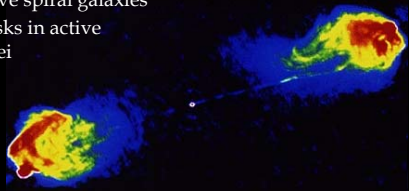


**Today in Astronomy 142**

- ❑ More evidence for black holes in quasars: observations of relativistic motion in jets
- ❑ Radio galaxies, quasars and blazars: the same objects seen from different orientations
- ❑ Seyferts: active spiral galaxies
- ❑ Accretion disks in active galactic nuclei

False-color VLA image of the archetype radio galaxy Cygnus A (Perley, Dreher and Cowan 1996)



7 April 2009 Astronomy 142, Spring 2009 1

---

---

---

---

---

---

---

---

---

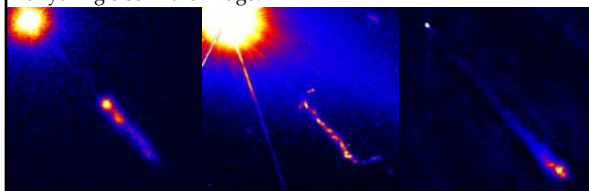
---

---

---

**Quasar jets**

Another hallmark of quasars is that faint, **single** jets are seen to be associated with them, as in 3C 273, here. In each image, the quasar (upper left) is starlike and much brighter than anything else in the image.



3C 273 in X rays, by CXO.      ...in visible light, by HST.      ...in radio light, by MERLIN.

7 April 2009 Astronomy 142, Spring 2009 2

---

---

---

---

---

---

---

---

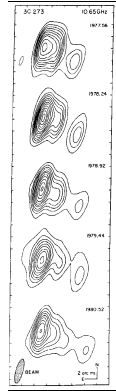
---

---

---

---

**Superluminal (apparently faster-than-light) motion in some quasar jets**



The innermost parts of the radio jet in 3C 273 consists mainly of small “knots” with separation that changes with time, as shown in these radio images taken over the course of three years (Pearson *et al.* 1981, *Nature* 290, 366). The brightest (leftmost) one corresponds to the object at the center of the quasar.

One tick mark on the map border corresponds to 20.2 light years at the distance of 3C 273. Thus the rightmost knot looks to have moved about 21 light years in only three years.

**It moves at seven times the speed of light?**

7 April 2009 Astronomy 142, Spring 2009 3

---

---

---

---

---

---

---

---

---

---

---

---

### Superluminal motion in quasar jets: an optical illusion

Positions of knot when two pictures were taken, one year apart.

Speed of knot (close to the speed of light)

Light paths: A, B

Small angle: the knot's motion is mostly along the line of sight.

**Light path B is shorter than path A.** If the knot's speed is close to the speed of light, B is almost a light-year shorter than A. This "head start" makes the light arrive sooner than expected, giving the **appearance** that the knot is moving faster than light. (Nothing actually needs to move that fast.)

7 April 2009 Astronomy 142, Spring 2009 4

---

---

---

---

---

---

---

---

---

---

### Superluminal motion (continued)

From the geometry (see APP, pp. 359-361):

$$v_{\perp, \text{apparent}} = \frac{v \sin \theta}{1 - \frac{v}{c} \cos \theta} \quad (v_{\perp, \text{apparent}})_{\text{max}} = v \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \gamma v$$

Thus **apparent** speeds in excess of the speed of light can be obtained. However: the apparent speeds only turn out to be much in excess of the speed of light if the actual speed of the radio-emitting knots is pretty close to the speed of light.

Ejection speeds in astrophysics tend to be close to the escape speed of the object that did the ejecting. What has escape speeds near the speed of light?

- Neutron stars (but they can't produce the quasar's luminosity)
- Black holes - like the one that can produce the quasar's luminosity!

