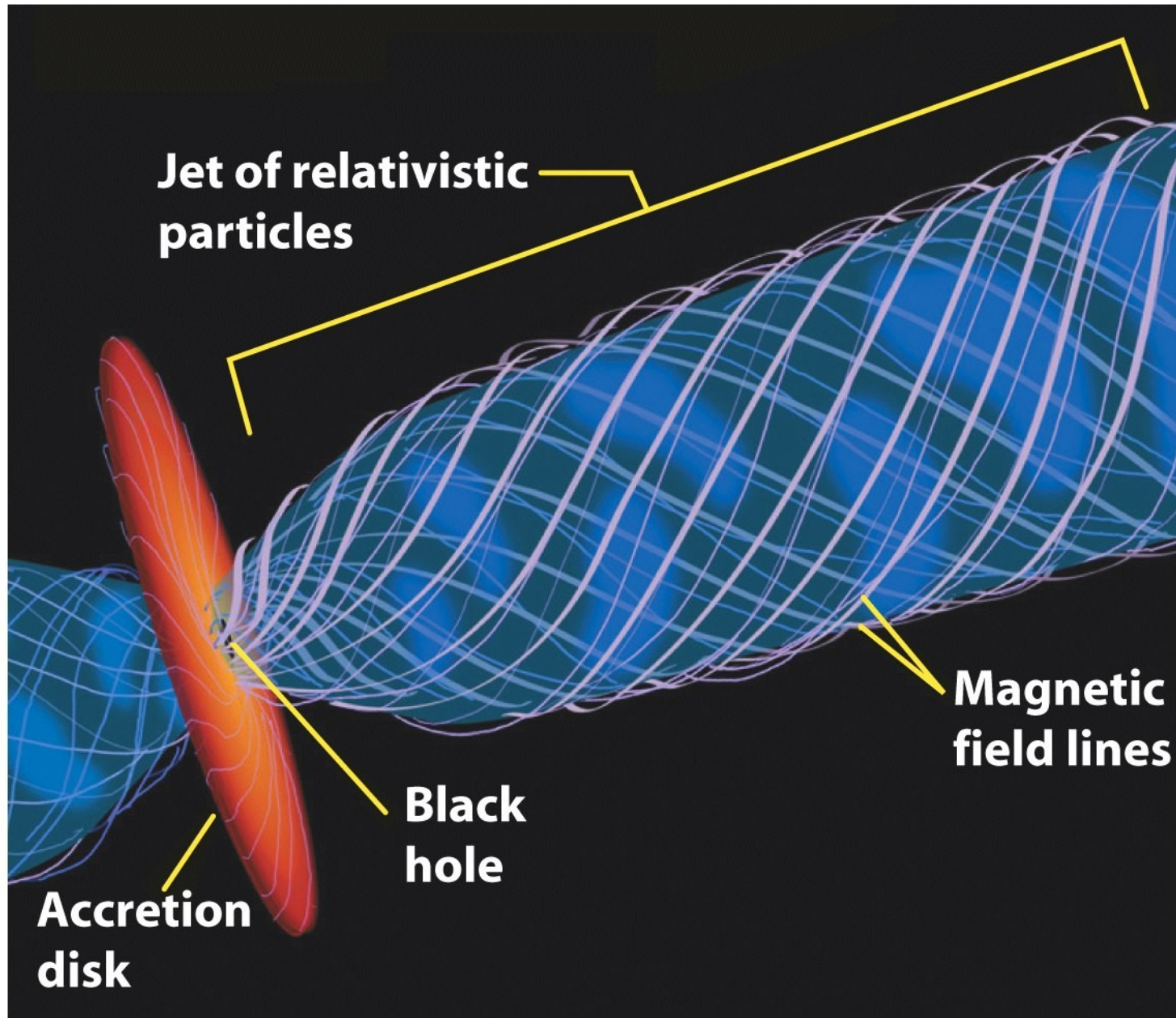


Jets

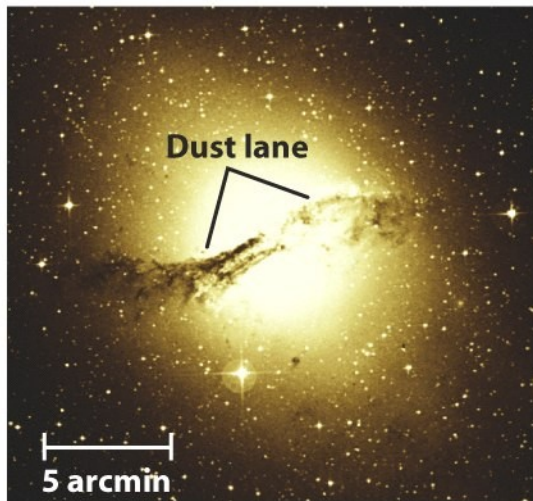
- In Radio Galaxies and Quasars
- Relativistic Jets
- Superluminal Motion

Radio Galaxies

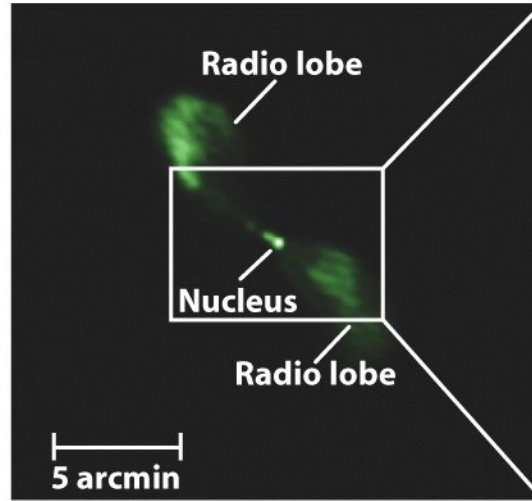
- A few galaxies are very strong radio emitters
- Radio structure often dominated by two enormous lobes
- These are located at distances up to 10-100 times the radius of the optical galaxy
- The central galaxy is located between the lobes and is usually a giant elliptical
- Jet originates from an AGN



