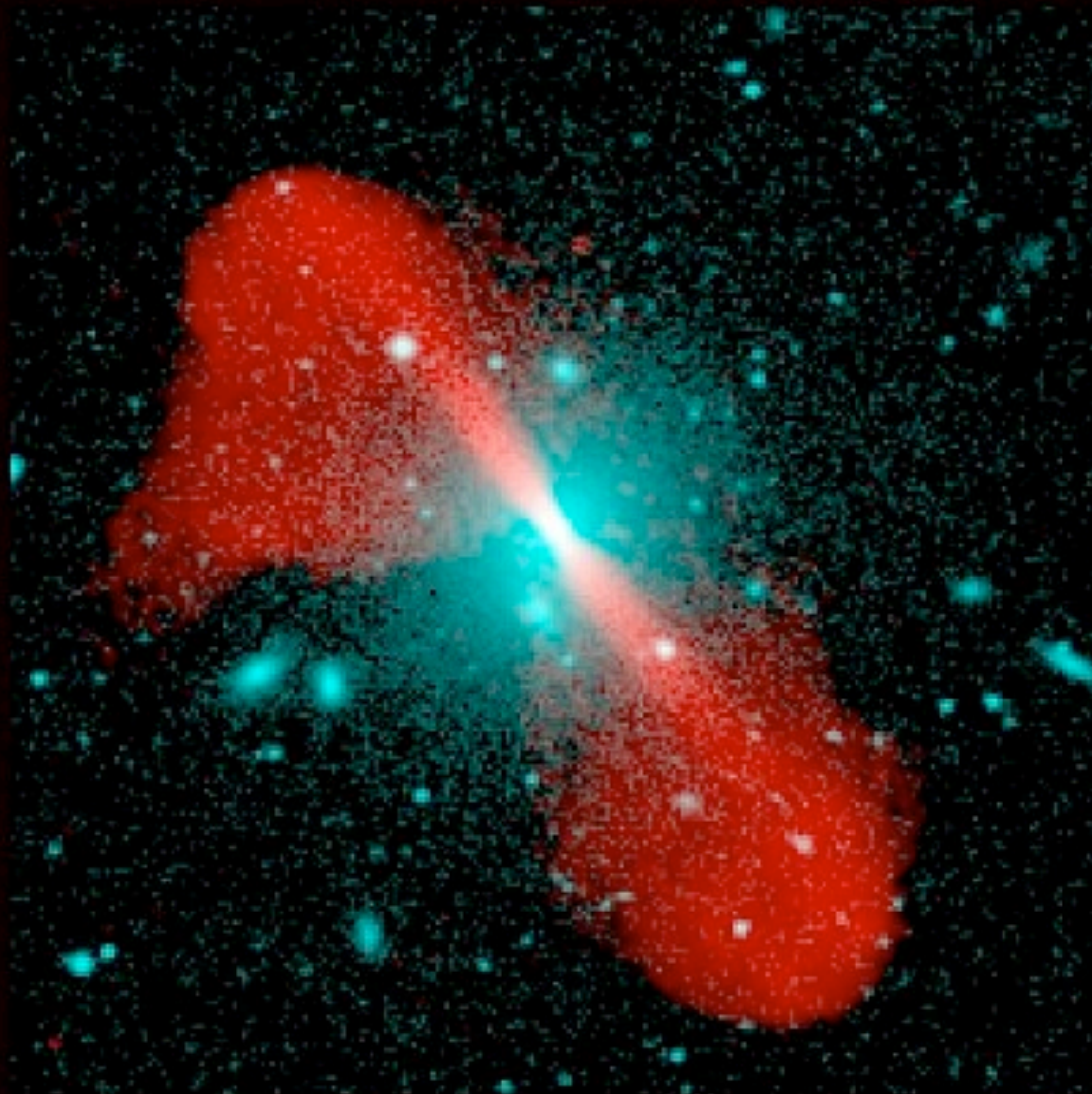
Read JL pages 142 – 143

M87

http://www.seds.org/messier/m/m087.html



http://hubblesite.org/newscenter/newsdesk/archive/releases/1994/23/image/a



Radio Galaxy 3C296
Radio/optical superposition

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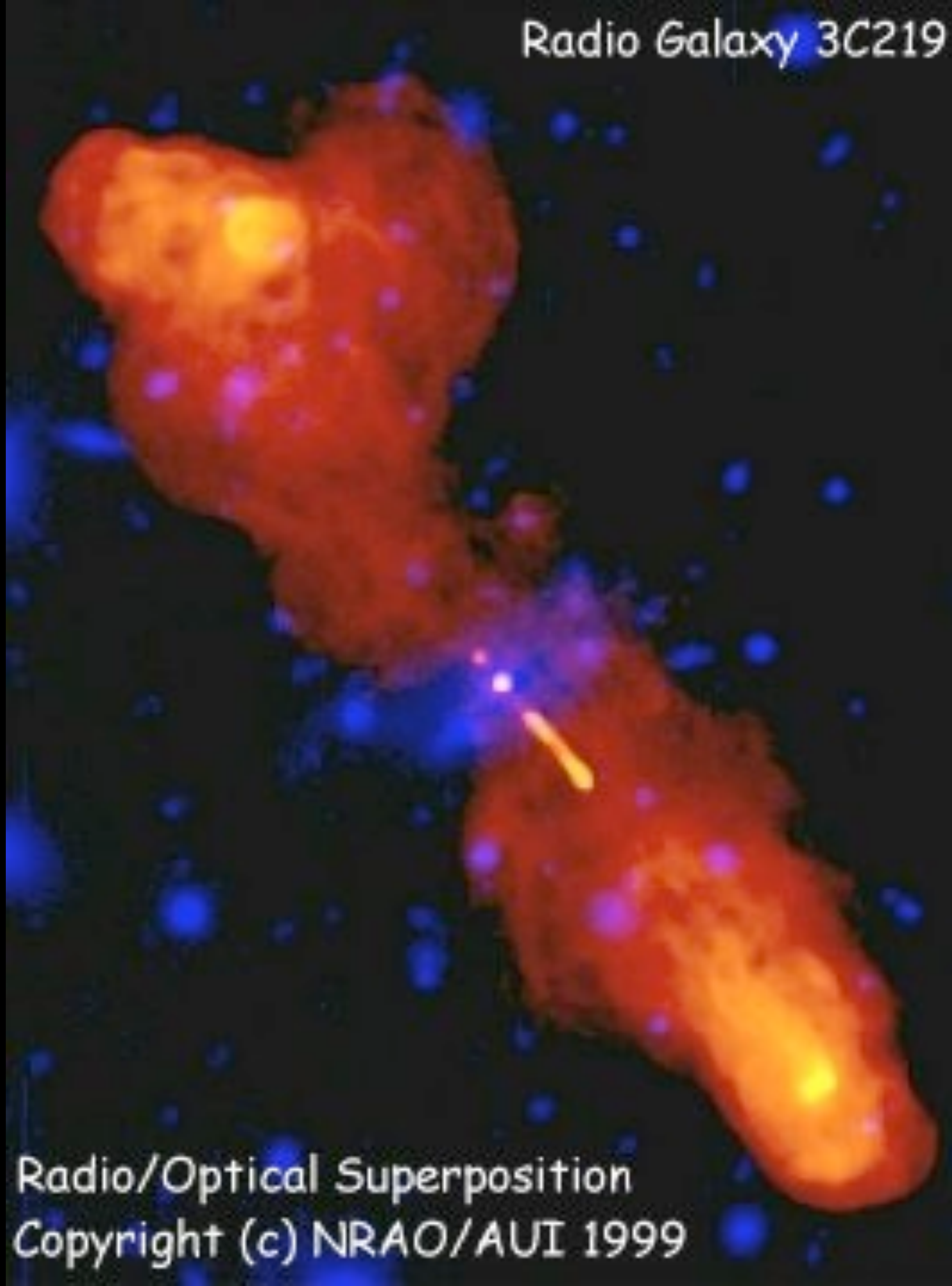
http://www.cv.nrao.edu/~abridle/3c296digss.htm



http://www.cv.nrao.edu/~abridle/nrao94.htm

Blazars

- Like quasars, but variable on days or less
- All radio loud
- Two subclasses
  - BL Lac: emission lines are absent or weak
    - Not very bright
    - Originally thought to be a variable star
  - OVVs: Optically violent variables
    - Much brighter
    - Strong broad emission lines

Read JL page 145

2.2 The central engine

List of topics:

- The size of AGNs (JL 3.4.1)
- The mass of the supermassive black hole
  - based on Schwarzchild radius (JL 3.4.3)
  - based on Eddington Limit
  - based on reverberation mapping (JL p163)
- Accretion power (JL 3.4.5)

The size of AGNs

- Nuclei are unresolved in optical and radio
  - Radio resolution ~0.001 arcsec (VLBI)
  - Nearest AGN (NGC 4395) 4.3 Mpc away
  - Must be <~ 0.02 pc = 4000 AU
    - Size = θ (in radians) x distance
- Nuclei are highly variable ~ hours ~10^4 s
  - Size ~ c x time ~ 10^{-4}pc = 20 AU
- Quasars are brighter than entire galaxies

  ~10^{11} L_{solar} in 20 AU !

  Believed to contain a black hole

If object bigger than 20 A.U. then can't explain fast variation.