7 April 2009 Astronomy 142, Spring 2009 5

---

---

---

---

---

---

---

---

---

---

### Objects related to quasars: radio galaxies and blazars

Radio galaxies: discovered in the 1950s at about the same time as quasars.

- Quite distinct from quasars, which in the 50s were seen to be point-like and associated only with pointlike optical objects: radio galaxies consisted of a pair of extended radio lobes on either side of a visible, elliptical galaxy.
- As radio interferometric techniques improved, radio galaxies were shown also to possess compact, pointlike central objects coincident with the galaxy nuclei, connected to the lobes by very narrow, usually straight jets. The lobes themselves have fine, filamentary structure; many have hot spots at the ends of the jets.

7 April 2009 Astronomy 142, Spring 2009 6

---

---

---

---

---

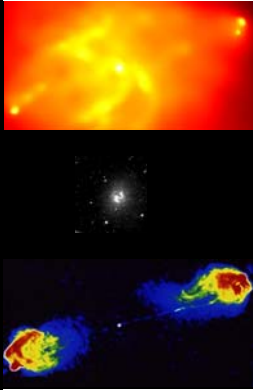
---

---

---

---

---



**The archetypical radio galaxy, Cygnus A**

Not to be confused with Cygnus X-1.

**Top:** X-ray image, by the CXO (Wilson *et al.* 2001).

**Middle:** visible-light image, from the HST-WFPC2 archives.

**Bottom:** radio image, by Rick Perley *et al.*, with the VLA.

7 April 2009 Astronomy 142, Spring 2009 7

---

---

---

---

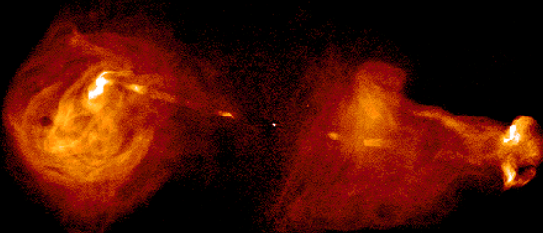
---

---

---

---

**3C353**



Swain and Bridle 1997, with the VLA

7 April 2009 Astronomy 142, Spring 2009 8

---

---

---

---


---

---

---

---

**3C288**



VLA image by Alan Bridle (NRAO), 1996.

7 April 2009 Astronomy 142, Spring 2009 9

---

---

---

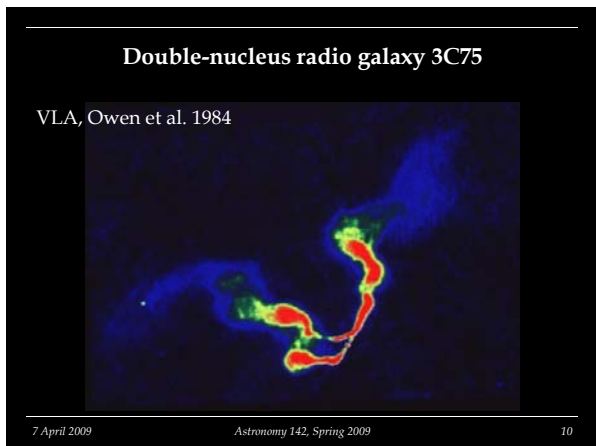
---

---

---

---

---




---

---

---

---

---

---

---

---

---

---

**Blazars (BL Lacertae objects)**

- ❑ Bright and starlike. Only recently has very faint luminosity been detected around them to indicate that they are the nuclei of galaxies.
- ❑ Smooth spectrum: hard to measure Doppler shift. Thus it was not realized at first that these objects were far enough away to be galaxy nuclei.
- ❑ Most are strong point-like radio sources. (Stars aren't; this was the first real indication that blazars are distant galaxies.)
- ❑ Violently variable brightness: large luminosity produced in a very small volume. (Sounds like a quasar so far.)
- ❑ **No long jets seen.**

7 April 2009 Astronomy 142, Spring 2009 11

---

---

---

---

---

---

---

---

---

---

**Active spiral galaxy nuclei: Seyfert galaxies**

Discovered in the 1940s by Carl Seyfert: spiral galaxies with starlike nuclei, often brighter than the rest of the galaxy, with ionized gas associated with these centers.