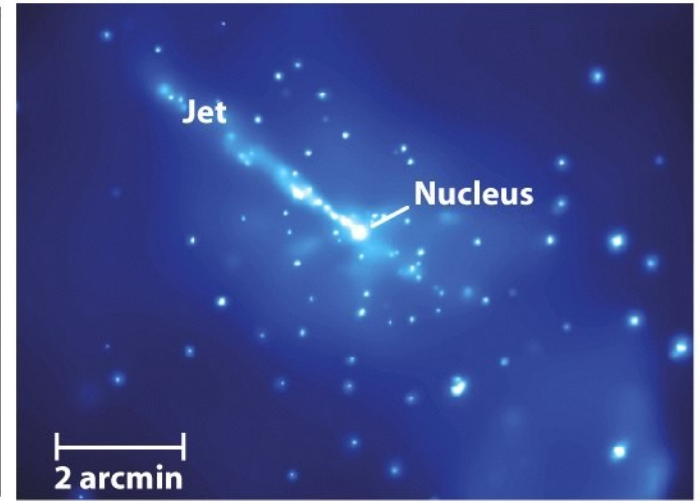
Radio Galaxy Centaurus A



(a) Centaurus A: light from stars

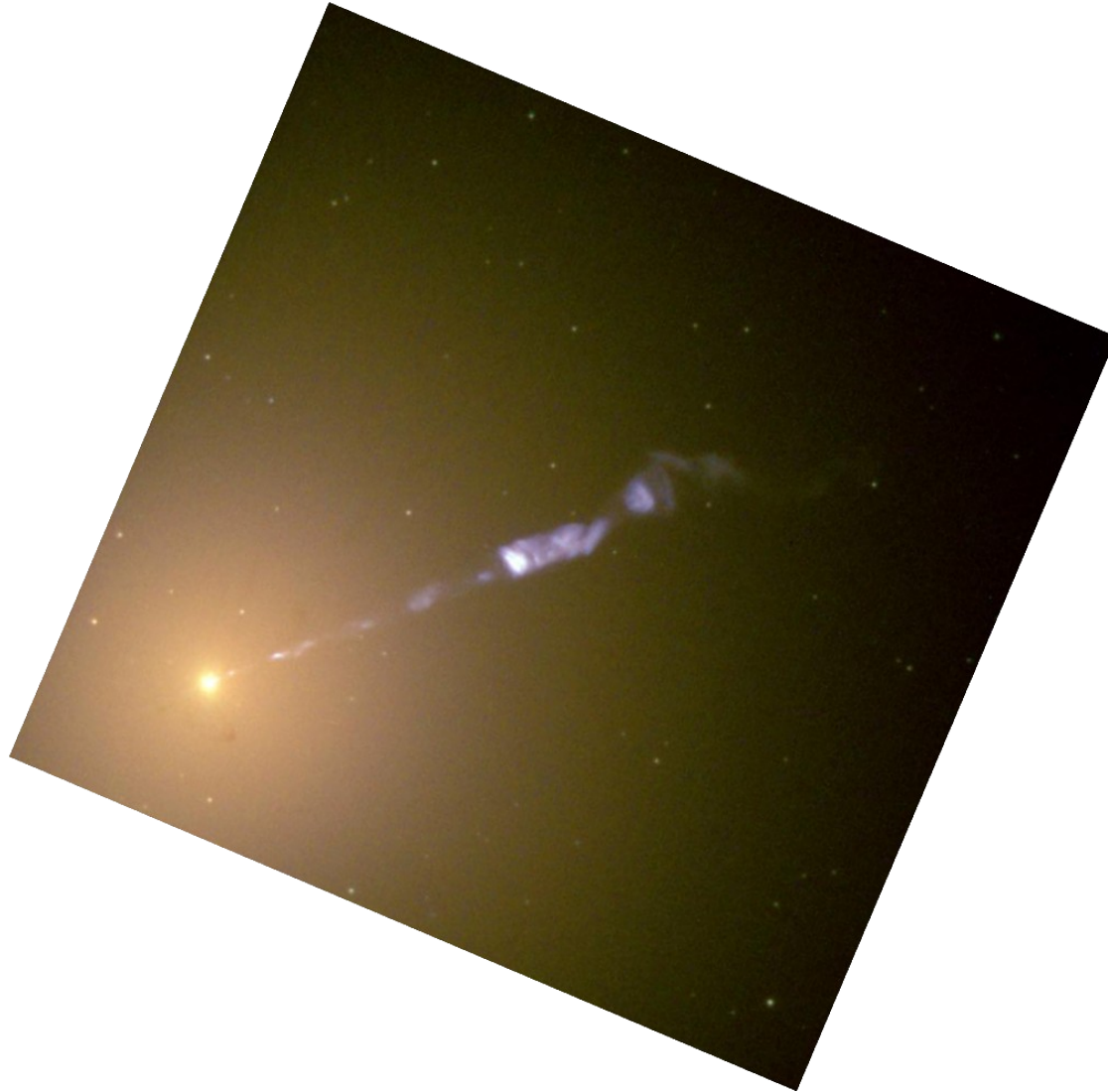


(b) Centaurus A: radio lobes



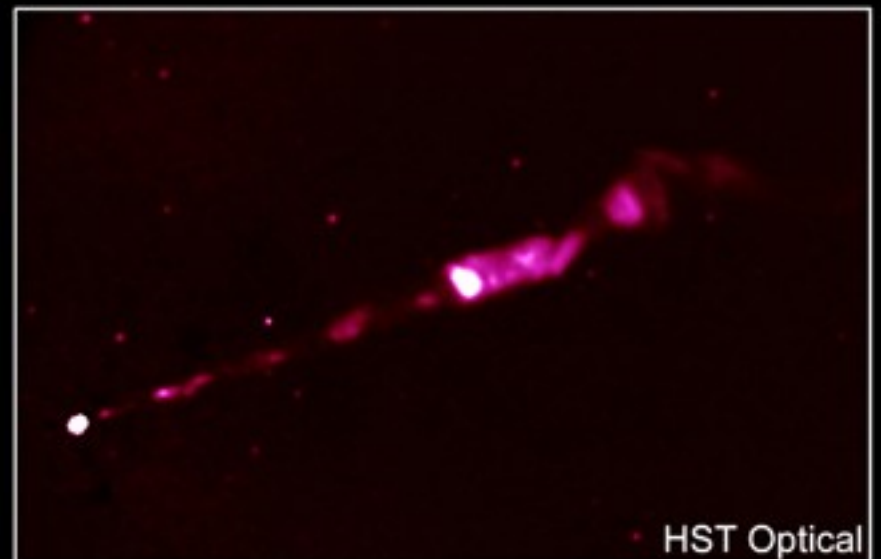
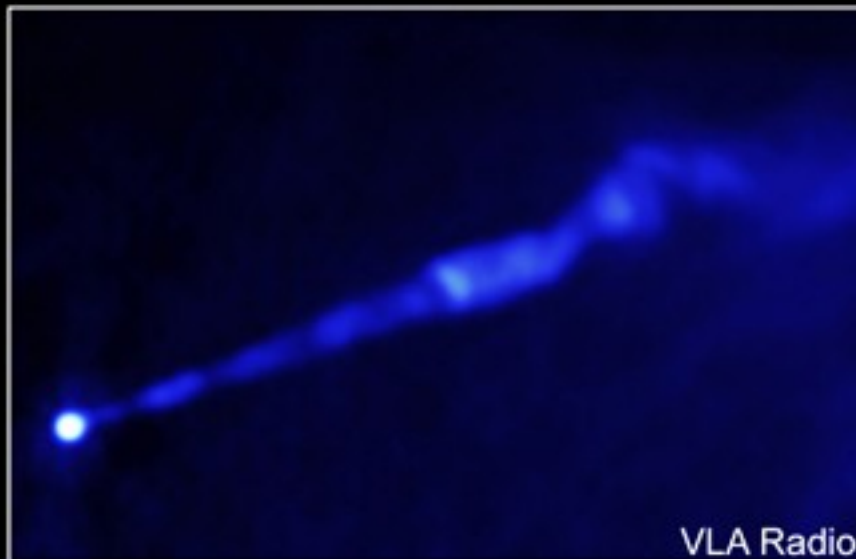
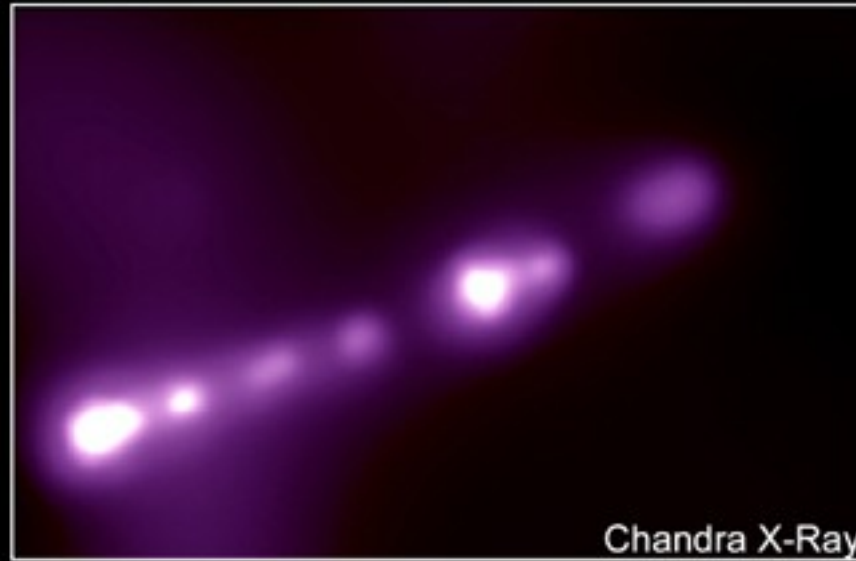
(c) An X-ray-emitting jet emanates from the nucleus

