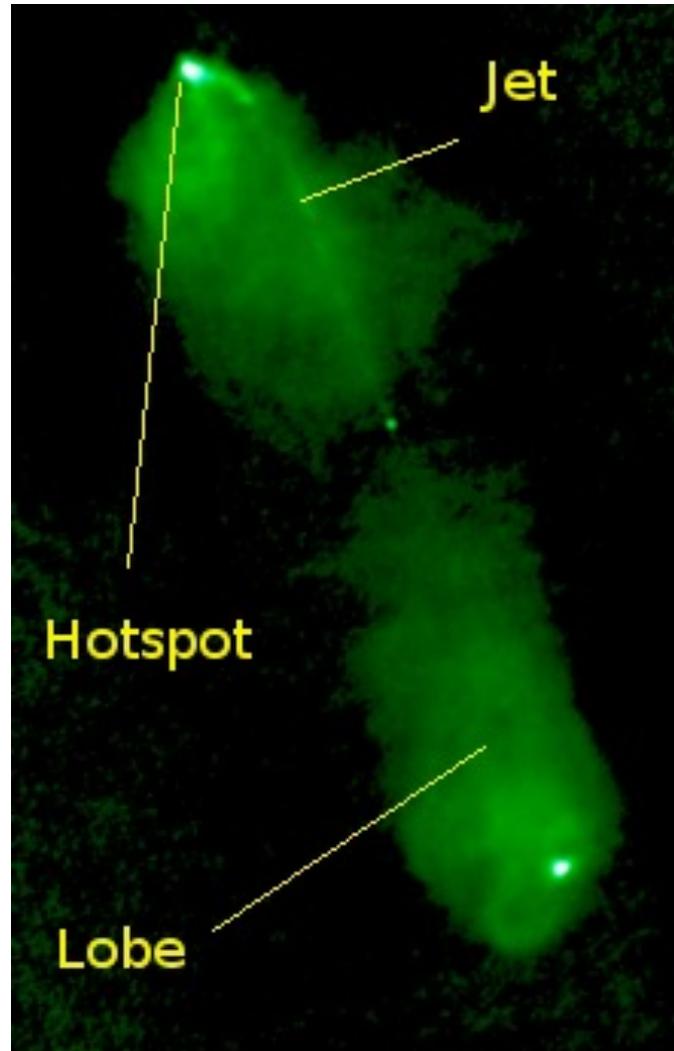


Jets



Radio Astronomy

The first radio waves of an astronomical origin were discovered by **Karl Jansky** in the early 1930s.

Jansky was trying to figure out what was causing interference at 20 MHz with a transatlantic radio link. He built a steerable **radio antenna** to search for the source of the noise.

He concluded that an **astronomical object** in the direction of the constellation Sagittarius must be causing the radio interference.

In 1936 **Grote Reber** built the first parabolic "dish" radio telescope and conducted the first sky survey in the radio frequencies.



Reber's radio telescope

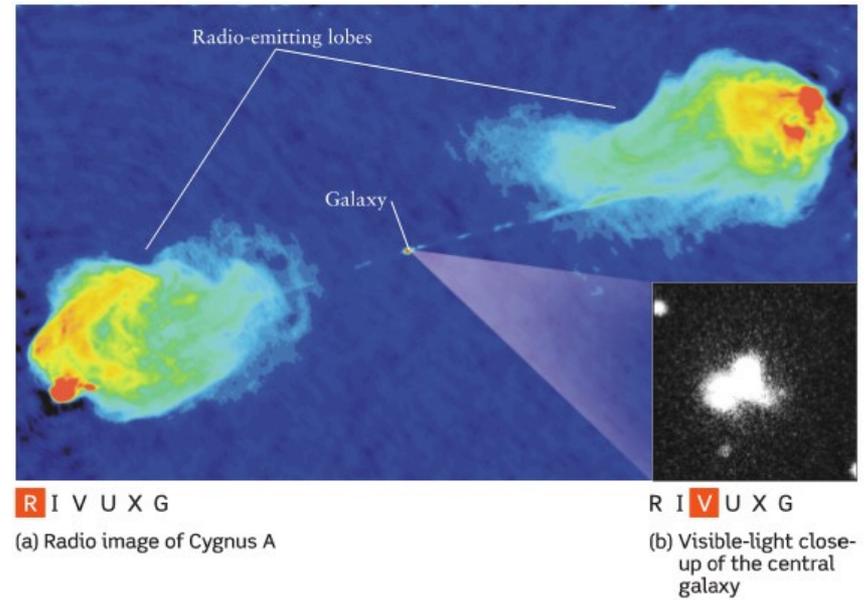


Very Large Array (VLA)
in New Mexico

Quasars and Active Galaxies

Grote Reber was the first to build a true radio telescope and map the radio sky. Some of the radio sources Grote Reber discovered included **Cassiopeia A** (a supernova remnant), **Sagittarius A** (the center of our Galaxy) and **Cygnus A**.

The optical spectrum of Cygnus A contained strong emission lines.



The VLA radio image of Cygnus A shows two bright radio lobes and jets on opposite sides of the central galaxy. Like all radio galaxies, Cygnus A contains an **active galactic nucleus (AGN)**.

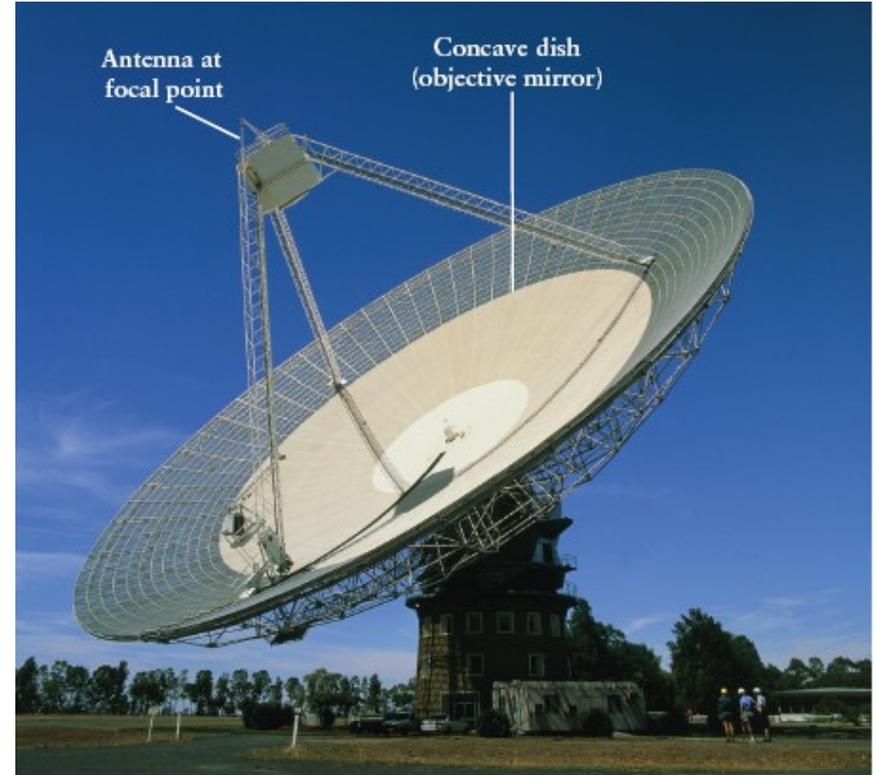
Radio Telescopes

A modern telescope consists of :

- a parabolic dish
- an antenna tuned to the desired frequency located at the focus.

The signal picked up by the antenna is relayed to an amplifier and recording instruments usually located at the base of the telescope pier.

The radio waves will not penetrate a mesh with spacing less than their wavelength.



PARKES, NSW, Australia
(64 m diameter)

DISH



Radio Telescopes: Dealing with Diffraction

The diffraction limited angular resolution of a 64 m radio dish at $\lambda = 21$ cm is $\theta \sim 2.5 \times 10^5$ (0.21 m /64 m) = 820 arcsec $\sim 0.23^\circ$

To improve the angular resolution of radio telescopes, astronomers use the **interferometry** technique.

The **Very Large Array (VLA)** consists of 27 parabolic dishes, each 25 m in diameter. By pointing all 27 telescopes at the same object and combining the 27 radio signals, the VLA can produce radio views of the sky with an angular resolution as small as 0.05 arcsec.



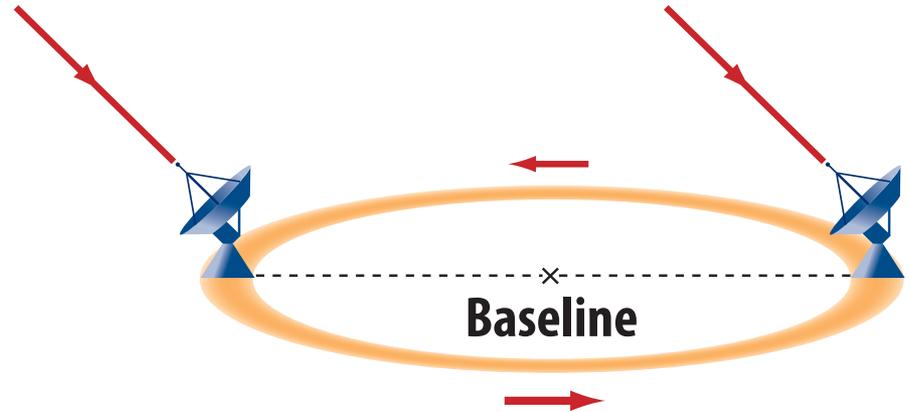
[CONTACT](#)



Jets



Martin Ryle of Cambridge University pioneered the technique of aperture synthesis.