Mass from Schwarzschild radius

- Observed size > Schwarzschild radius
  - Puts an upper limit on the mass of a BH
- $R_s = 2\,GM / c^2 <$ Observed size $\sim 10^{-4}$ pc = 20 A.U.

A. $M < 10^9\ M_{solar}$

B. $M < 10^{11}\ M_{solar}$

C. $M < 10^{13}\ M_{solar}$

1pc = 3e16 m
c = 3e8 m/s
G = 6.7e-11 N m^2 kg^-2
M_solar = 2e30 kg

Why is light emitted by an accretion disk?

A. Infalling material strikes the surface
B. Stars in the disk
C. Viscous differential rotation
D. Nuclear reactions in the disk

Hydrogen burning releases 0.7% of rest mass energy. How much does accretion release?

A. ~ 0.1%
B. ~1 %
C. ~10 %

What is the momentum of a photon?

A. $h\nu$

B. $h\lambda$

C. h/λ $= \frac{E}{c}$

Mass from Eddington limit

- Gravitational attraction > radiation pressure
- Consider HI on spherical shell, lit by luminosity L
  - Radiation pressure = momentum flux $= \frac{L}{4\pi r^2 c}$
- Force on an electron = pressure x cross section
- Gravitational attraction > radiation pressure

$$\frac{GM m_p}{r^2} > \frac{L}{4\pi r^2 c} \sigma_e$$

$$M > 4 \times 10^{-5} \left(\frac{L}{L_{solar}} \right) M_{solar} > \sim 10^6 M_{solar}$$

- Supermassive black hole
  - cf black hole produced on death of massive star

Mass from reverberation mapping

- Broad lines imply rotation at 7000 km s^{-1}
  - Can't be thermal broadening since HI is seen
- Broad line variation lags continuum by ~10 days
  - Assume is due to light travel time to BL region
  - Radius of BL region is ~ 0.01 pc
- Apply virial theorem to get the mass

$$M = \frac{r v^2}{G} \sim 10^8 M_{solar}$$

- Concensus of all three methods: M ~10^8 M_{solar}

JL p163

2.3 Models of AGNs

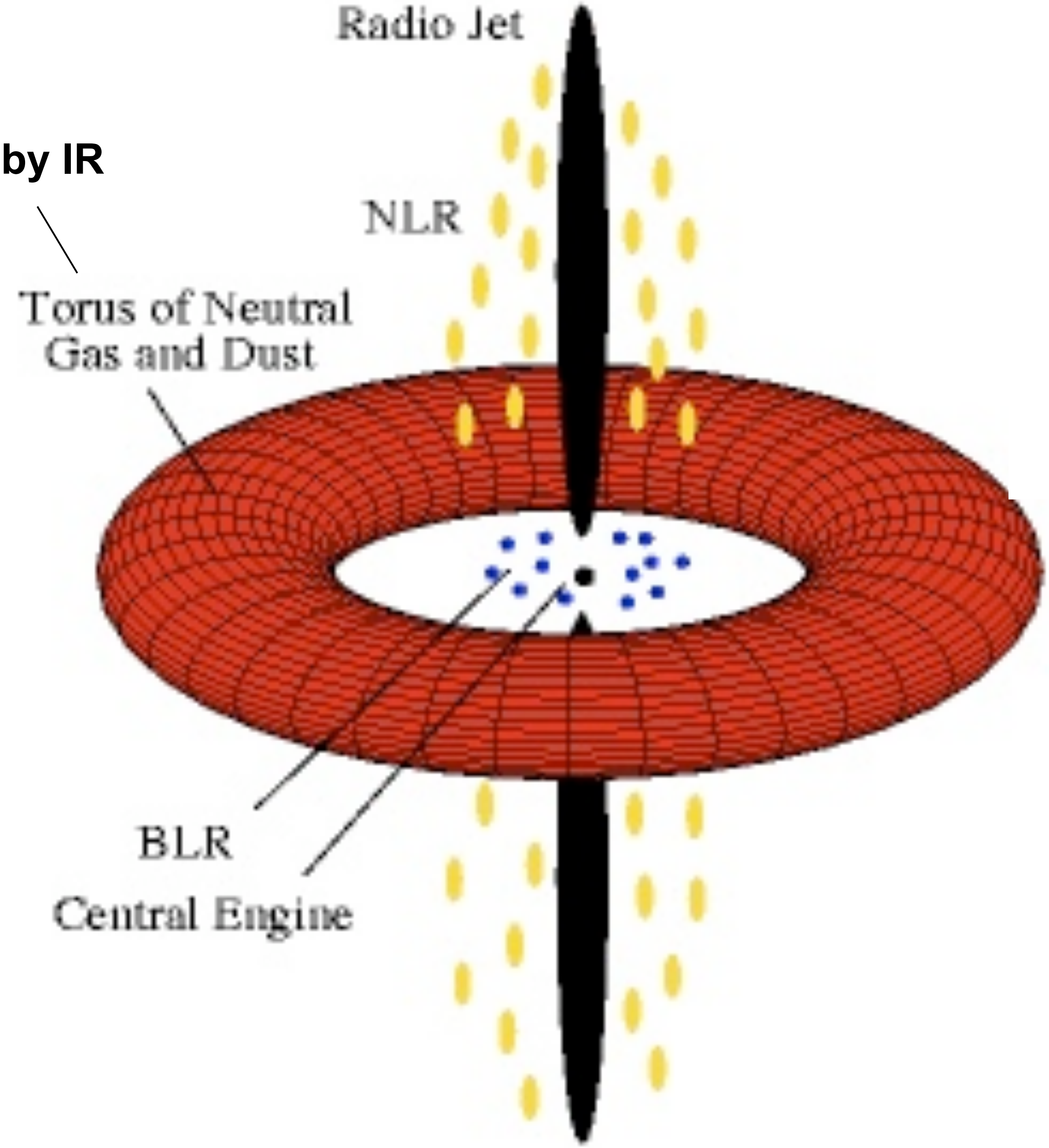
List of topics:

- The dusty torus (JL 3.5.1)
- The broad line regions (JL 3.5.2)
- Unified models (JL 3.5.3)

First task:

Dust evaporates at ~2000K
Estimate the minimum radius of the torus

Implied by IR



Adapted from
http://www.jb.man.ac.uk/research/agn/neutral.html

Dust evaporates at ~2000K
Estimate the minimum radius of the torus

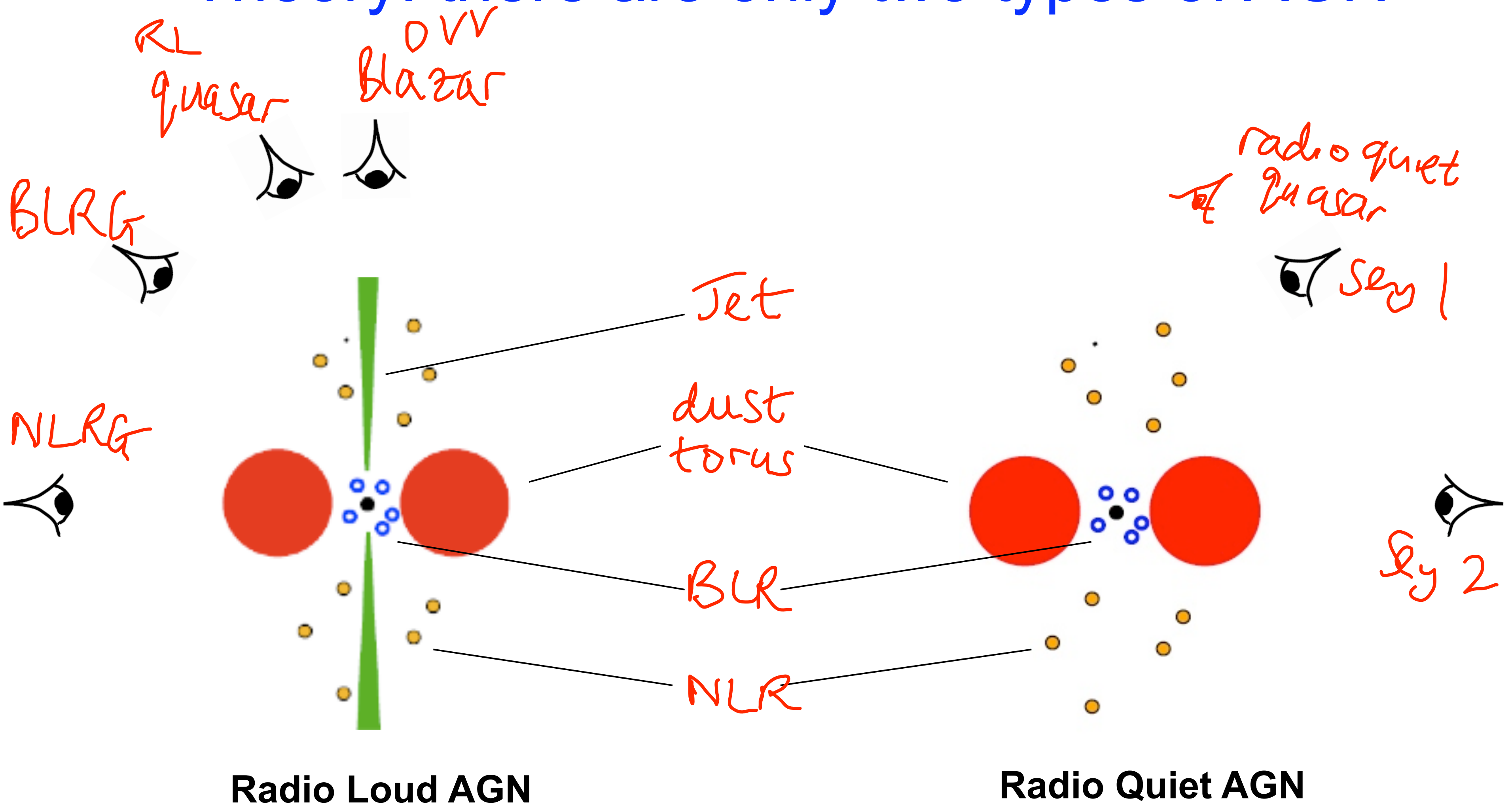
- Flux density at radius r ~ $L/(4 \pi r^2)$
- Dust grain of radius a absorbs power
  - ~ flux x area = $\pi a^2 L/(4 \pi r^2)$
- Dust grain radiates as black body at T
  - power radiated = $4 \pi a^2 \sigma T^4$
- In equilibrium the above are equal
  - r ~ sqrt(L / (16 \sigma T^4))
- If dust is at 2000K at minimum radius
  - assume L ~ 10^{38} W
  - r ~ 0.05 pc