Jet in radio galaxy Virgo A or M87

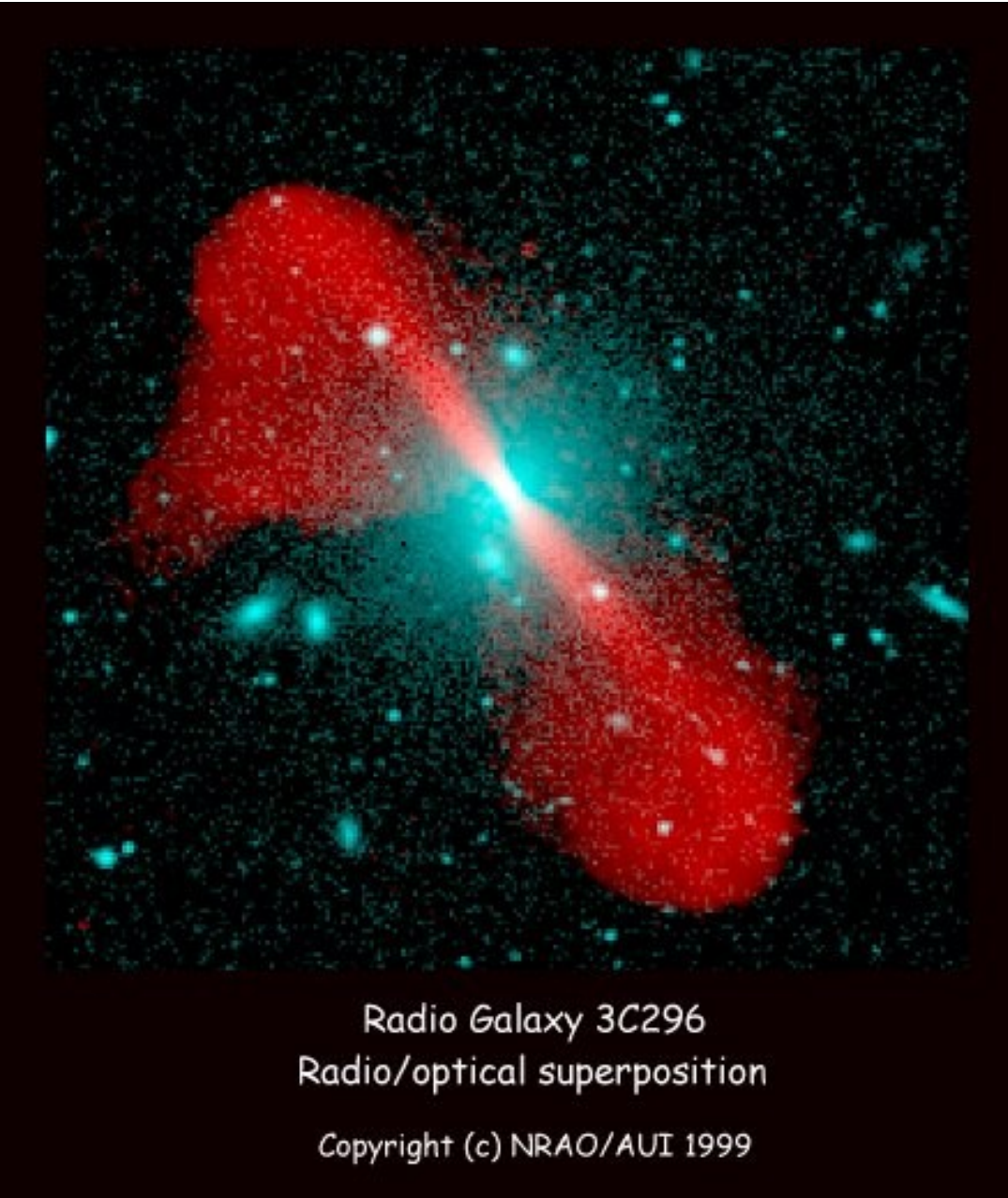


“short exposure optical picture from Hubble Space Telescope
(elliptical galaxy underexposed compared with jet)”

Jet in radio galaxy Virgo A or M87



- The jet and the lobes both have non-thermal emission due to the synchrotron mechanism
- Relativistic electrons from the core travel up the jet
- They interact with the intergalactic medium to produce the lobes
- The jet and lobes have strong magnetic fields



Radio Galaxy 3C296
Radio/optical superposition

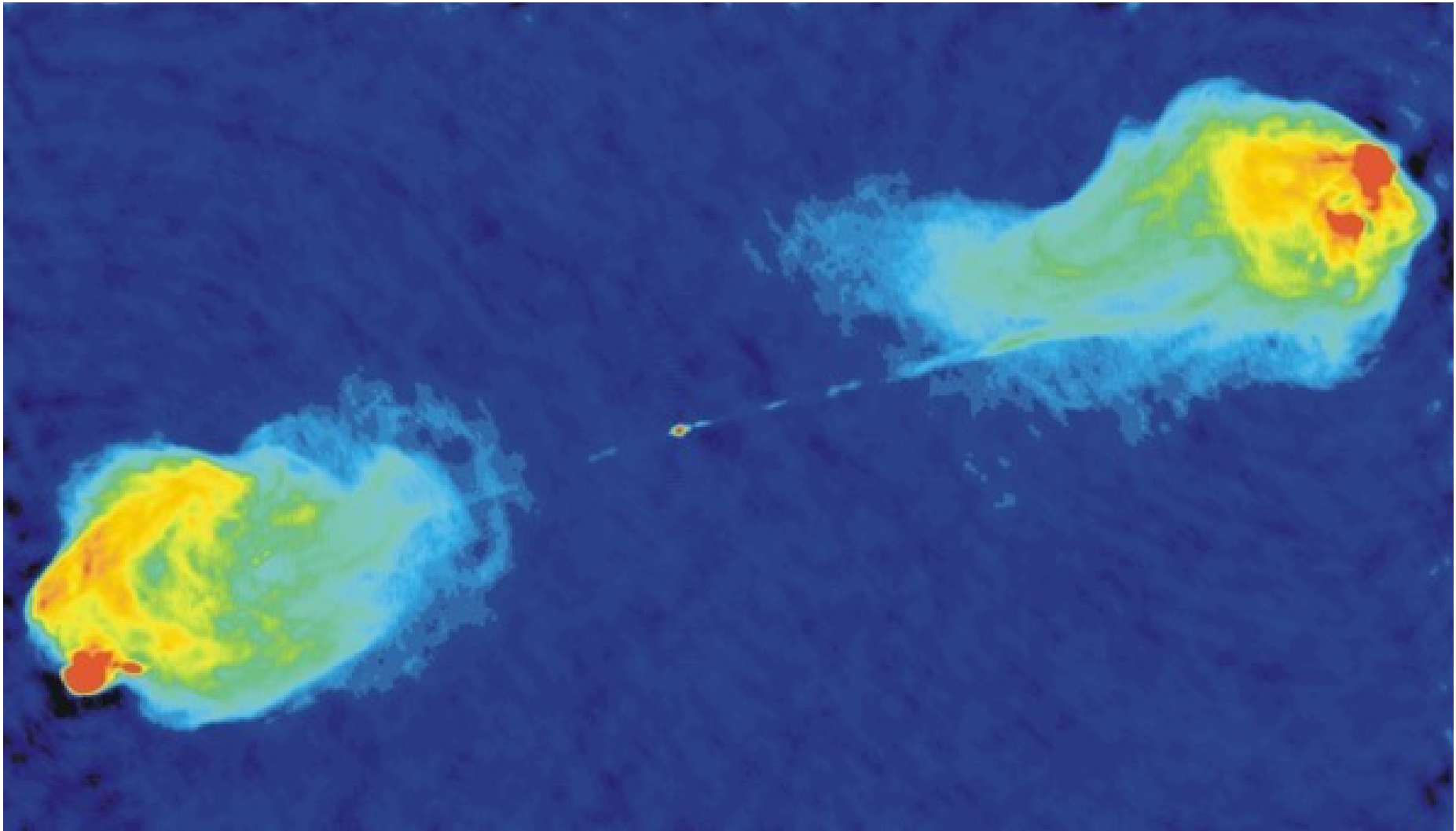
Copyright (c) NRAO/AUI 1999

An “FR1” radio galaxy

Less powerful jets entrain
Material along their way out
and are gradually slowed
down and eventually stop in
in the intergalactic medium
- outside the body of the
host galaxy.

FR II Radio Galaxies

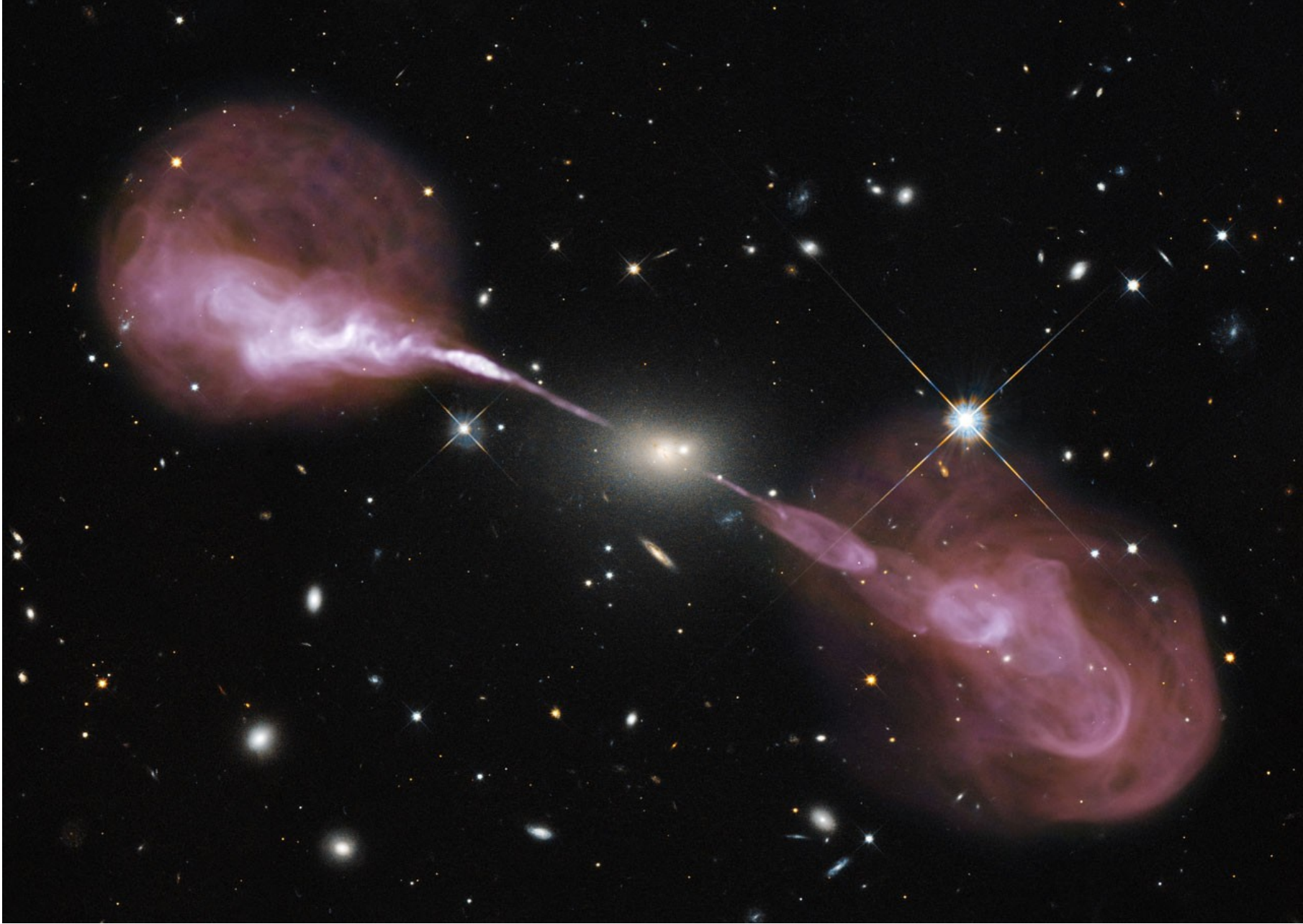
- When jets are more powerful they emerge at relativistic speeds and are highly collimated → a thin radio jet is seen emanating from a compact nucleus
- Often this is only seen on one side and not the other (a relativistic beaming effect)
- Where the jet hits the lobe there is a hotspot where the jet is being braked