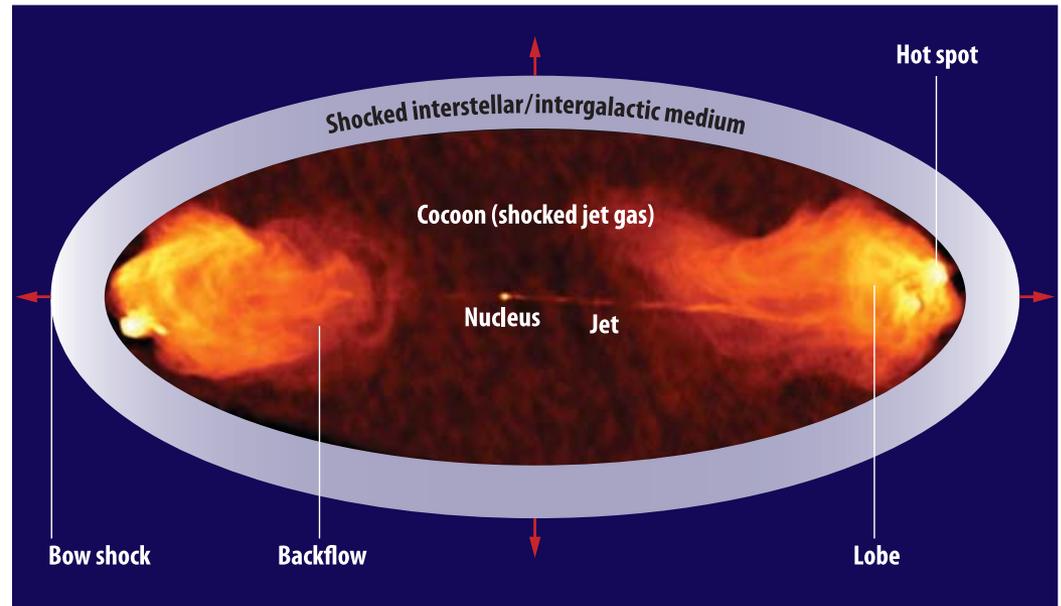
Aperture synthesis: As the Earth rotates, the small dishes trace out an annulus whose diameter equals the baseline separation. After combining the signals from these dishes for 12 hours, astronomers can synthesize the resolution of a reflecting dish with the size and shape of an annulus. To speed up the process, arrays of several dishes are used rather than just two.

What powers the lobes and hot spots?

Researchers from Cambridge University first proposed that lobes were powered by twin streams of fast-moving gas, created in the nucleus of the galaxy.

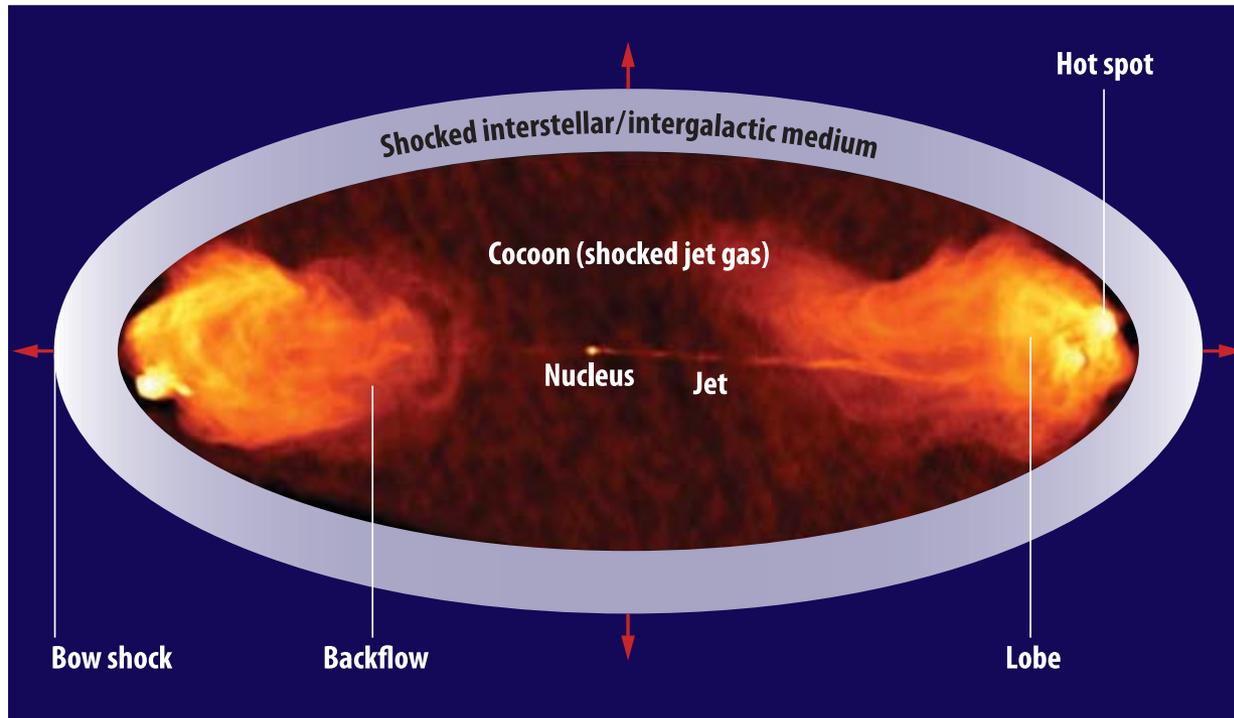
Space between stars is filled with an **interstellar medium (ISM)** of gas.
Space between galaxies is filled an **intergalactic medium (IGM)** of gas.

Jet Model: As the gas in the jet moves through the IGM it pushes the medium out of the way; hence the end of the jet moves slower than the gas flowing inside the jet. As a result, **energy accumulates at the end of the jet** forming the hot spots.

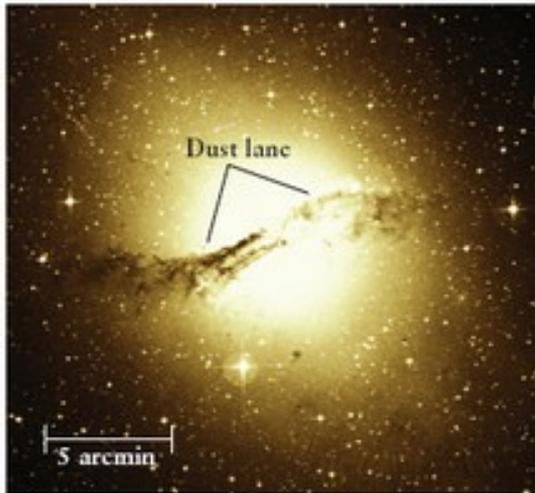


What powers the lobes and hot spots?

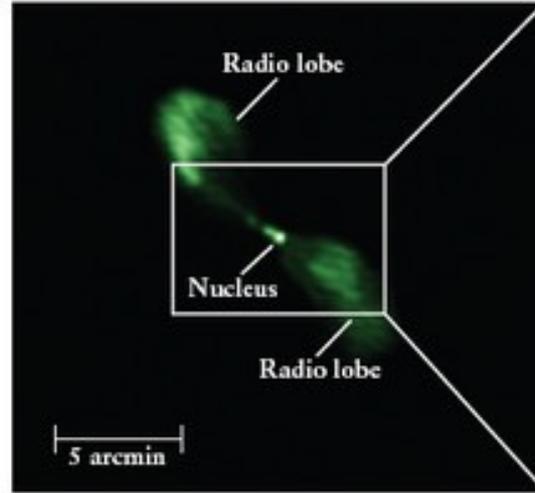
The speed of the gas in the jet is faster than the speed of sound in the gas. The flow is thus referred to as **supersonic**. As the fast-moving gas approaches the almost stationary hot spot the gas suddenly decelerates forming a **shock wave across the jet**.