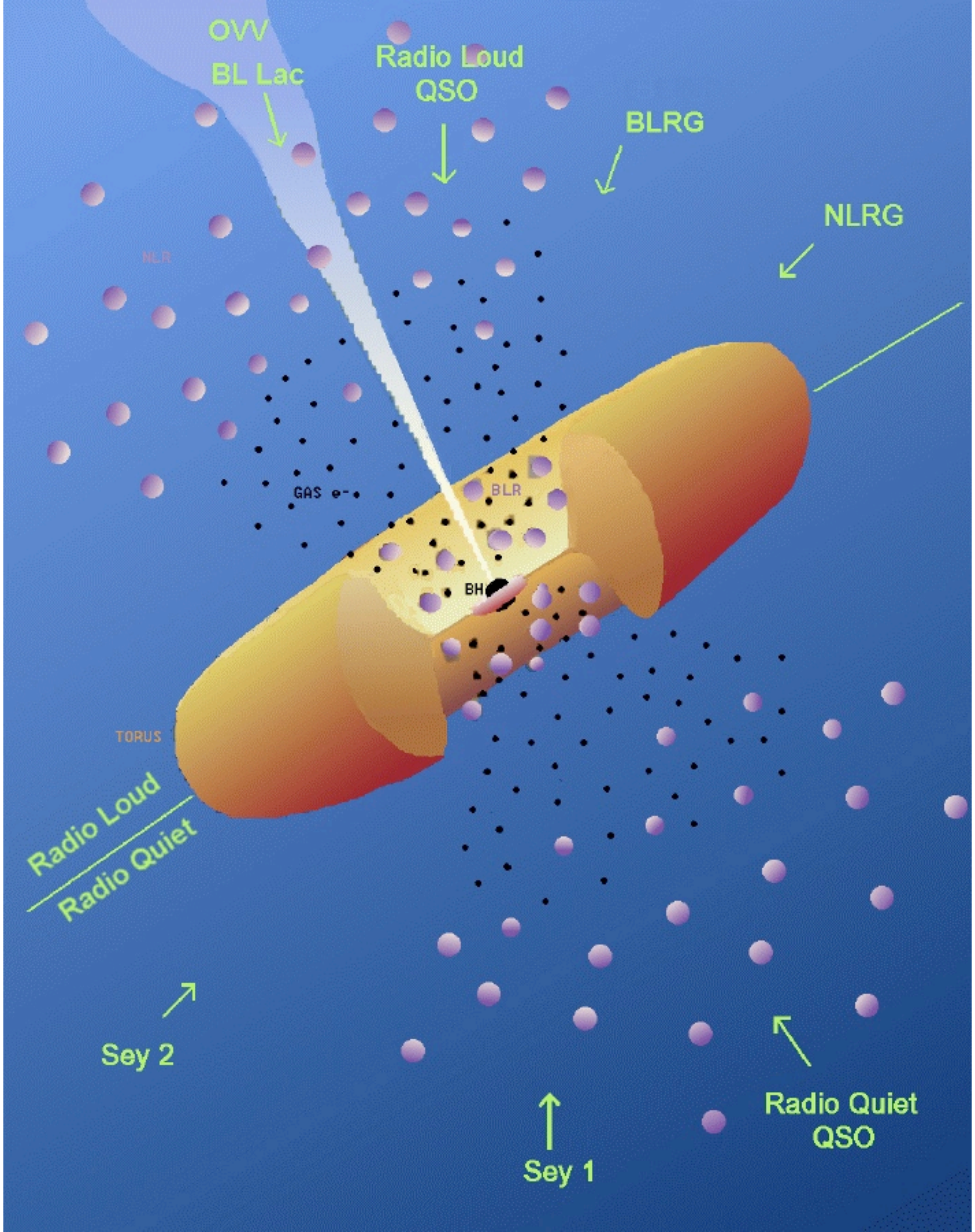
The broad-line region

- Made up of gas clouds
  - illuminated by central engine esp uv, X-ray
  - re-emit energy as emission lines
  - see similar gas content to galactic HII regions
- No forbidden lines, so not very underdense
- From reverberation mapping slide
  - radius ~0.01 pc
  - rotation speed ~ 7000 km s^{-1}
- Current estimates:
  - ~10^{10} individual clouds
  - total mass of gas ~ 10 M_{solar}

Unified models

- Theory: there are only two types of AGN





http://www.asdc.asi.it/bepposax/calendar/

2.4 Quasars as cosmological probes

List of topics:

- Gunn-Peterson test
- log(N)-log(S) test
- V/V_{max} test

Not in JL. See Peterson

Gunn-Peterson Test

- Quasar light is absorbed by intervening material
  - Hydrogen clouds
  - Damped Ly-α systems (proto-galaxies?)
- If continuous neutral hydrogen exists over range of z
  - Expect rest-frame Ly-α to be absorbed