Radio image of the radio galaxy Cyg A. VLA courtesy of NRAO/AUI



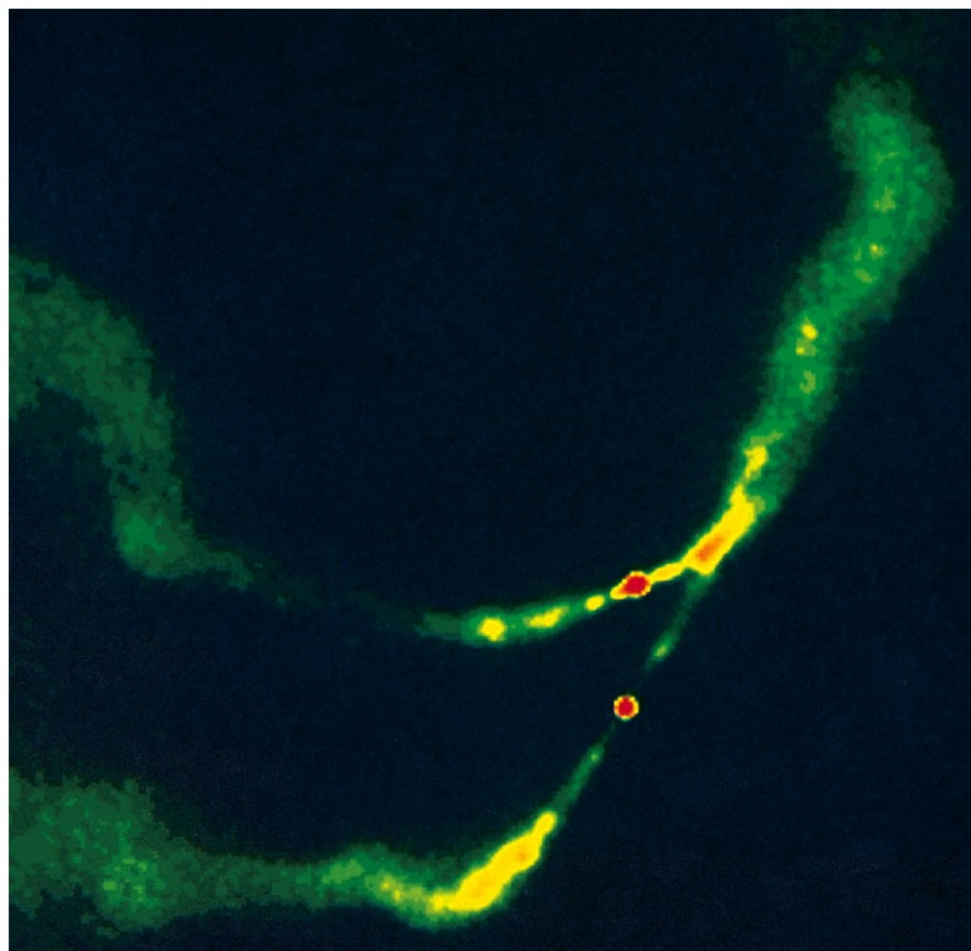
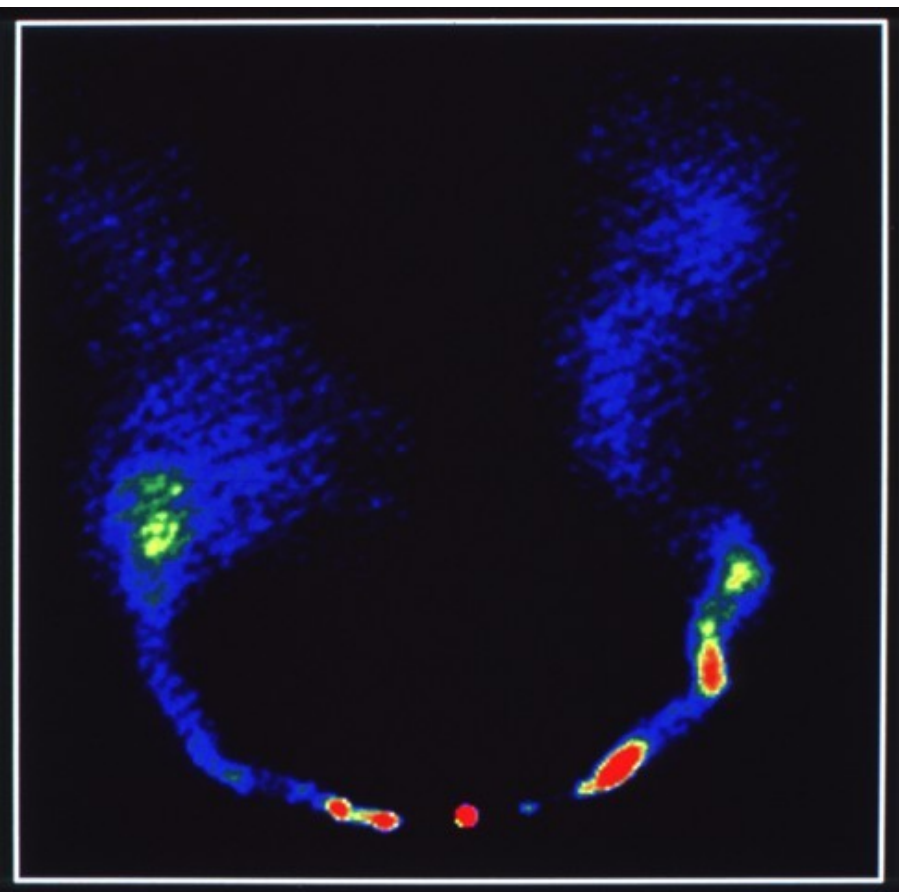
3C288
VLA,
NRAO/AUI



Radio image of Hercules A on top of HST image

Head-Tail Galaxies

- Some radio galaxies have bent jets that give the appearance of motion through space
- The core of the galaxy (head) leads whilst the lobes trail behind (tail)



Radio images of the head-tail radio galaxy 3C83.1 and 3C75

VI A courtesy of NRAO/AUII

Images of extended AGN radio sources

Thousands of images of extended radio sources associated with AGN have been made – in particular with the NRAO VLA/JVLA.

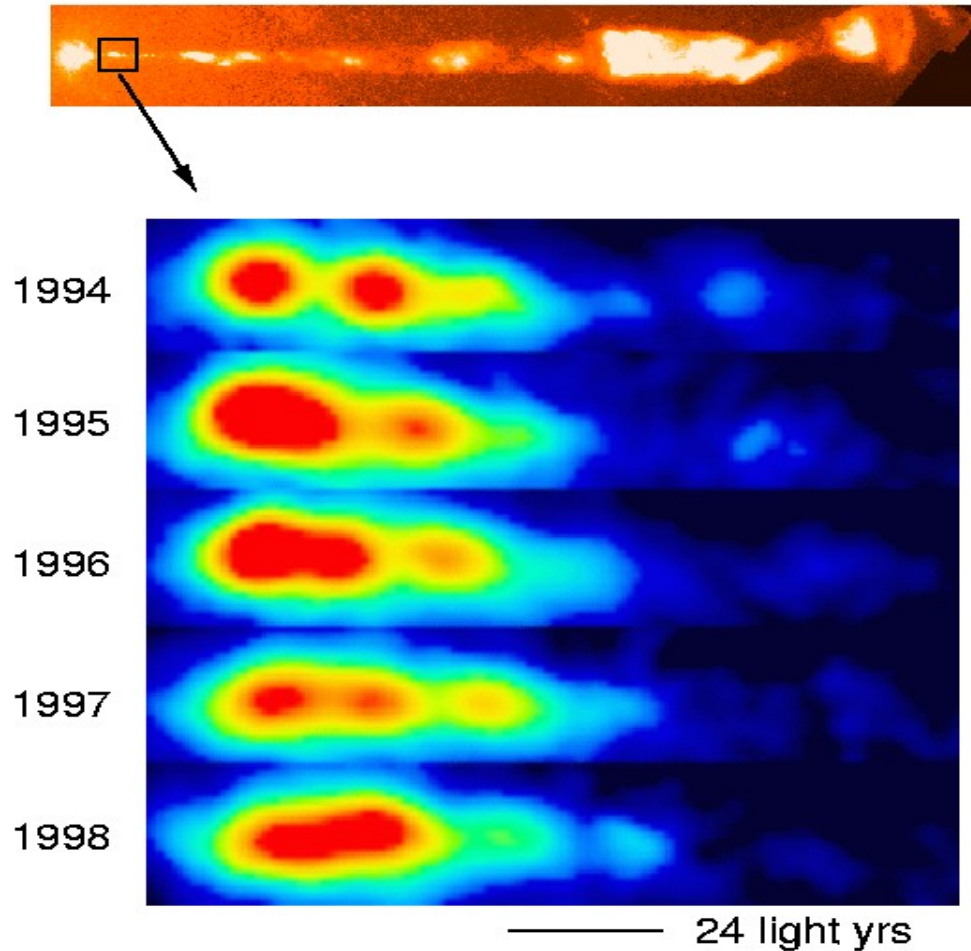
A good place to start is “An Atlas of DRAGNs” compiled and maintained by P. Leahy, A. Bridle and R. Strom <http://www.jb.man.ac.uk/atlas/>.