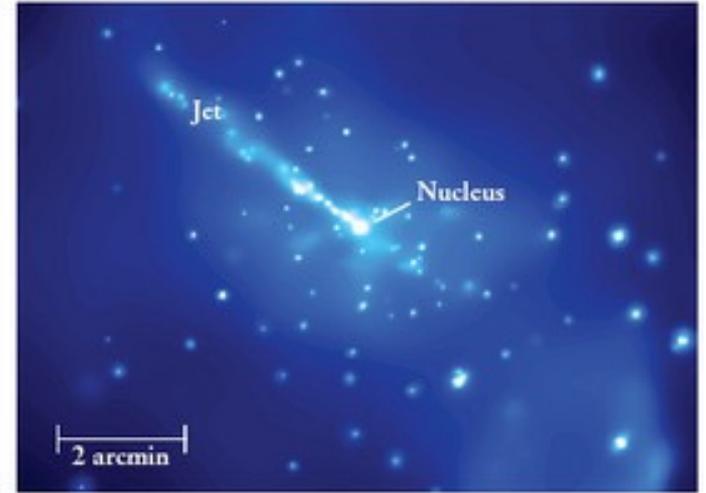
Jets and Radio Lobes



(a) Centaurus A: light from stars
R I **V** U X G



(b) Centaurus A: radio lobes
R I V U X G

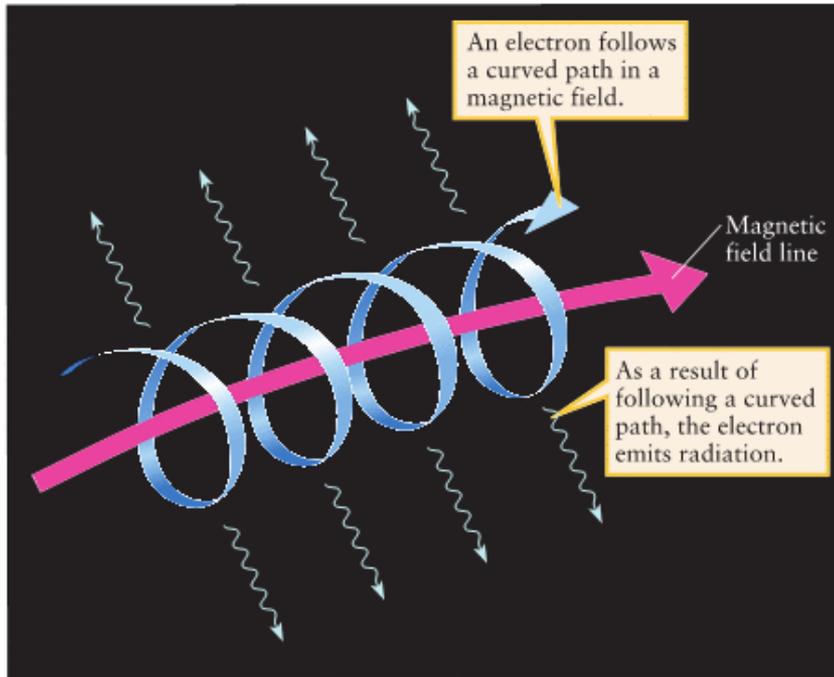


(c) An X-ray-emitting jet emanates from the nucleus
R I V U **X** G

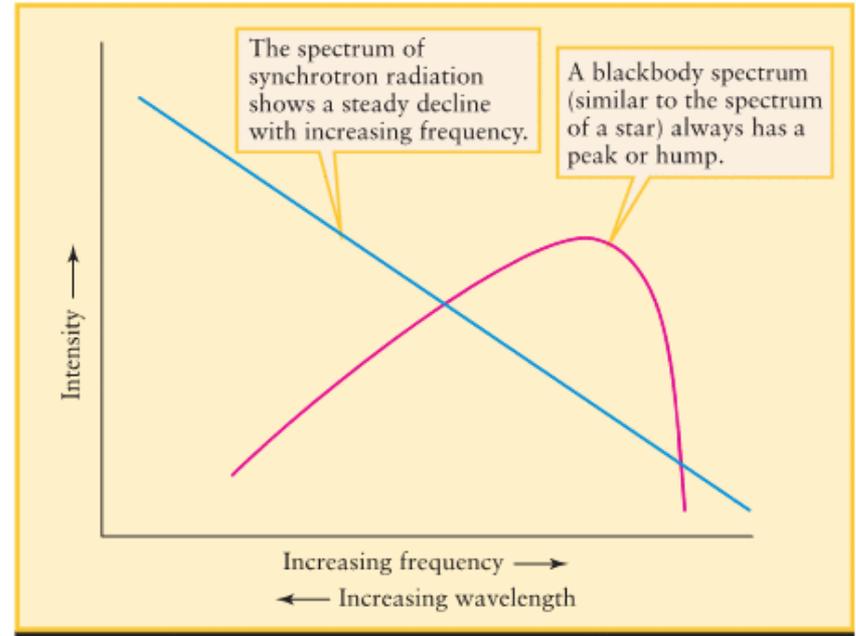
Images of the radio galaxy Centaurus A in visible, radio, and X-ray

The **emission from the jets and lobes is partially polarized** supporting the model of relativistic charged particles being accelerated in these jets. The distance between the lobes can be >10 times larger than the size of the galaxy.

Jets and Radio Lobes



(a)



(b)

Some of the kinetic energy of the charged particles in the jet is converted in synchrotron radiation.

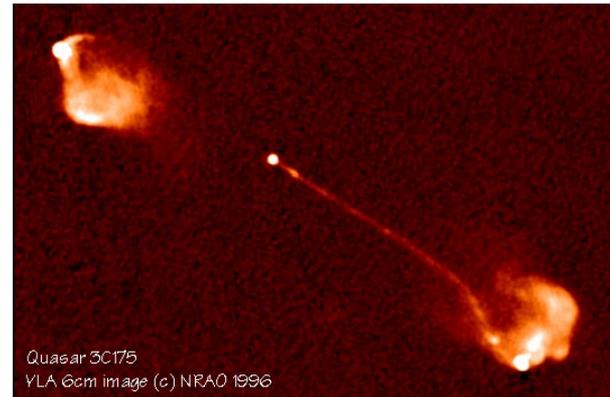
After colliding at the hot spots, the jet material moves back towards the galaxy and *inflates* the lobes. The lobes accumulate gas material for a period of about 100 million years.

Streams of Flowing Gas

Once the VLA went online many images of radio galaxies showed narrow beams extending up to millions of light years from the centers of the galaxies.

Questions:

- Are jets streams of flowing gas?
- Why are there one-sided jets?
- How can jets be stable, narrow and straight over distances as long as \sim million light years?
- Why do blobs in the jets sometimes appear to be moving faster than the speed of light?
- How do jets form and where do they get their energy from?

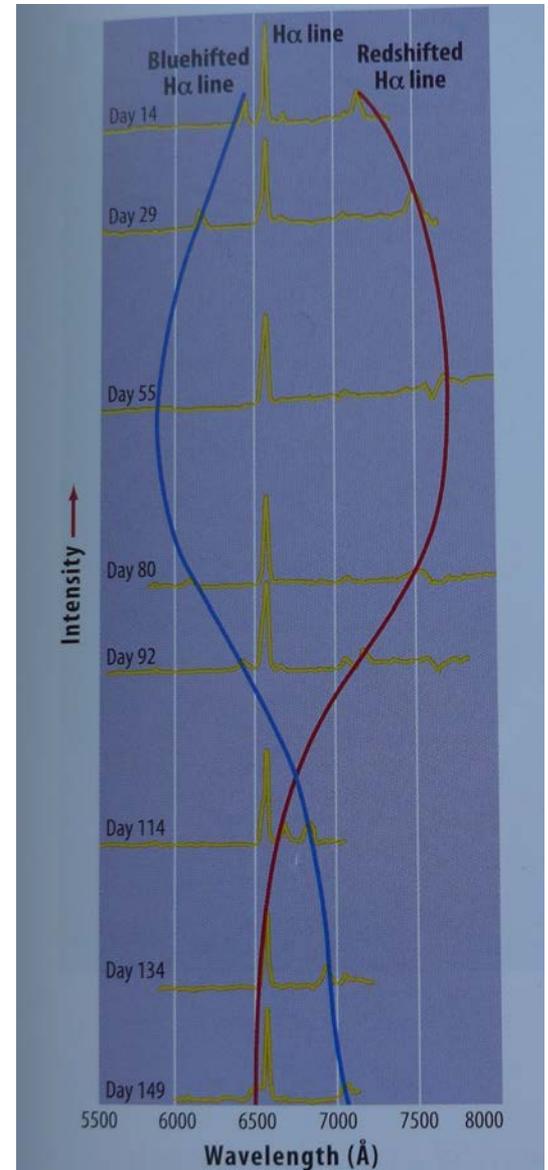


Jets are Streams of Fast Flowing Gas

The breakthrough to addressing the question of whether jets are streams of fast moving gas came with observations of SS433 (An eclipsing X-ray binary in our galaxy where the compact object is most likely a BH).

Spectroscopy of the jets of SS433 showed:

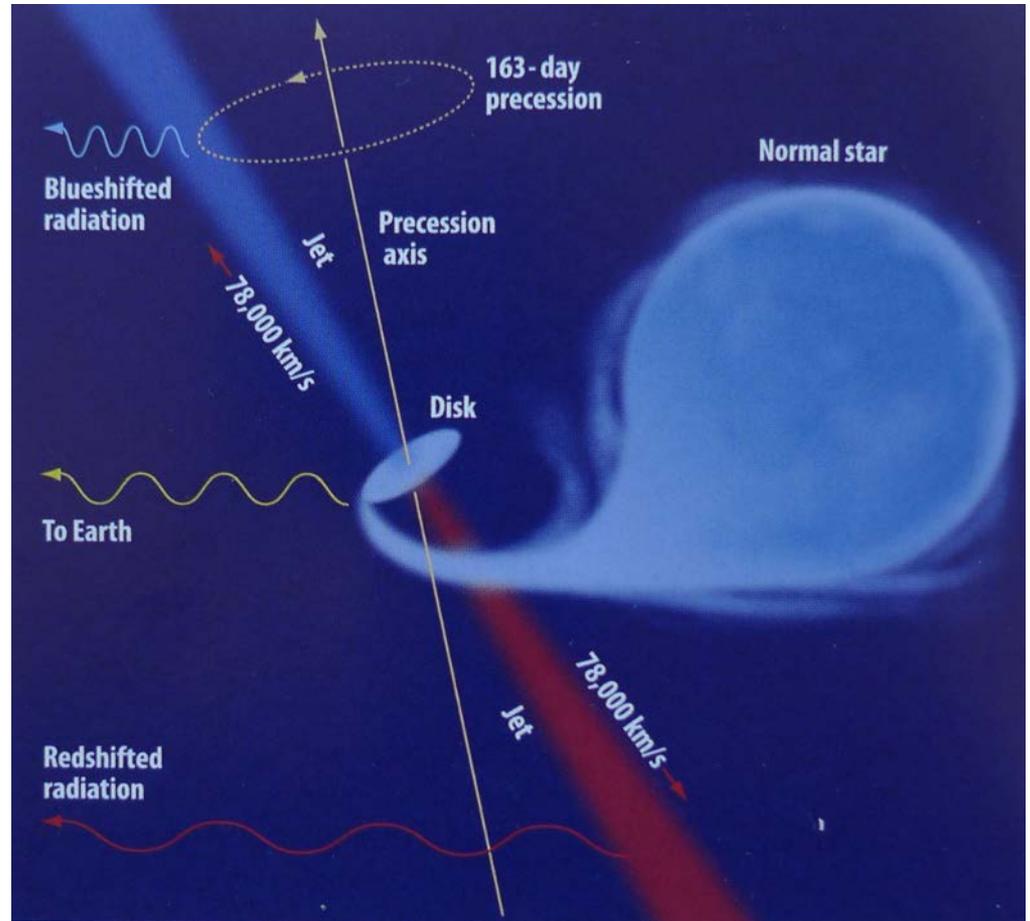
- They were made primarily of hydrogen gas moving at a speed of $\sim 0.25c$
- The spectrum shows three sets of H_{α} lines. A mostly **redshifted** H_{α} component, a mostly **blueshifted** H_{α} one and a stationary H_{α} one.