  - Expect absorption bluewards of quasar Ly-α
  - Called Gunn-Peterson trough
- Only observed in 2001 at z~6

arXiv:astro-ph/0108097 v3

EVIDENCE FOR REIONIZATION AT $Z \sim 6$: DETECTION OF A GUNN-PETERSON TROUGH IN A $Z = 6.28$ QUASAR[1,2]

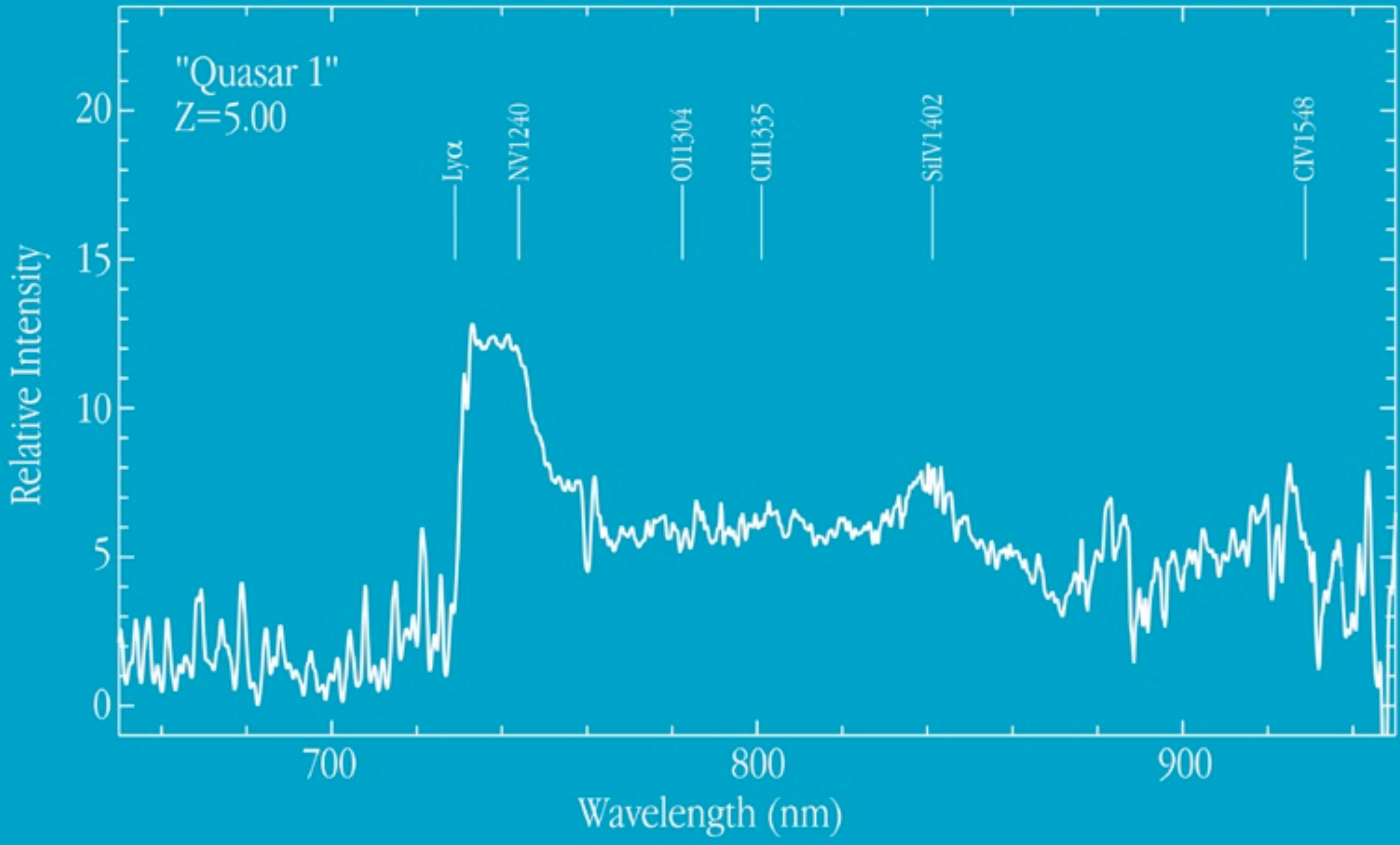
Robert H. Becker[3,4], Xiaohui Fan[5], Richard L. White[6], Michael A. Strauss[7], Vijay K. Narayanan[7], Robert H. Lupton[7], James E. Gunn[7], James Annis[8], Neta A. Bahcall[7], J. Brinkmann[9], A. J. Connolly[10], István Csabai[11,12], Paul C. Czarapata[8], Mamoru Doi[13], Timothy M. Heckman[11], G. S. Hennessy[14], Željko Ivezić[7], G. R. Knapp[7], Don Q. Lamb[15], Timothy A. McKay[16], Jeffrey A. Munn[17], Thomas Nash[8], Robert Nichol[18], Jeffrey R. Pier[17], Gordon T. Richards[19], Donald P. Schneider[19], Chris Stoughton[8], Alexander S. Szalay[11], Anirudda R. Thakar[11], D. G. York[15,20]