Another rich source of material is the NRAO Image Gallery <http://images.nrao.edu/> and the NRAO Public Gallery <https://public.nrao.edu/gallery/>. Here we showed just a few illustrative examples.

Superluminal Motion

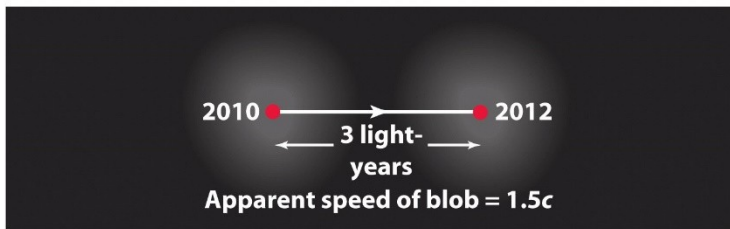
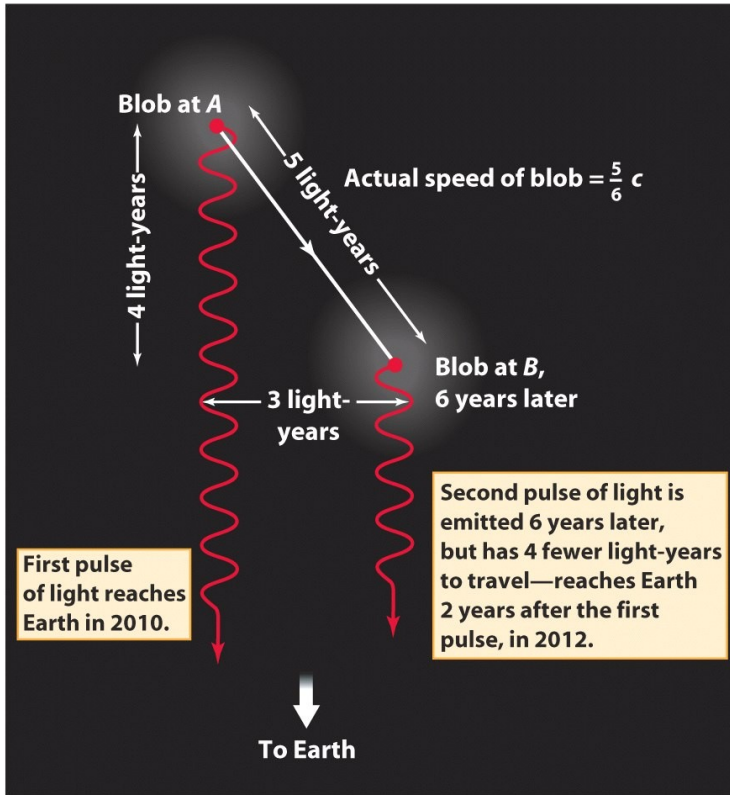
- Many jets have blobs or knots in them
- These can be seen to move over time
- This 'proper motion' can be used to measure the velocity of the jet
- Sometimes this velocity appears to be larger than the speed of light
- A result of the jet being close to our line of sight

Superluminal Motion in the M87 Jet

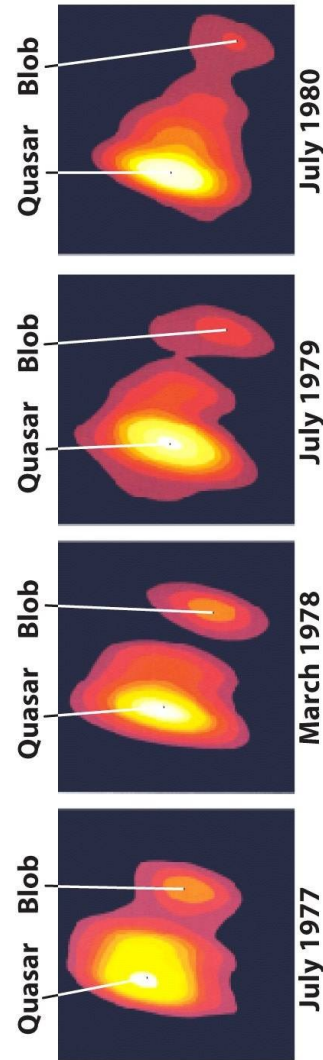


For a recent movie see

<https://www.aoc.nrao.edu/~cwalker/M87/>



View from Earth

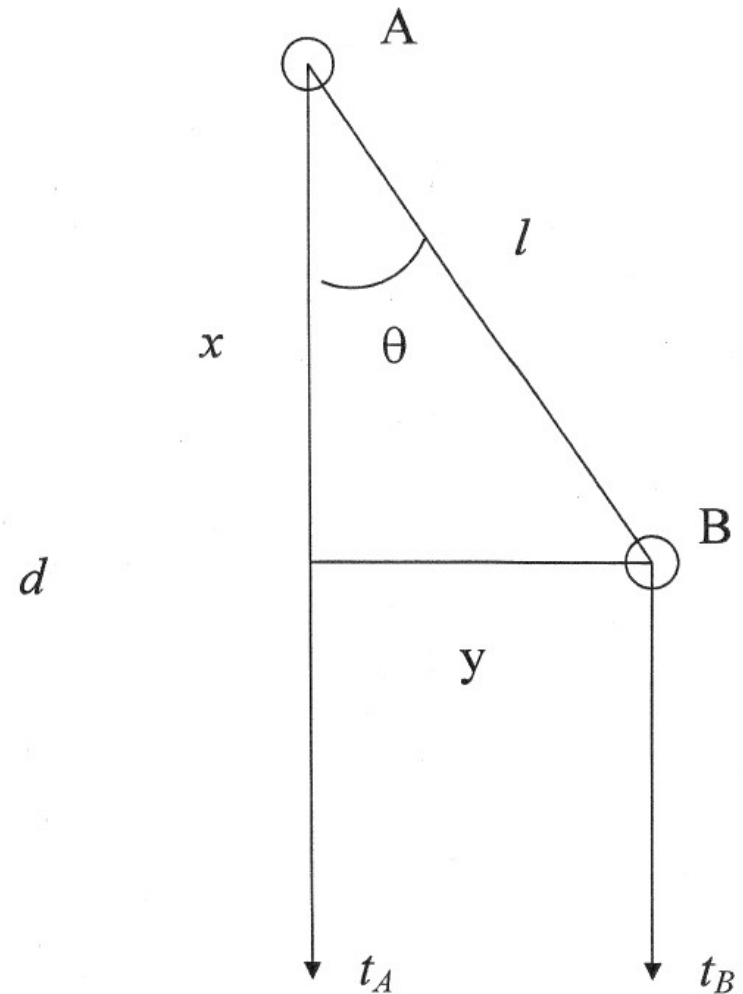


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More typical speeds 0.98-0.99c → Lorentz Factor $\gamma = 5 - 7$ sometimes higher

More generally...

- Consider an AGN jet a distance d away
- A blob is observed from Earth at time t_A in the core (A)
- A time interval t_{int} later the blob has moved to B and this is observed from Earth to occur at time t_B
- The blob is moving at a speed $v = \beta c$ where $\beta < 1$ at an angle θ to the line of sight



- Apparent velocity on sky is

$$v_{app} = \frac{y}{t_B - t_A}$$

- arrival time at Earth from A is

$$t_A = \frac{d}{c}$$

- arrival time at Earth from B is

$$t_B = t_{int} + \frac{(d - x)}{c}$$

- from geometry

$$l = vt_{int} = \beta ct_{int}$$

$$y = l \sin \theta$$

$$x = l \cos \theta$$

• So

$$\begin{aligned}v_{app} &= \frac{l \sin \theta}{\left(t_{\text{int}} + \frac{(d-x)}{c}\right) - \frac{d}{c}} \\&= \frac{l \sin \theta}{t_{\text{int}} - \frac{x}{c}} \\&= \frac{\beta c t_{\text{int}} \sin \theta}{t_{\text{int}} - \frac{\beta c t_{\text{int}} \cos \theta}{c}} \\&= \frac{\beta \sin \theta}{1 - \beta \cos \theta} c\end{aligned}$$