Microquasar SS 433

George Abell and Bruce Morgan first interpreted the spectrum of SS433 as resulting from the precession of a pair of jets ($v_j \sim 0.25c$) around a fixed axis every 163 days.

As the jets swing steadily around the component of velocity directed along our line of sight varies. Because of the Doppler shift, the observed wavelengths trace out patterns that repeats every precession period.



Jets are Streams of Fast Flowing Gas

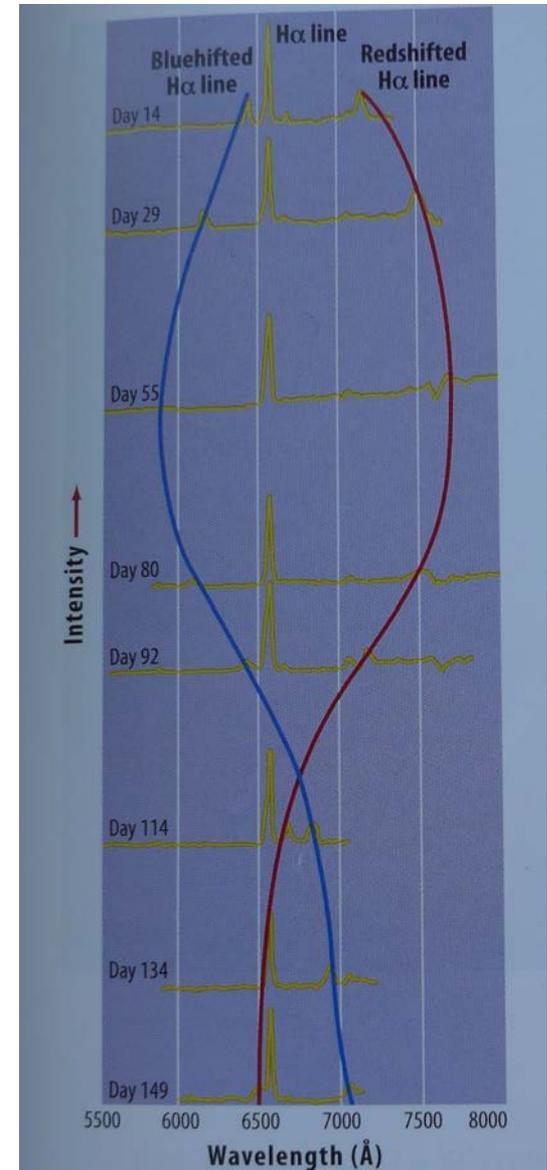
$$\text{Doppler Shift of Light: } \frac{\lambda_{rest}}{\lambda_{obs}} = \frac{\sqrt{1 - \left(\frac{u}{c}\right)^2}}{\left[1 + \frac{u \cos \theta}{c}\right]}$$

The **red** and **blue** radio velocity curves meet at about a wavelength of 675 nm. This occurs when the radial velocity component along our line of sight is zero ($\theta = 90^\circ$).

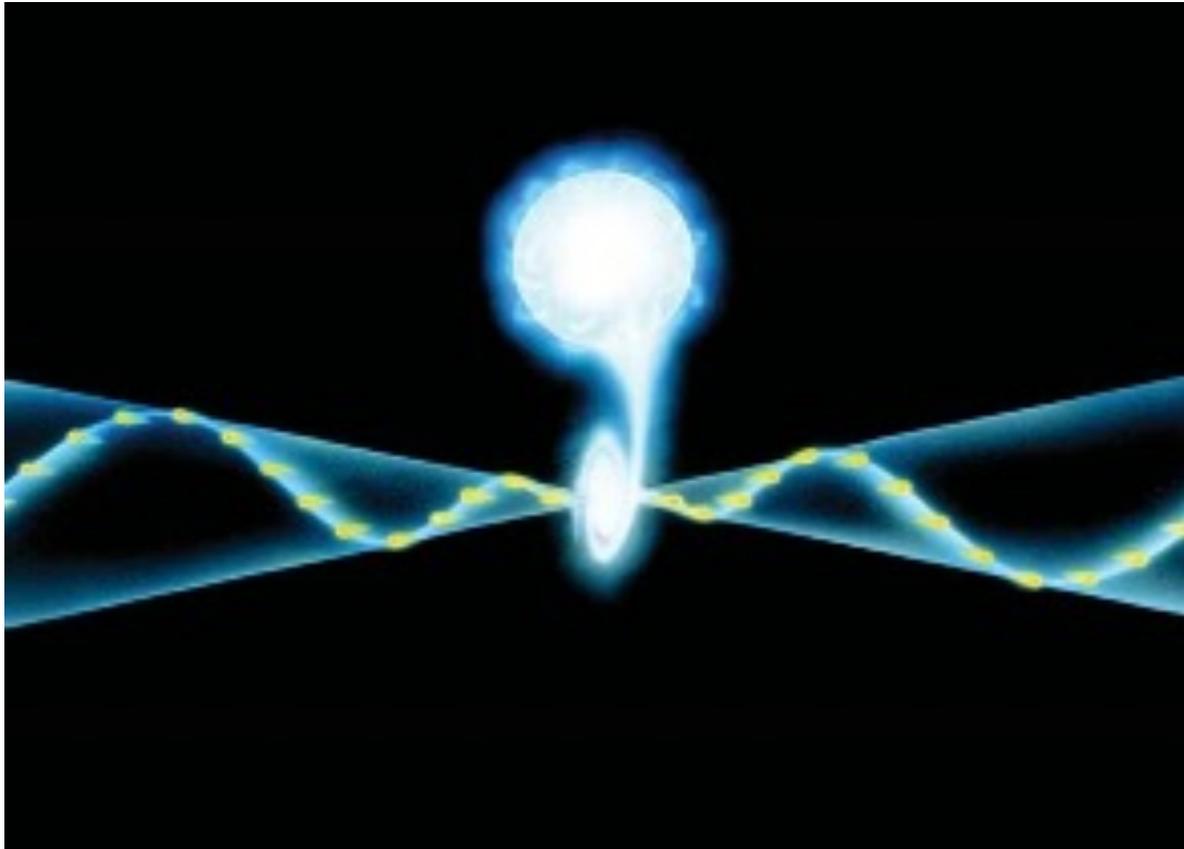
$$\lambda_{rest} = 656 \text{ nm}, \lambda_{obs} = 675 \text{ nm}$$

$$\text{For } \theta = 90^\circ: \frac{656 \text{ nm}}{675 \text{ nm}} = \frac{\sqrt{1 - \left(\frac{v}{c}\right)^2}}{1} \rightarrow$$

$$\left(\frac{656}{675}\right)^2 = 1 - \left(\frac{v}{c}\right)^2 \rightarrow \frac{v}{c} \sim 0.25c$$