Accepted by the Astronomical Journal

ABSTRACT

We present moderate resolution Keck spectroscopy of quasars at $z = 5.82$, 5.99 and 6.28, discovered by the Sloan Digital Sky Survey (SDSS). We find that the Lyα absorption in the spectra of these quasars evolves strongly with redshift. To $z \sim 5.7$, the Lyα absorption evolves as expected from an extrapolation from lower redshifts. However, in the highest redshift object, SDSSp J103027.10+052455.0 ($z = 6.28$), the average transmitted flux is 0.0038 ± 0.0026 times that of the continuum level over 8450 Å $< \lambda <$ 8710Å ($5.95 < z_{abs} < 6.16$), consistent with zero flux. Thus the flux level drops by a factor of > 150, and is consistent with zero flux in the Lyα forest region immediately blueward of the Lyα emission line, compared with a drop by a factor of ~ 10 at $z_{abs} \sim 5.3$. A similar break is seen at Lyβ; because of the decreased oscillator strength of this transition, this allows us to put a considerably stronger limit, $\tau_{eff} > 20$, on the optical depth to Lyα absorption at $z = 6$.

This is a clear detection of a complete Gunn-Peterson trough, caused by neutral hydrogen in the intergalactic medium. Even a small neutral hydrogen fraction in the intergalactic medium would result in an undetectable flux in the Lyα forest region. Therefore, the existence of the Gunn-Peterson trough by itself does not indicate that the quasar is observed prior to the reionization epoch. However, the fast evolution of the mean absorption in these high-redshift quasars suggests that the mean ionizing background along the line of sight to this quasar has declined significantly from $z \sim 5$ to 6, and the universe is approaching the reionization epoch at $z \sim 6$.



Spectrum of Quasar at Z=5.00 (VLT UT1 + FORS1)

ESO PR Photo 14c/99 (27 February 1999)