Example for class

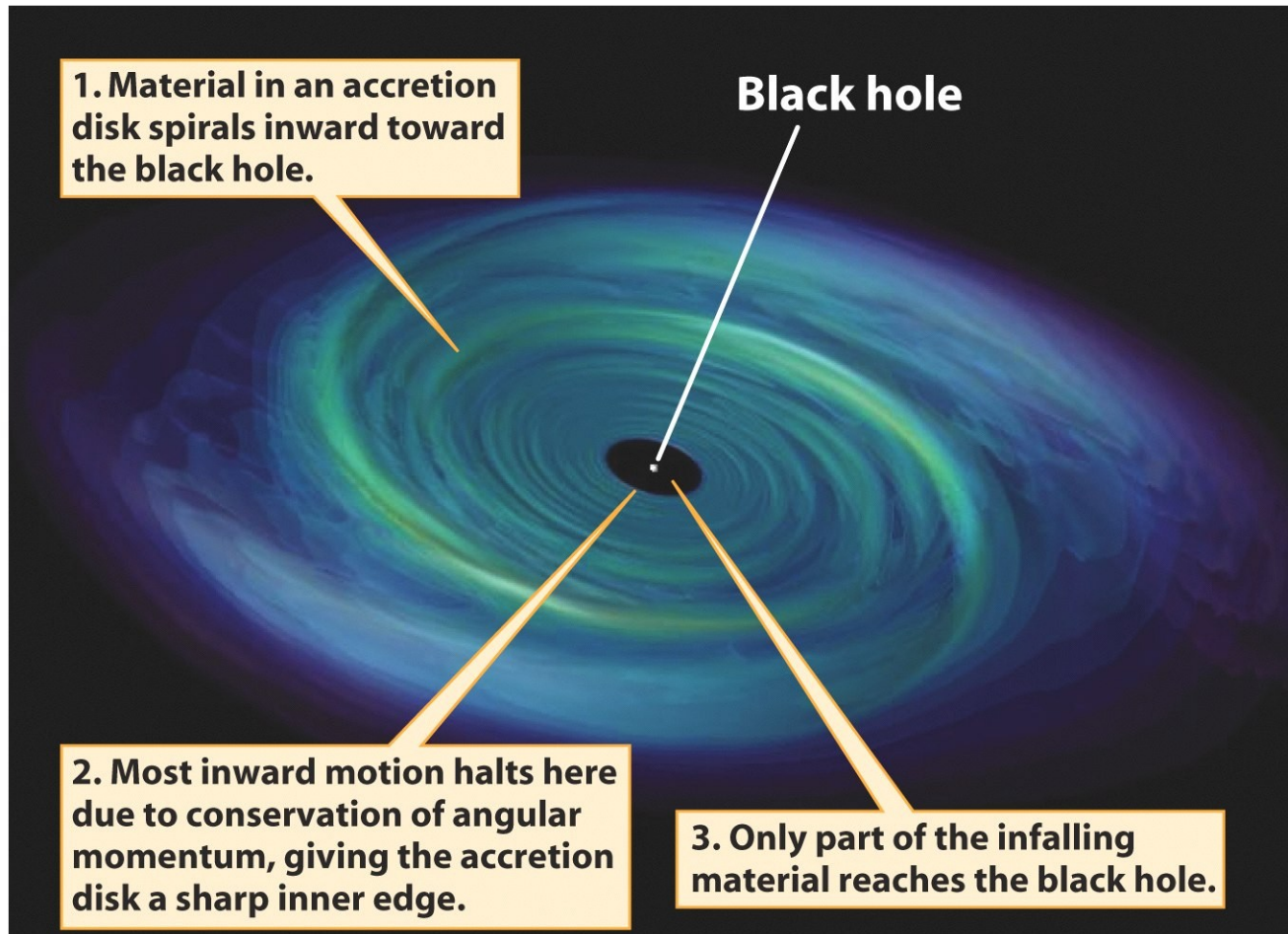
$$v_{\text{app}} = \left[\beta \cdot \sin \theta / (1 - \beta \cos \theta) \right] c$$

If $\beta = 0.98$ and $\theta = 10^\circ$

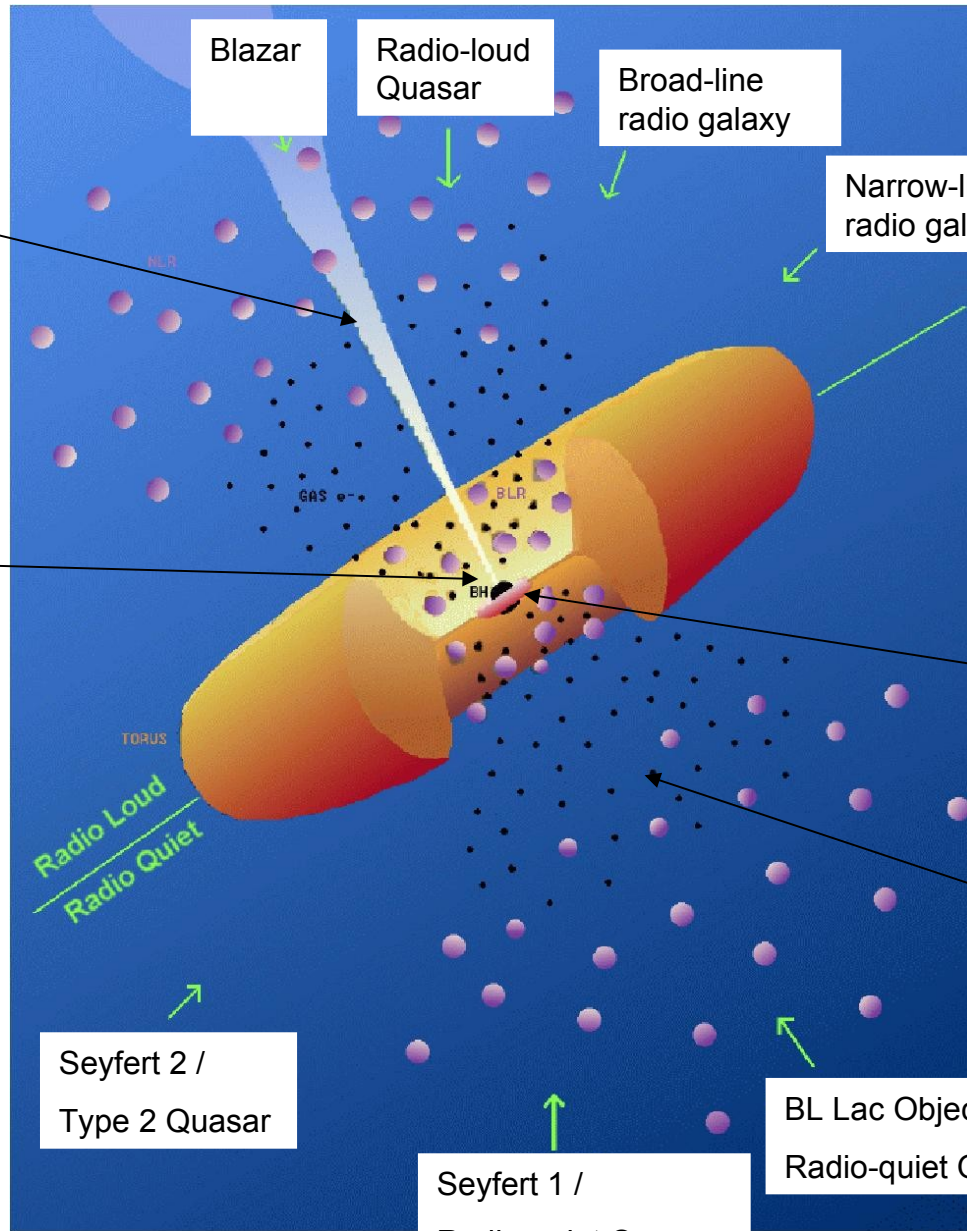
Calculate v_{app} in terms of c

Unified Model for AGN

- Currently thought that all the different types of AGN can be understood as the same phenomena, but with different viewing angles and nuclear luminosities



Remind you about the star formation scenario?