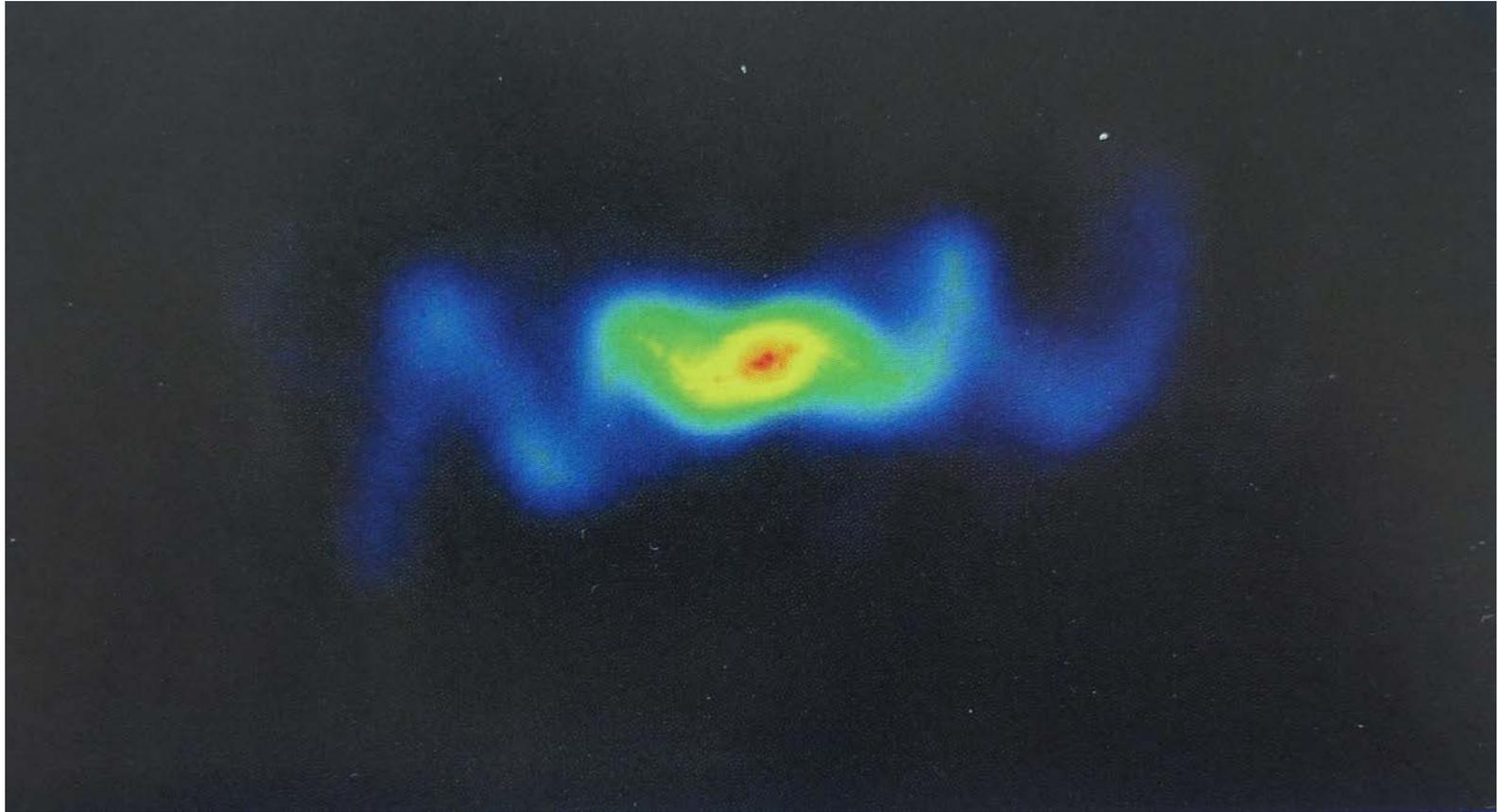


Microquasar SS 433



As the jets of SS433 precess, blobs of gas ejected will trace a corkscrew pattern. Shown is a predicted image of how the ejected blobs should appear. Robert Hjellming and Kenneth Johnson first observed the predicted pattern using the VLA.

Microquasar SS 433

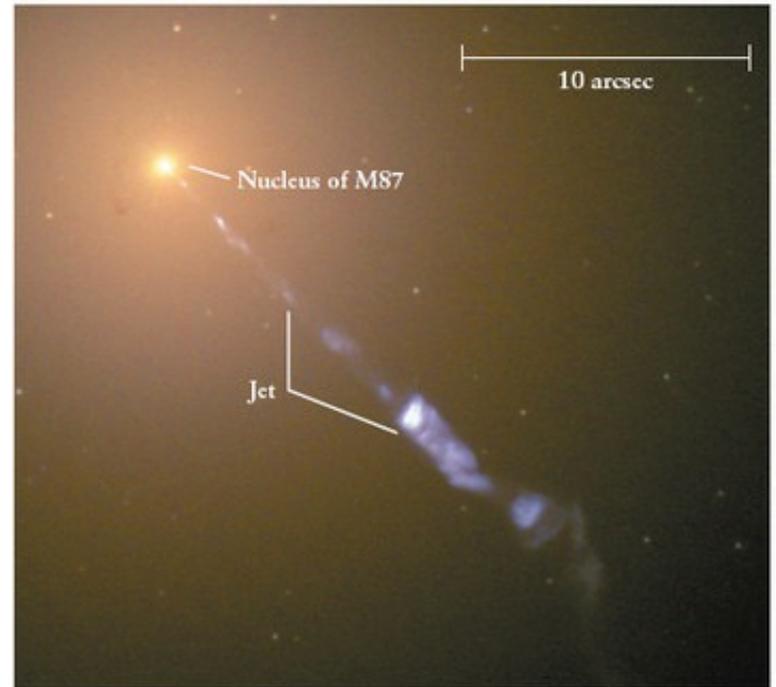


Two turns of the corkscrew pattern of SS 433's jets, mapped by Katherine Blundell and Michael Bowler using VLA.

Explaining the Observed Properties of Jets

One of the amazing properties of **jets** is that they **are stable over lengths of millions of light years**. Typically, when fluids pass each other instabilities set in that disrupt the flow.

Numerical simulations of supersonic jets that assume densities and magnetic fields of similar values as those found in real jets are able to simulate their stability across large distances.

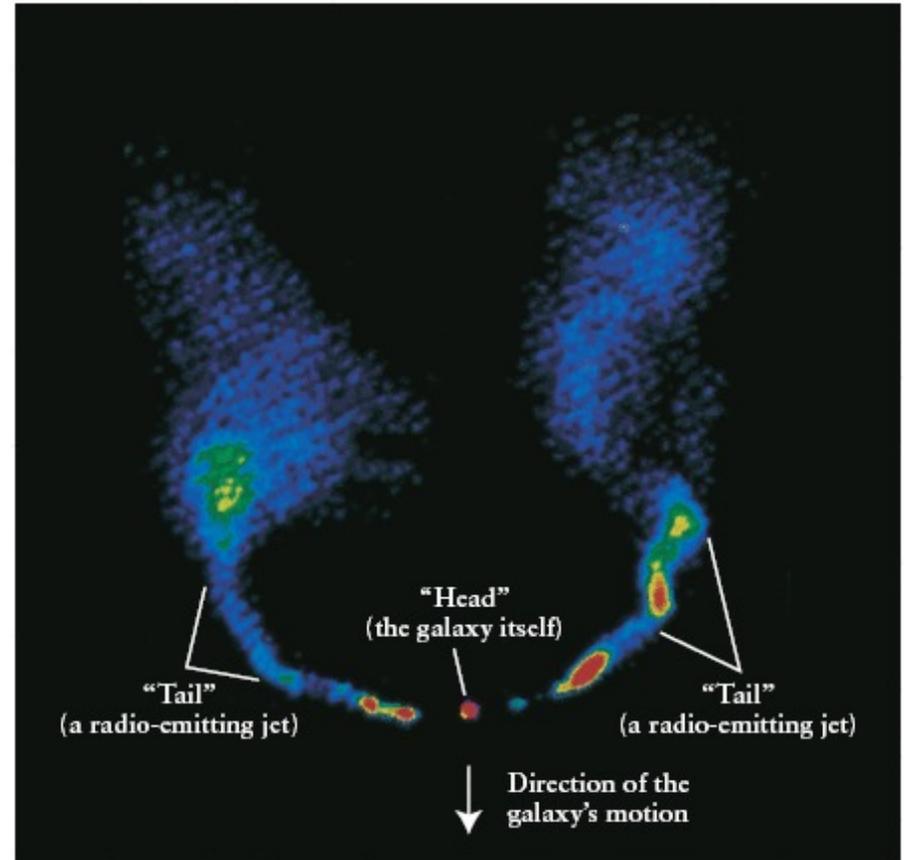


(b) A shorter exposure reveals M87's jet

Head Tail Sources

Some jets show **bent trails**. We now think these are formed when a radio galaxy is moving through the **intergalactic medium**. This may happen when a radio galaxy moving inside a cluster of galaxies interacts with the IGM gas.

By measuring the length of the trail and the velocity of the galaxy it is possible to estimate the age of the radio source (time since jet turned on). Typical ages 300×10^6 years.



Head Tail Sources are radio galaxies with jets and lobes moving through the intracluster medium. The jets are swept backwards into tails as the galaxy moves along.