- ❑ Some found with very broad (thousands of km/s wide) recombination lines associated with the nuclei: these are called Type 1 Seyferts. NGC 4151 is one of these.
- ❑ Others have only narrow-line spectra (< a few hundred km/s at the nucleus): type 2 Seyferts. NGC 1068 is the paradigm of this class.
- ❑ There are intermediate types as well.
- ❑ The rotational and random speeds inferred from spectral lines near the centers indicate supermassive black holes for these galaxies, too.

7 April 2009 Astronomy 142, Spring 2009 12

---

---

---

---

---

---

---

---

---

---

**Quasars, radio galaxies and blazars are the same thing, seen from different angles.**

If the jets are relativistic (speeds close to  $c$ ) then their brightness should increase the closer to "head on" they are viewed, and decrease if they recede from the observer.

☐ **Quasar jets: radio galaxy jets viewed closer to head-on?**  
 If viewed straight down the jet, the vicinity of the central "engine" as well as the amplified, approaching jet would not be obscured by the disk. The brightness may be highly variable as a result.

☐ **Blazars: radio galaxies viewed exactly head on?**  
 It is possible to predict from these suggestions what the relative numbers of quasars, radio galaxies and blazars should be.

---

7 April 2009 Astronomy 142, Spring 2009 13

---

---

---

---

---

---

---

---

---

---

---

---

**Quasars, radio galaxies and blazars are the same thing, seen from different angles (continued)**

Relativistic Jets

Galaxy

An observer whose line of sight makes a small angle with the jet would see the object as a quasar. (For an extremely small angle, it appears as a blazar.)

An observer whose line of sight is closer to perpendicular to the jet would see the object as a radio galaxy.

---

7 April 2009 Astronomy 142, Spring 2009 14

---

---

---

---

---

---

---

---

---

---

---

---

**Quasars, radio galaxies and blazars are the same thing, seen from different angles (continued)**

45°

QSO

RG

QSO

Jet axis

Line of sight

$\theta$

$\phi$

Suppose jets within  $45^\circ$  of the line of sight appear as quasars (i.e. have one jet), and those outside as radio galaxies (two).

☐ Then our chances of seeing a given AGN as a quasar are the same as our chances of being in the cones within  $45^\circ$  of the jets.

☐ This, in turn, is the fraction of the AGN's sky's solid angle that the cones occupy.

☐ Similarly for radio galaxies and the solid angle outside the cones.

---

7 April 2009 Astronomy 142, Spring 2009 15

---

---

---

---

---

---

---

---

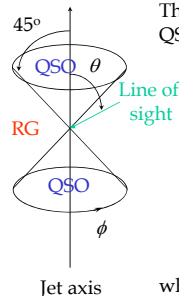
---

---

---

---

**Quasars, radio galaxies and blazars are the same thing, seen from different angles (continued)**



Thus the ratio of numbers of RGs and QSOs we see in a given volume of space is

$$\Omega_{RG} = \int d\Omega = \int_0^{2\pi} d\phi \int_{\pi/4}^{3\pi/4} d\theta \sin\theta$$

$$= 2\pi(-\cos\theta)_{\pi/4}^{3\pi/4} = 2\pi\sqrt{2}$$

$$\Omega_{QSO} = 4\pi - \Omega_{RG} = 2\pi(2 - \sqrt{2})$$

$$\frac{N(RG)}{N(QSO)} = \frac{\Omega_{RG}}{\Omega_{QSO}} = \frac{2\pi\sqrt{2}}{2\pi(2 - \sqrt{2})} = \frac{1}{\sqrt{2} - 1}$$

which agrees with observations (e.g. [Barthel 1989](#)).