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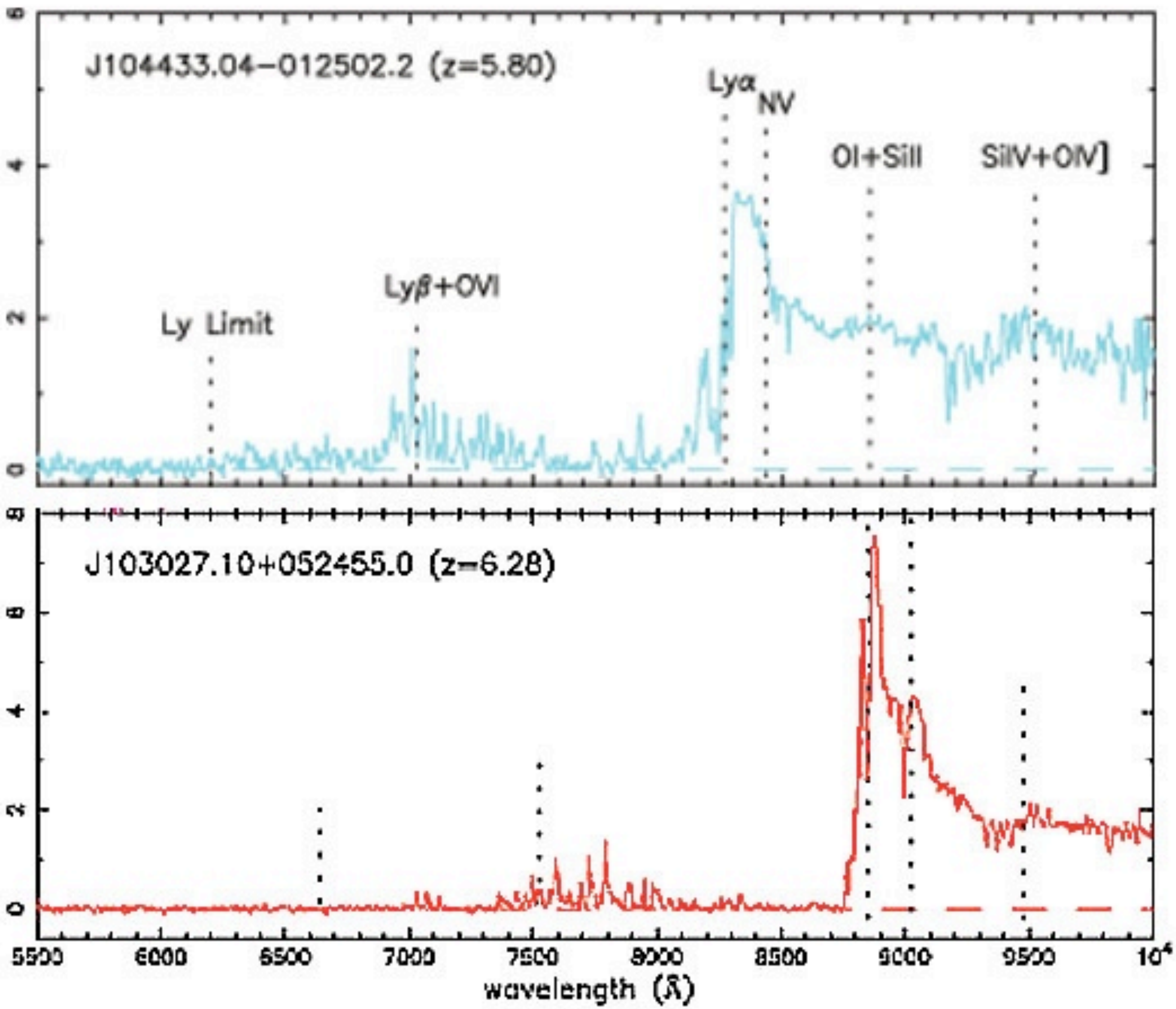
http://www.eso.org/outreach/press-rel/pr-1999/pr-05-99.html



Becker et al astro-ph/0108097

log(N) – log(S) test

- Aim: see if quasar numbers change with z
- If quasar no. density is constant $n(r)=n_0$
  - and quasars all have the same luminosity L
- Observe with a limiting flux S
  - See all objects out to $r_{max} = (L/(4\pi\ S))^{-0.5}$
  - See a number $N(S) = \int_0^{r_{max}} n(r)\ r^2\ dr$

    $= n_0\ r_{max}^3 / 3 = n_0\ (L/(4\pi\ S))^{-1.5} /3$
- Plot log(N) vs log(S).
  - Should see slope of -1.5 if no evolution
- Problems with log(N) – log(S)
  - Assumes one L, or non-evolving lum. fn.
  - Gives false-positive if survey is incomplete (objects missing close to S)

Peterson p 159 - 161

V/V_{max} test

- Does not give false positive if incomplete
- Consider each object, distance r
  - Find maximum distance at which could have seen object = r_{max}
  - Calculate $V/V_{max} = (r/r_{max})^3$
- If uniform number density $\langle V/V_{max} \rangle = 0.5$

Peterson p179, 180

Prove that for a single object, expect $\langle V/V_{max} \rangle = 0.5$

- Object has some r_{max} so $V_{max} = 4\,\pi\, r_{max}^3 / 3$
- Average over possible positions of object, r
  - If uniformly distributed $n(r) = n_0$
- $\langle V \rangle = [\int_{V_{max}} n(r)\, V\, dV\,] / [\int_{V_{max}} n(r)\, dV\,]$

  $= [\int_0^{rmax} (4\,\pi\, r^3 / 3)\, r^2\, dr\,] / [\int_0^{rmax} r^2\, dr]$

  $= (4\pi/3)\,(r_{max}^6 / 6) / (r_{max}^3 / 3)$

  $= V_{max} / 2$

We observe $\langle V/V_{max} \rangle = 0.65 +/- 0.03$ for quasars

So there were more quasars in the past!