Very Long Baseline Array

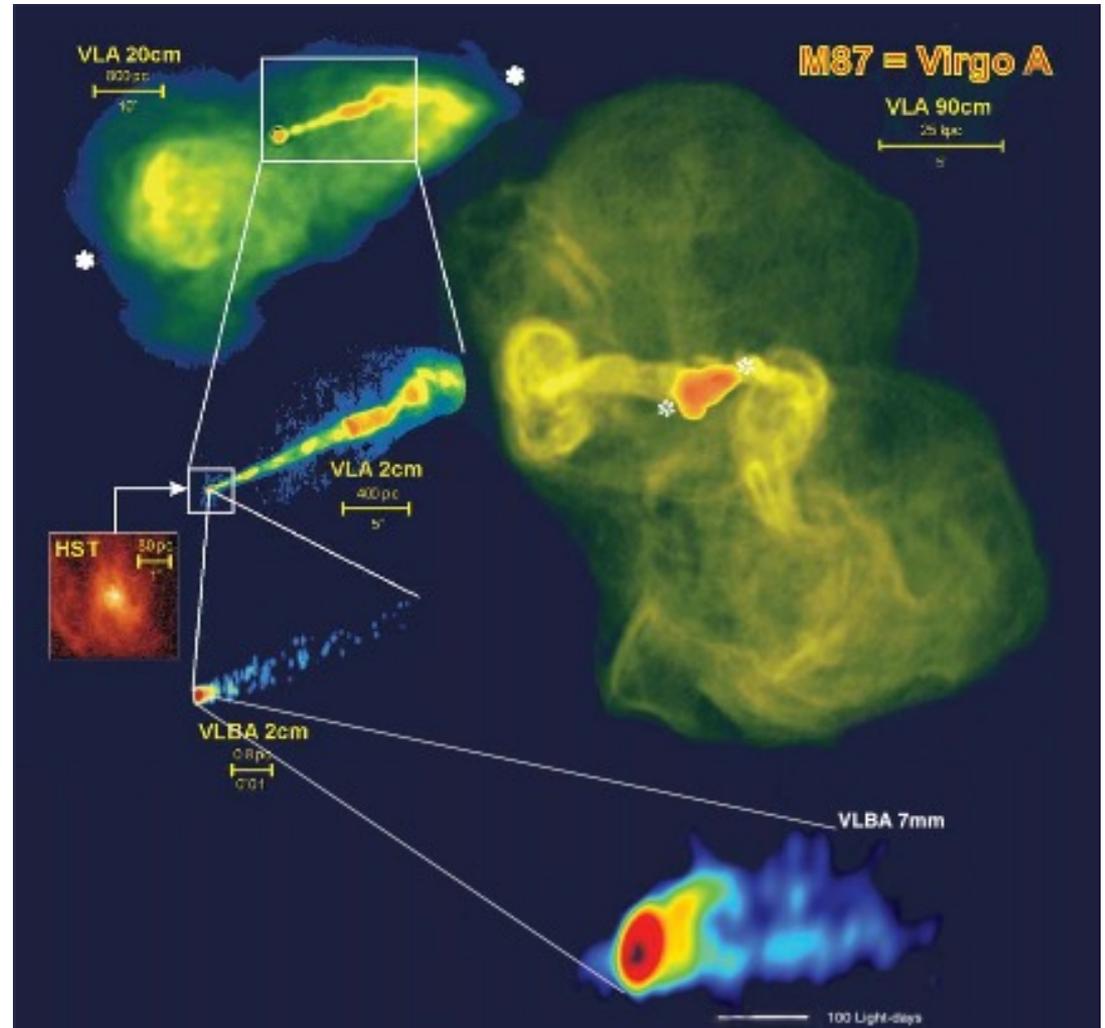


The Very Long Baseline Array (VLBA) consists of 10 dishes extending 8000 km across the United States. Operated as an interferometer the array serves as a telescope with the same resolution as a single dish the size of the Earth. The Y indicates the location of the VLA which provides additional data with lower angular resolution but greater sensitivity and FOV. The VLBA can achieve angular resolution of about 10^{-4} arcsec.

Resolving Radio galaxy M87 at Different Scales

By using radio telescopes of different angular resolution it is possible to construct an exploded view of a radio galaxy showing its structure at different scales.

With images of a radio galaxy at different scales we can follow the jet from near the black hole all the way out to the radio lobes located $\sim 250,000$ light years from the core.

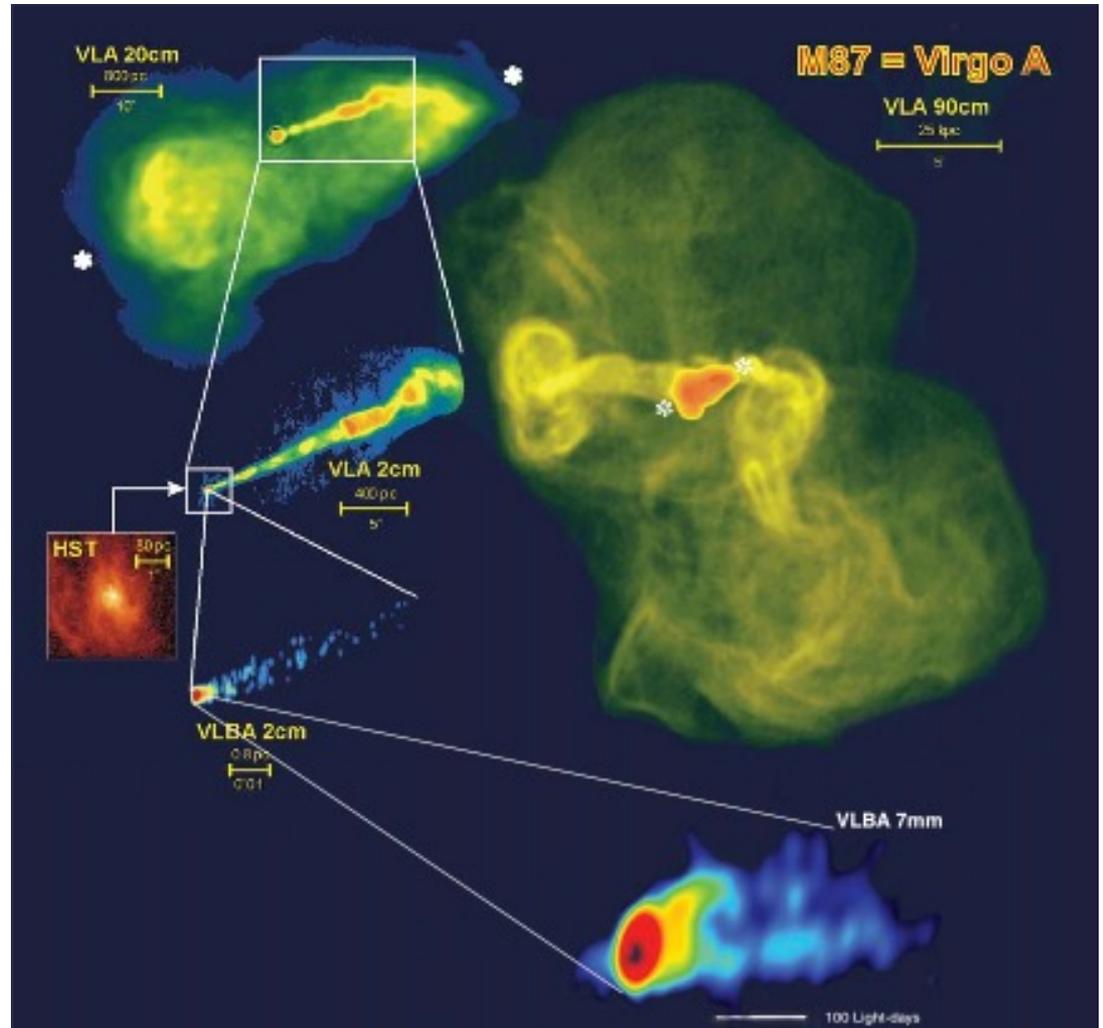


Resolving Radio galaxy M87 at Different Scales

The main reason for single sided jets is now thought to be the result of **beaming**.

Assume a blob that radiates photons equally in all directions when at rest.

The same blob when moving will appear to shine within a beam along the direction of motion.



Beaming

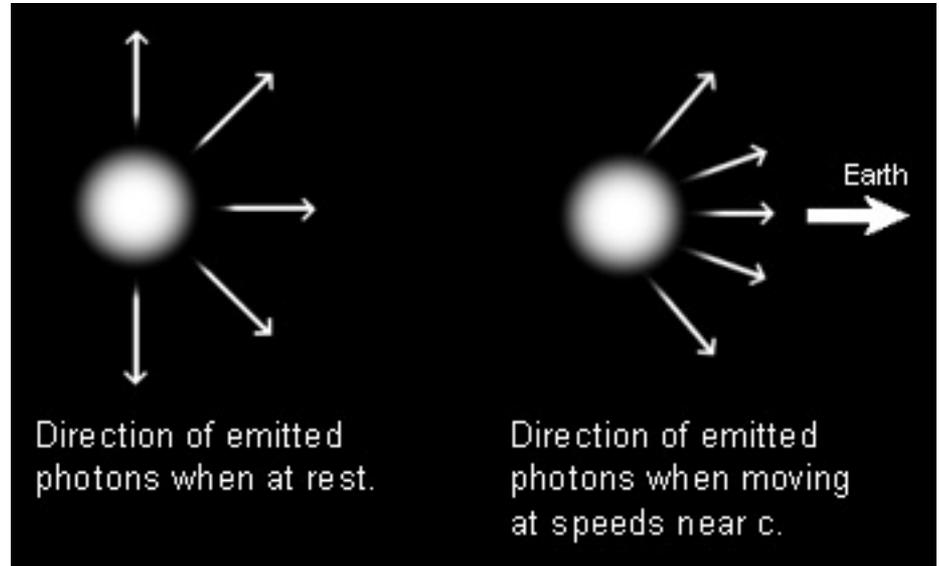
The luminosity of a jet is increased due to various relativistic effects including beaming and the Doppler shift (the energy of each photon appears to have increased).

Beaming Angle:

Half of the opening angle

is $\theta = 1/\gamma$,

$$\gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$



A sphere at rest emits photons in all directions (not all are shown). If the sphere is moving at relativistic speeds, then we would observe these same photons to be emitted from a cone centered around the direction of motion.

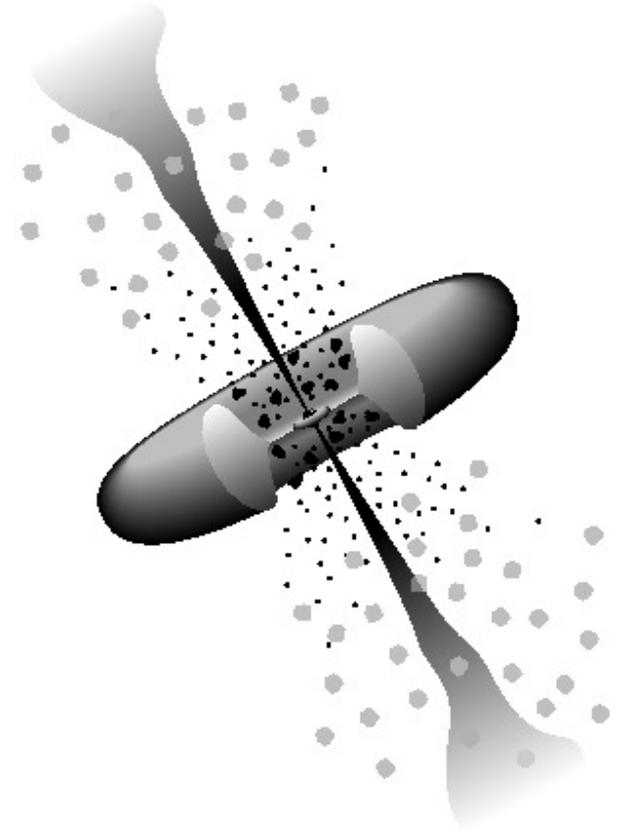
Blazars

Blazars are AGN with a relativistic jet that is pointing in the general direction of the Earth. We observe "down" the jet, or nearly so, and this accounts for the rapid variability and compact features of blazars.