7 April 2009 Astronomy 142, Spring 2009 16

---

---

---

---

---

---

---

---

---

---

**Matter falling into AGN black holes: large accretion disks**

A disk-shaped collection of matter surrounding the black hole in an AGN arises rather naturally from the influence of the black hole on stars and other material in the galactic center, just as it does in galactic black holes and young stellar objects. In this case,

- ❑ stars in a galaxy perpetually interact with each others' gravity as well as the gravity of the galaxy at large.
- ❑ These interactions - long-range collisions - usually result in transfers of energy and momentum between stars. Two stars, originally in similar orbits and undergoing such a collision, will usually find themselves pushed to different orbits, one going to a smaller-circumference orbit, and one going to a larger orbit.

7 April 2009 Astronomy 142, Spring 2009 17

---

---

---

---

---

---

---

---

---

---

**Matter falling into AGN black holes: large accretion disks (continued)**

Thus some stars are pushed to the very center of the galaxy after a number of these encounters. What happens if there is a black hole there?

- ❑ The star begins to fall in, but its orbital angular momentum, and the tidal forces that tend to rip the star apart, keep this from happening all at once.
- ❑ Stellar material spreads out into a rotating, flat distribution around the black hole: the beginnings of an accretion disk.

7 April 2009 Astronomy 142, Spring 2009 18

---

---

---

---

---

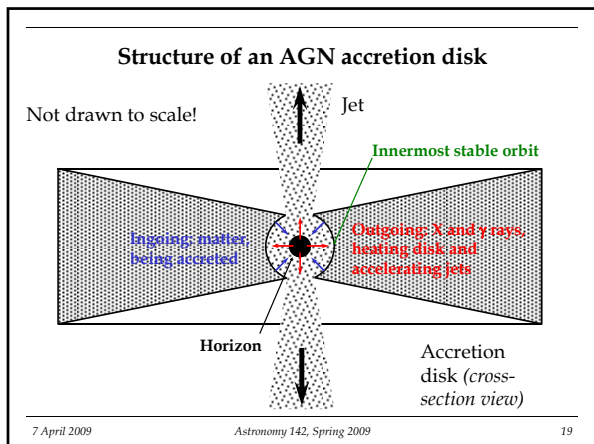
---

---

---

---

---




---

---

---

---

---

---

---

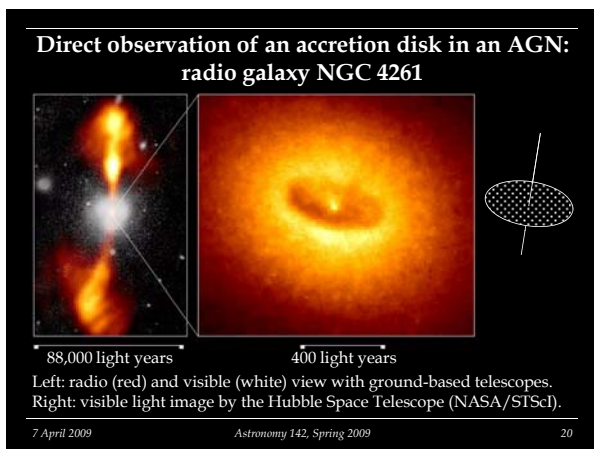
---

---

---

---

---




---

---

---

---

---

---

---

---

---

---

---

---

### Direct observation of an accretion disk in an AGN: Seyfert galaxy NGC 4258

The same things happen around the central black holes in Seyfert galaxies as happen in radio galaxies and quasars. But Seyfert galaxies are spirals, and have a lot more interstellar gas and dust than the elliptical hosts of RGs and quasars, which can stop the jets.