Blazar

Radio-loud Quasar

Broad-line radio galaxy

Narrow-line radio galaxy

Relativistic Jet

Super-massive black hole

Broad-line region

Narrow-line region

Radio Loud
Radio Quiet

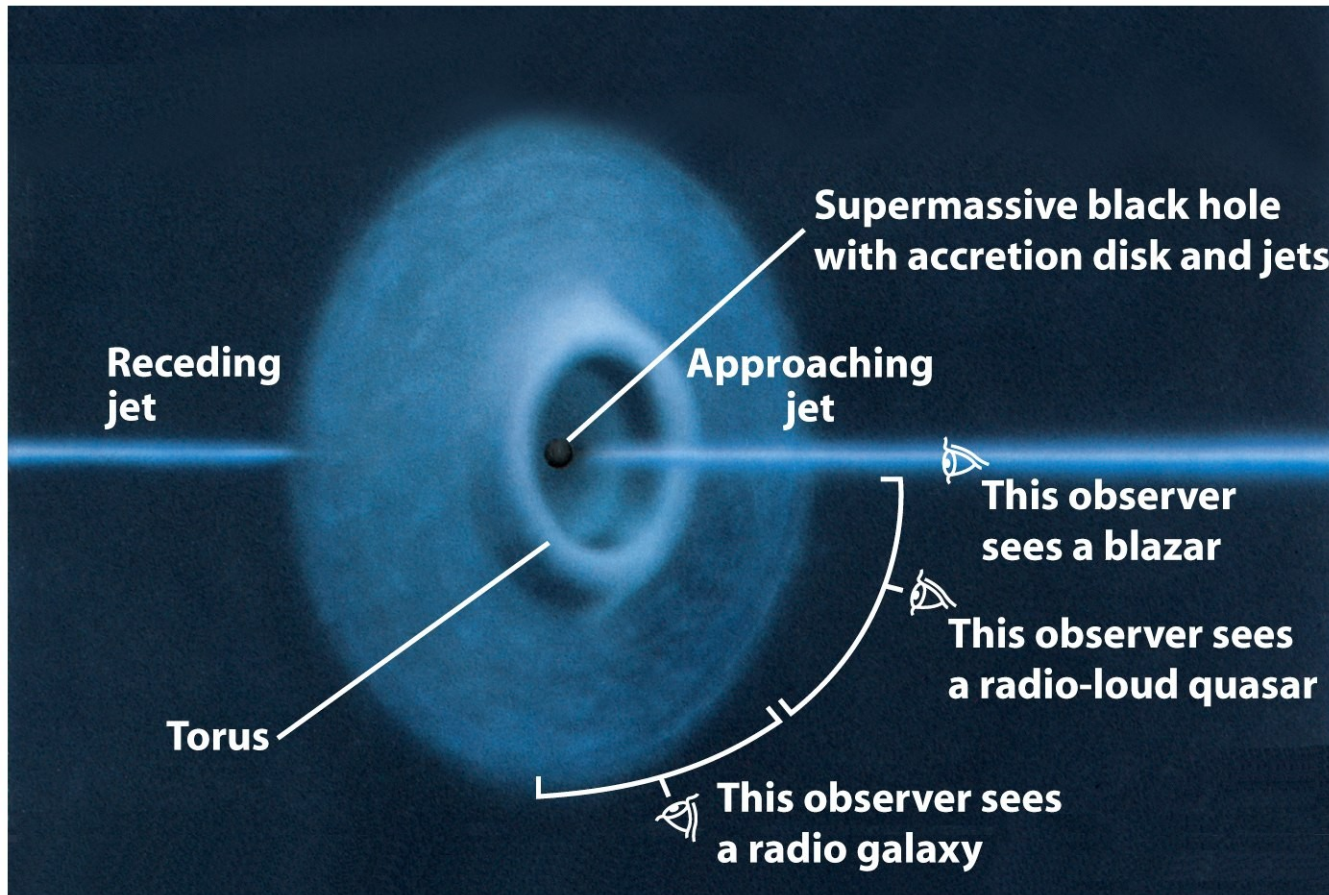
Seyfert 2 /
Type 2 Quasar

Seyfert 1 /
Radio-quiet Quasar

BL Lac Objects /
Radio-quiet Quasar

Low Luminosity /
High Luminosity

Quasars, blazars, and radio galaxies may be the same kind of object seen from different angles



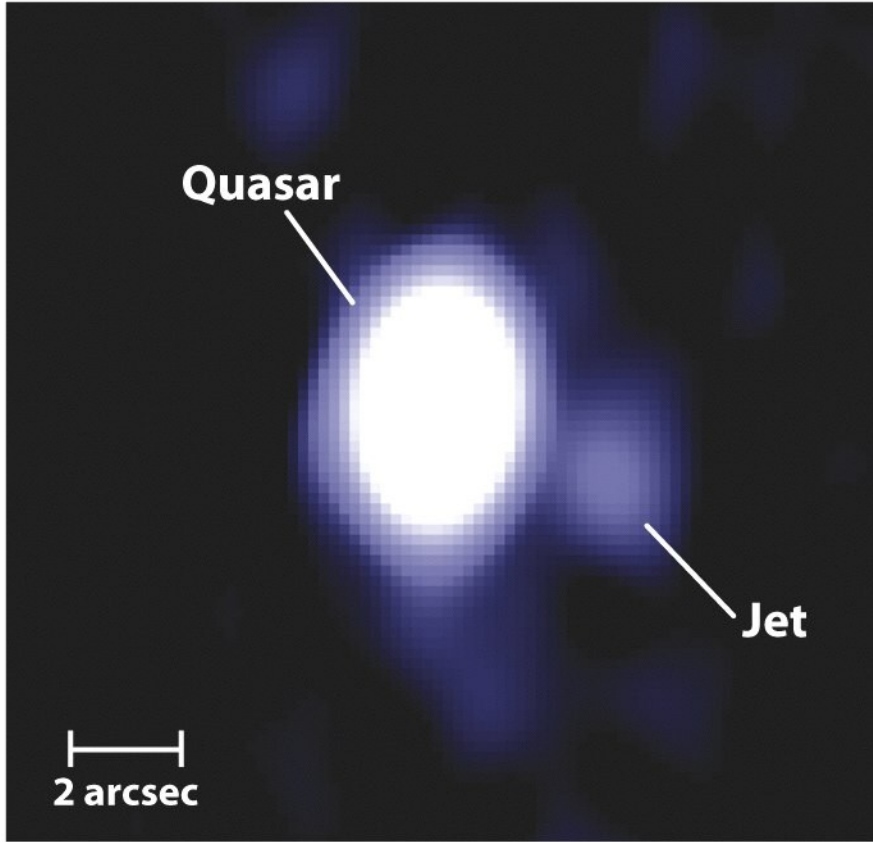
Summary

- Relativistic jets are associated with all “radio loud” AGN activity
- In radio loud AGN they are the most obvious sign of activity
- The non-thermal emission from jets can be seen across all wavelengths
- The majority of AGN are however “radio quiet” and don’t produce relativistic jets even though they have accretion disks – it is not clear why!

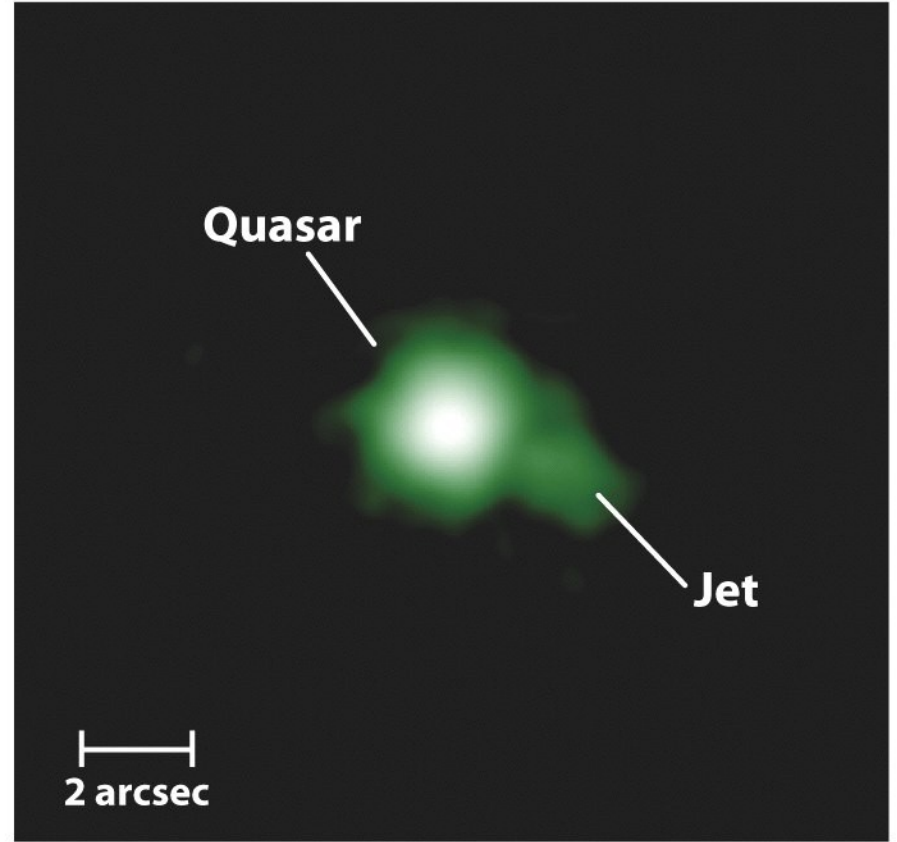
END

Other AGN Jets

- Radio galaxies are not the only AGN to show jets
- Radio-loud quasars show, usually short, jets coming from the core in radio, optical and X-rays
- Seyfert galaxies sometimes show weak, compact radio jets