Blazars, like all AGN, are thought to be ultimately powered by material falling onto a supermassive black hole at the center of the host galaxy.

Blazars are subdivided into **BL Lac objects** and optically violent variable **OVV quasars**.

BL Lac objects are intrinsically weak radio galaxies while OVV quasars are intrinsically powerful radio galaxies.



The bulk speed of the plasma in the jet can be as large as $\sim 99\%$ the speed of light.

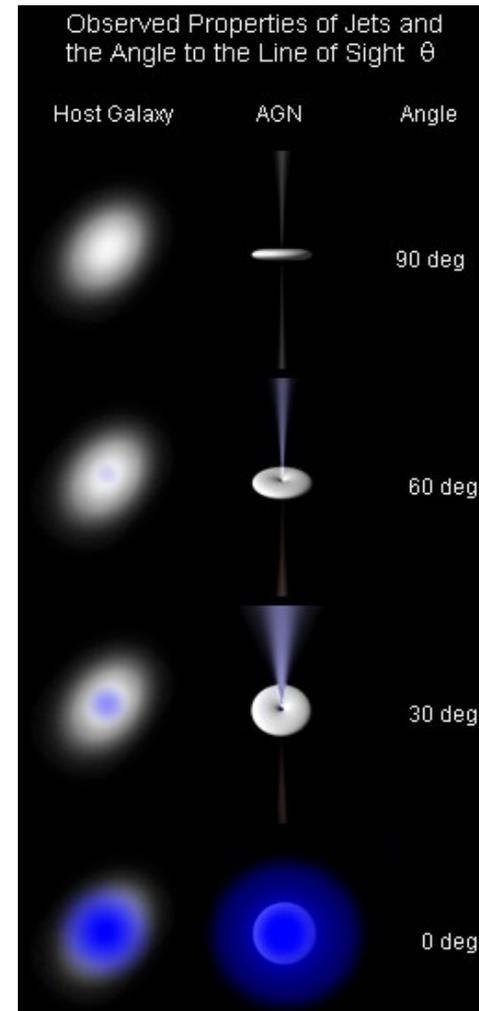
Unification of Radio Loud AGN

Unified models for radio galaxies:

Radiation sources that emit in an anisotropic way will appear different depending on how they are oriented with respect to our line of sight.

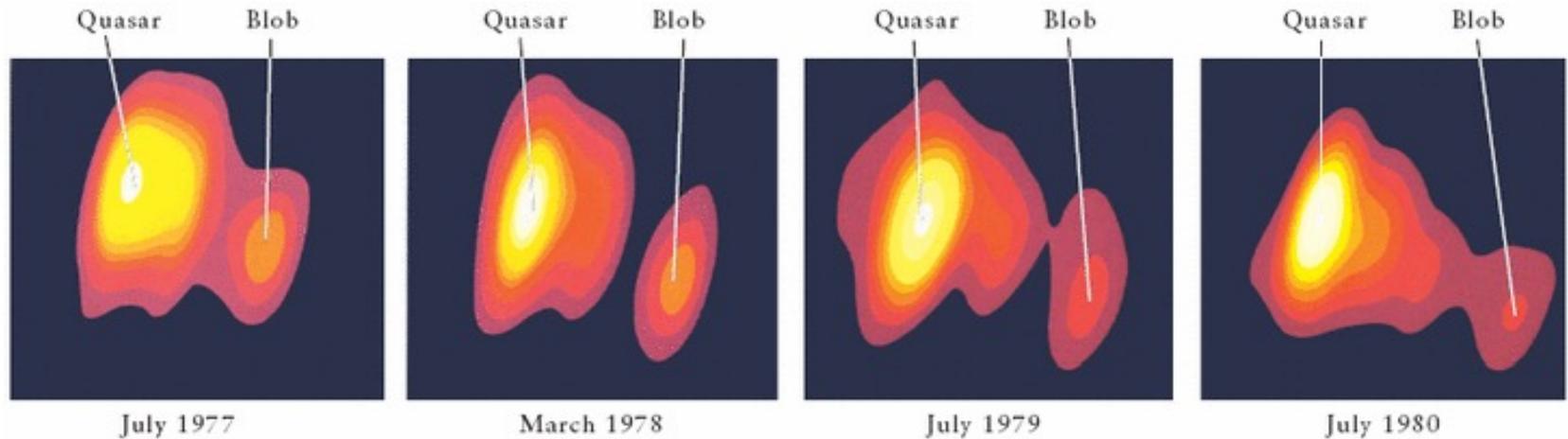
Examples: If we are looking close to one of the jet directions we only see the projected length of one beamed jet. The radio lobes will radiate isotropically but will not be resolved so only a **compact radio source** is observed.

If we are looking almost perpendicular to the jet direction, we see a **radio galaxy with two resolved lobes**. Emission from the jets is faint especially if they are relativistic.



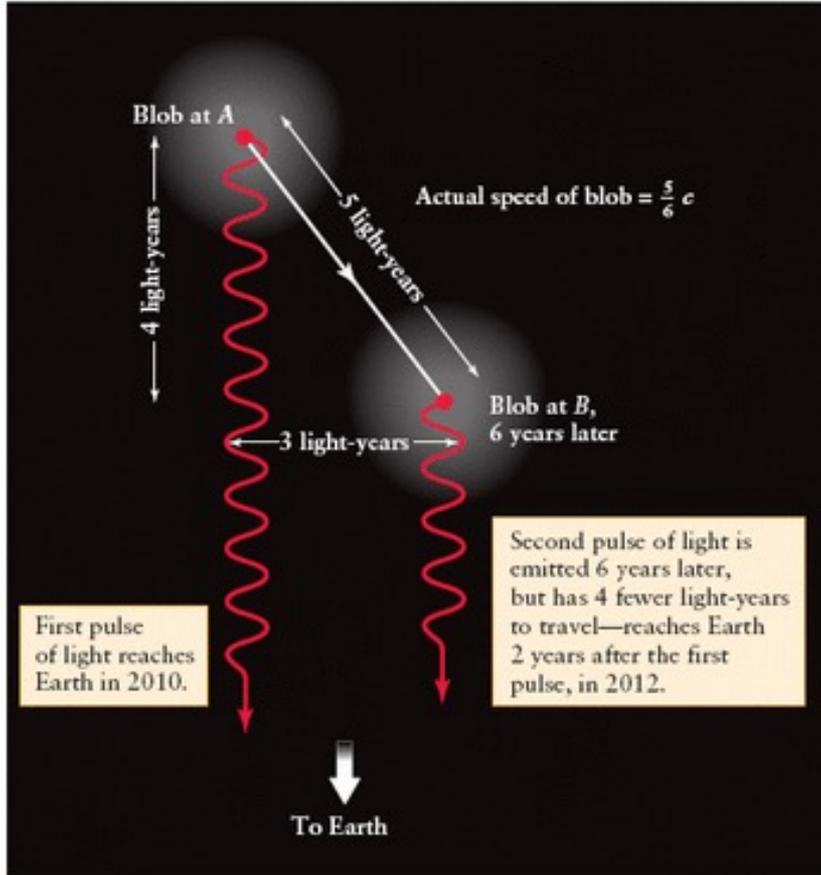
Unification. From bottom to top:
Down the jet – Blazar
 90° from jet – Radio Galaxy + 2 lobes

Superluminal Motion in Blazars

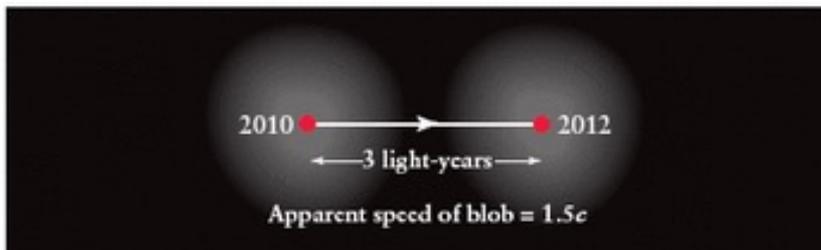


Superluminal Motion is motion that appears to involve speeds greater than the speed of light. In the observations of 3C 273 shown above the blob in 3 years covered a projected distance of 0.003 arcsec. The apparent velocity of the blob is ~ 10 times the speed of light. It turns out **the blob does not travel faster than the speed of light** and the apparent superluminal motion is just the result of projection effects combined with the relativistic motion of the blobs.

An Explanation of Superluminal Motion



(a) View from above



(b) View from Earth

(a) If a blob of material ejected from a quasar moves at five-sixths of the speed of light, it covers the 5 ly from point A to point B in 6 years. In the case shown here, it moves 4 ly toward Earth and 3 ly in a transverse direction. The light emitted by the blob at A reaches us in 2010. The light emitted by the blob at B reaches us in 2012. The light left the blob at B 6 years later than the light from A but had 4 fewer light-years to travel to reach us.

(b) From Earth we can see only the blob's transverse motion across the sky. It appears that the blob has traveled 3 ly in just 2 years, so its apparent speed is $3/2$ of the speed of light, or $1.5c$.

Making a Relativistic Jet

Proposed acceleration mechanisms of gas in jets.