In the center of NGC 4258, [Miyoshi et al. \(1995\)](#) detected a molecular disk about 1 ly in diameter, rotating at 1000 km/sec near the outer edge. This implies a black hole mass of about  $4 \times 10^7 M_{\odot}$ .  
(Radio and visible-light images: NRAO)

0.2 pc

2 Kpc

7 April 2009 Astronomy 142, Spring 2009 21

---

---

---

---

---

---

---

---

---

---

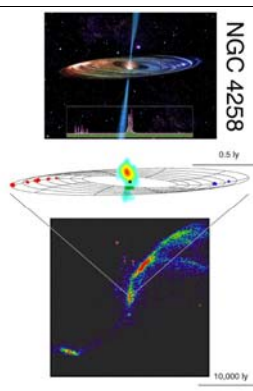
---

---

**Seyfert galaxy NGC 4258 (continued)**

A jet is seen emerging perpendicular to the disk, but is entrained by interstellar material in NGC 4258 and appears as an extra set of spiral features.

(Artwork and images by Inoue, Kagaya, Greenhill and De Pree.)



NGC 4258

8.5 ly

10,000 ly

7 April 2009 Astronomy 142, Spring 2009 22

---

---

---

---

---

---

---

---

---

---

**Dynamical evidence for supermassive black holes in radio galaxy/quasar nuclei**

With high angular resolution, one sees sharp “cusps” in the elliptical’s central stellar cluster, on much smaller scale than the core radius of the cluster.

With spectrographs at high angular resolution, one sees very small central regions, well within the “solid-body” part of the rotation curve, in which the rotation curve turns Keplerian and rises to high speeds, very close to the center.

- M87, radio galaxy with optical jet: spectra indicate central mass of about  $1 \times 10^9 M_{\odot}$ .
- M84, classic radio galaxy: HST/STIS rotation curve of center indicates a central mass of about  $3 \times 10^8 M_{\odot}$ .

7 April 2009 Astronomy 142, Spring 2009 23

---

---

---

---

---

---

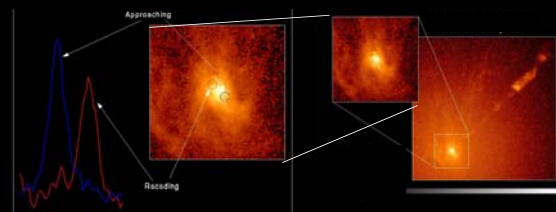
---

---

---

---

**High rotational velocities in the center of M87**



Approaching

Receding

The two apertures are separated by about 40 pc at the distance of M87, and the hydrogen recombination lines are seen there at velocities 550 km/s either side of the radial velocity of M87’s center (NASA/STScI).

7 April 2009 Astronomy 142, Spring 2009 24

---

---

---

---

---

---

---

---

---

---

**High rotational velocities in the center of M84**

Here the peak rotational speeds are 400 km/s at a distance of 8 pc from the center (NASA, STScI).

7 April 2009 *Astronomy 142, Spring 2009* 25

---

---

---

---

---

---

---

---

---

---

**High velocities and a massive pointlike object in the center of NGC 4151**

Peak speeds of several hundred km/s are seen in C IV] (UV, left) and two lines of [O III] (visible, right). (NASA/STScI)

7 April 2009 *Astronomy 142, Spring 2009* 26

---

---

---

---

---

---

---

---

---

---

**Active galaxy summary**

- ❑ All of them - quasars, blazars, radio galaxies and Seyferts - have compact "central engines" that produce galaxy-size luminosities in a space the size of the solar system.
- ❑ Some have very high Doppler velocities associated with emission lines near the central engines (broad-line regions): some quasars, Seyfert 1s.
- ❑ All have some evidence of high-speed outflow as well: relativistic speeds, in the case of quasars.
- ❑ Best explanation: supermassive black holes, accreting material from a surrounding gas disk. The heated inner parts of this disk are what we see as the central object.
- ❑ Evidence is mounting that **most** normal galaxies have the black holes, but not the accretion disk.

7 April 2009 *Astronomy 142, Spring 2009* 27

---

---

---

---

---

---

---

---

---

---