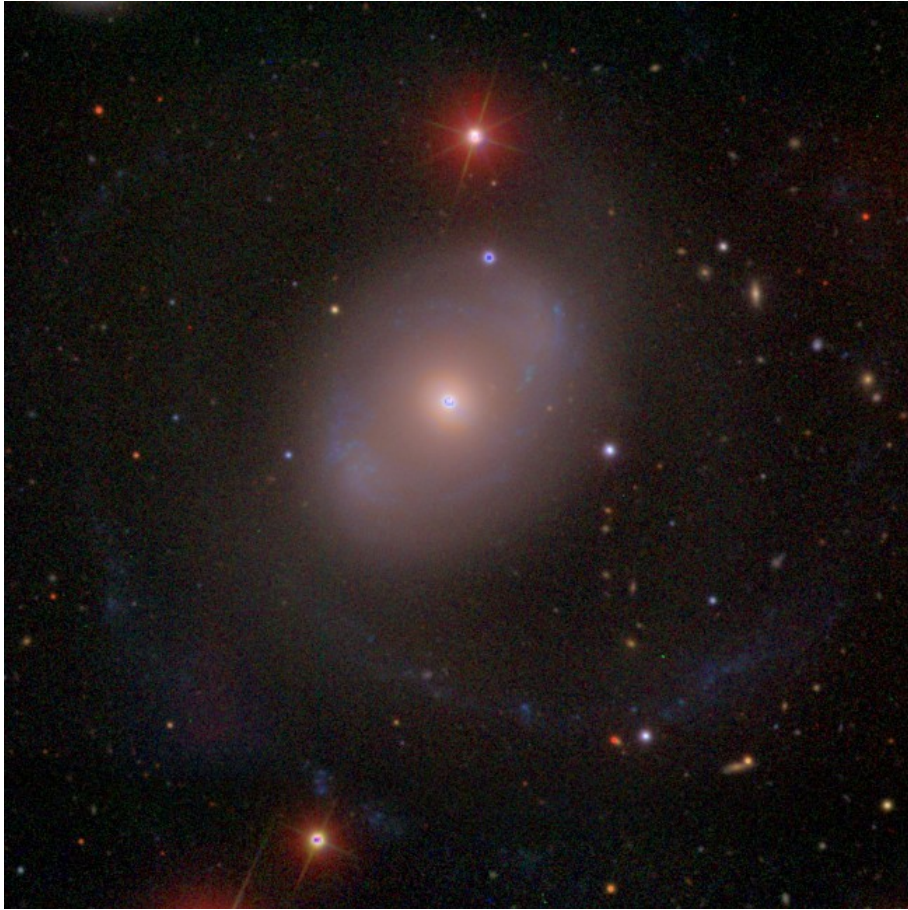
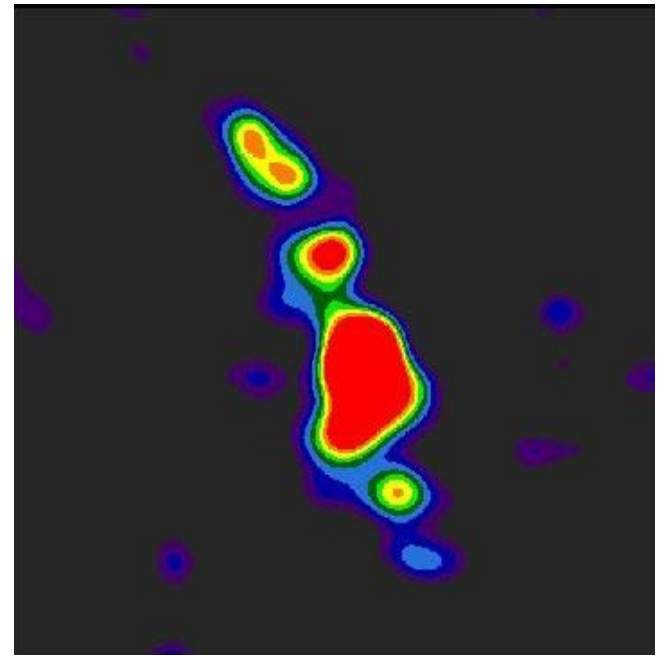


(a) A quasar jet at radio wavelengths...



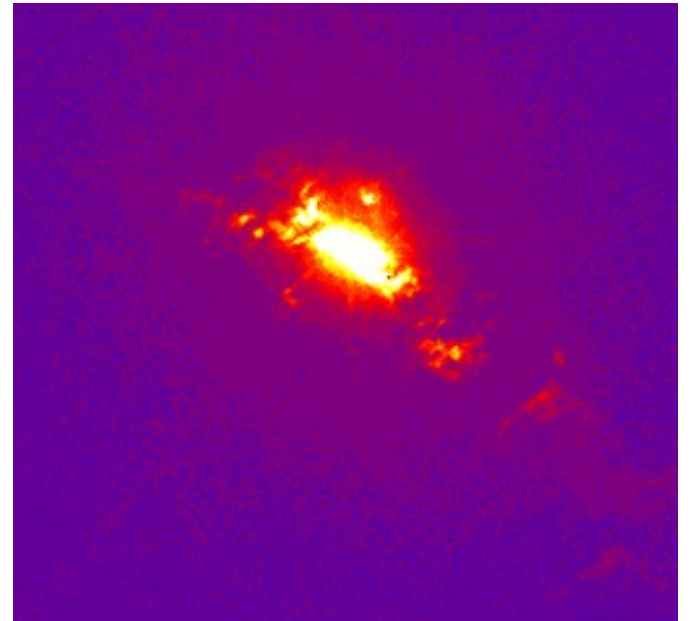
(b) ...and at X-ray wavelengths

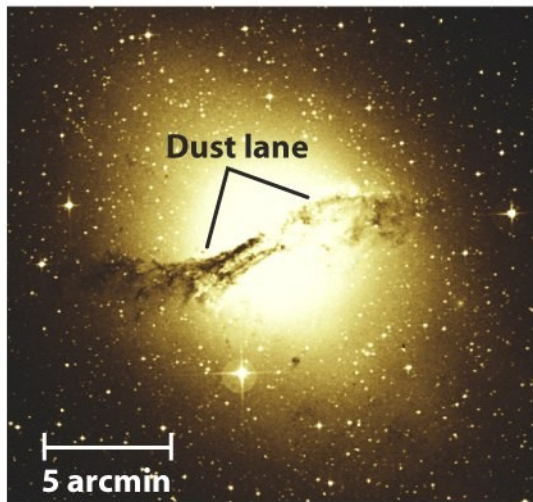
Radio VLBA
NRAO/AUI



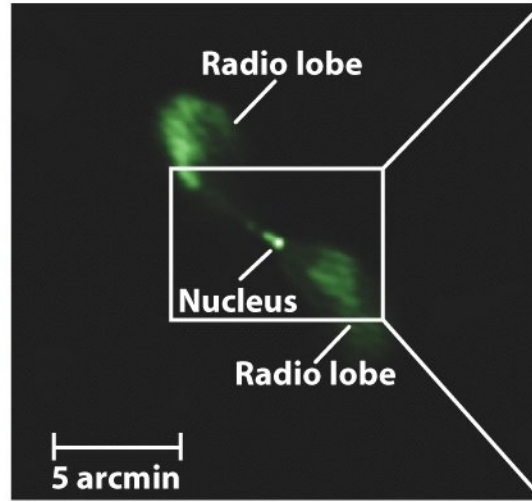
NGC 4151 Seyfert
galaxy, optical

Optical HST

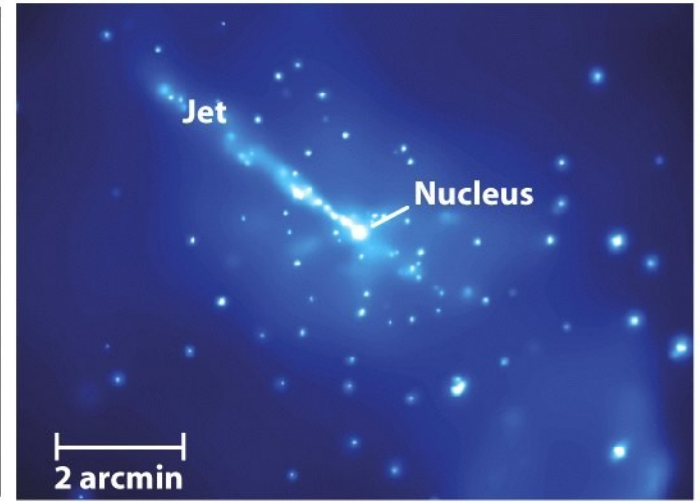




(a) Centaurus A: light from stars



(b) Centaurus A: radio lobes

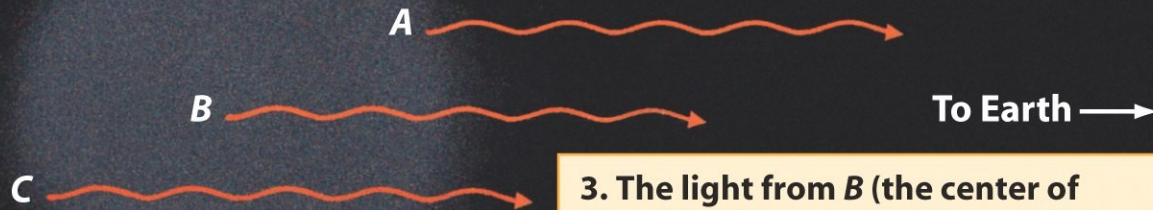


(c) An X-ray-emitting jet emanates from the nucleus

1. An object 1 light-year across emits a sudden flash of light.

1 ly

2. The first light that we receive comes from A (the part of the object nearest to Earth).



3. The light from B (the center of the object) has to travel an additional $\frac{1}{2}$ light-year to reach Earth, so we see this light $\frac{1}{2}$ year later than the light from A.

4. We see the light from C (the far side of the object) $\frac{1}{2}$ year later than the light from B and 1 year later than the light from A. Hence we see the sudden flash of light spread over a full year.