Not: Pressure from expanding gas may accelerate gas but not to speeds approaching c .

Possibly Not: Radiation pressure can push gas but relativistic beaming limits the ability of radiation pressure to accelerate gas to speeds approaching c (unless the gas is dense).

Most Likely: Most current jet-acceleration models invoke an acceleration mechanism that relies on magnetic fields playing a key role.

Making a Relativistic Jet

A simple viewpoint to describe electromagnetic properties of an ionized gas in a magnetic field was introduced by Hannes Alfvén.

Think of the magnetic field lines as being attached to the fluid.

The magnetic field lines give the **fluid resiliency**. For example, if the field lines are slightly curved, they will try to spring back but once bent into a loop they will try to contract.

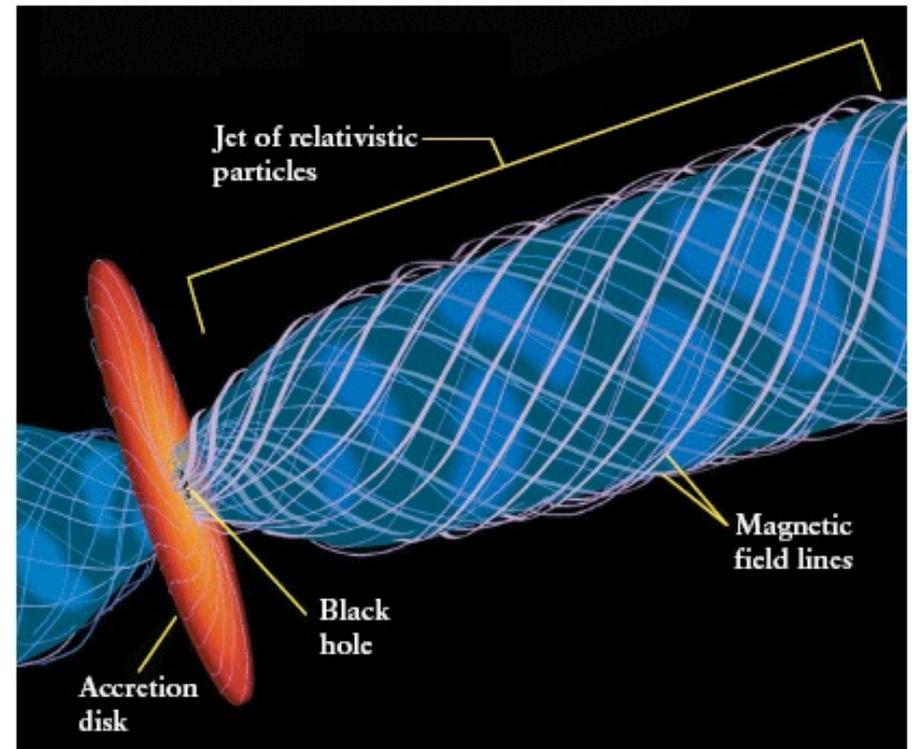
Because of the **differential rotation of the accretion disk**, field lines will follow the motion of the disk. Ionized particles below and above the disk will then follow the motion of the magnetic field lines. The centrifugal force then flings particles outward along magnetic field lines.

Inflows and Outflows from Active Galaxies

Magnetic forces play a crucial role in collimating fast-moving particles from the accretion disk into narrow beams.

The Keplerian rotation of the plasma in the disk creates a strong magnetic field that is twisted in helical shapes on either side of the plane of the disk.

Particles from the accretion disk follow these twisted magnetic field lines and are focused into two jets.



Jets from a Supermassive Black Hole

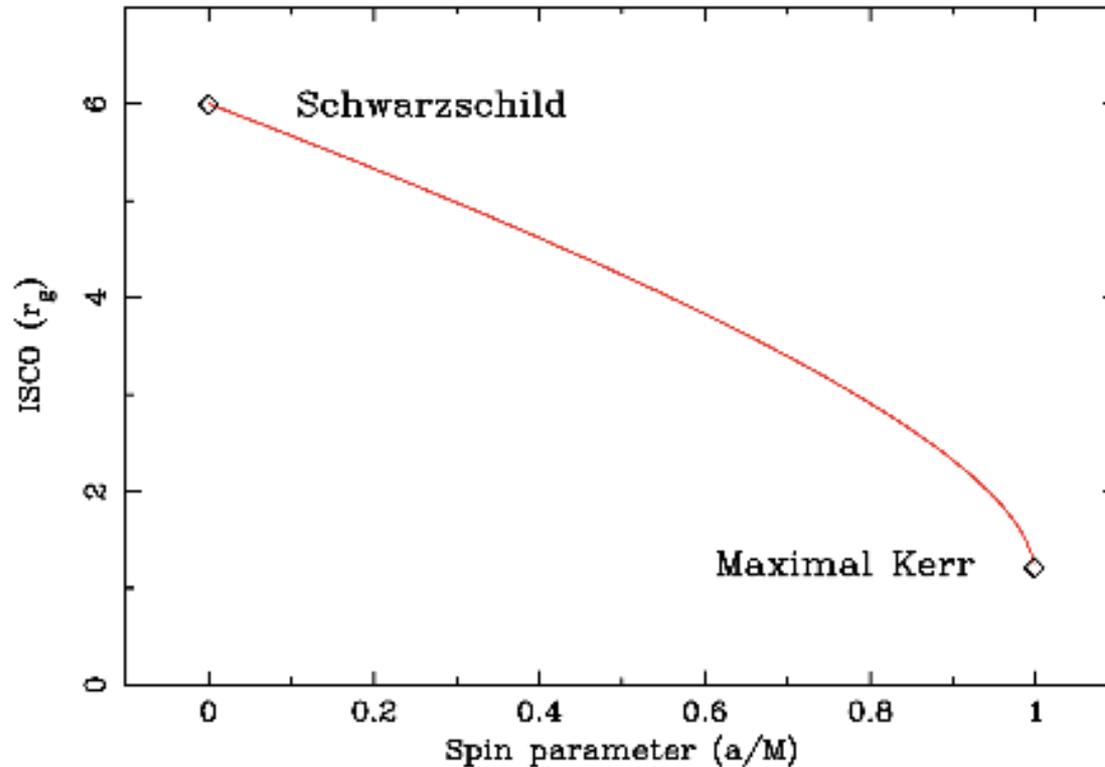
Where does the energy needed to accelerate jets come from?

possibly: The energy may come from the conversion of gravitational energy released by infalling material.

possibly: The energy may come from the spinning black hole. This mechanism was first proposed by Roger Penrose.

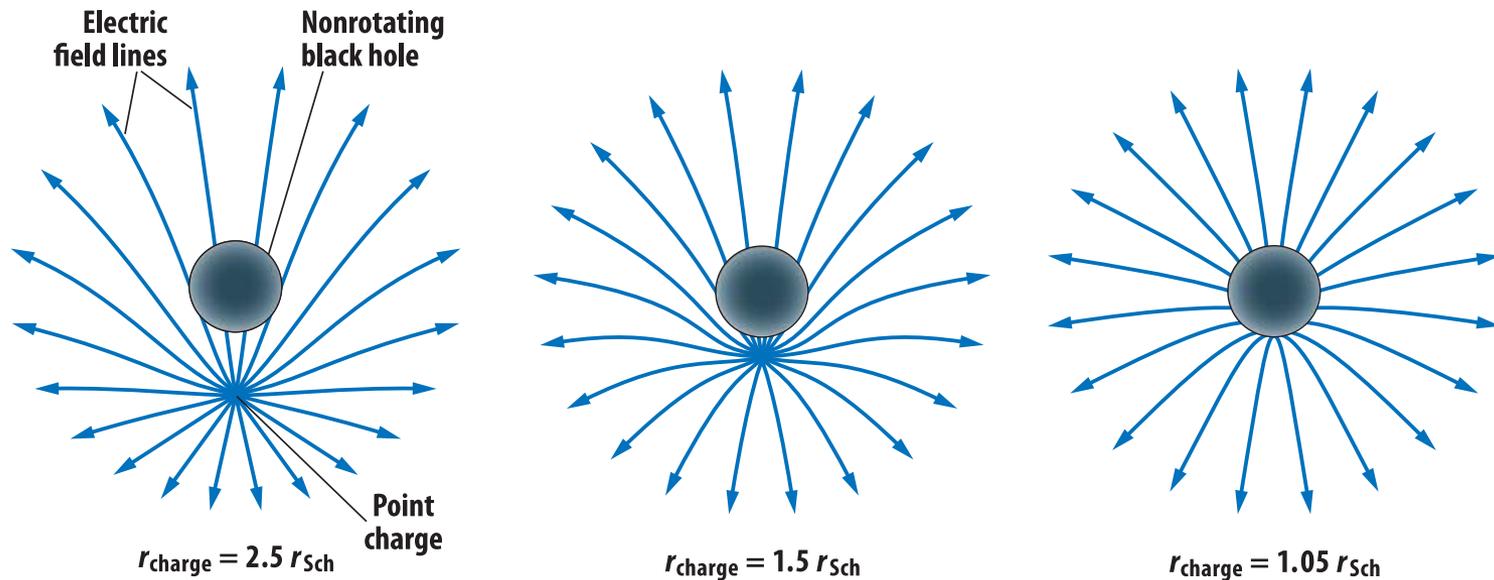
But wait, I thought you could not extract anything from a black hole. It turns out that the law governing the growth of black holes states that the surface area of a black hole's event horizon cannot decrease. This is not violated when the spin of a black hole is reduced.

Where does the energy needed to accelerate jets come from?



The surface area of a black hole's event horizon increases as the spin slows down.

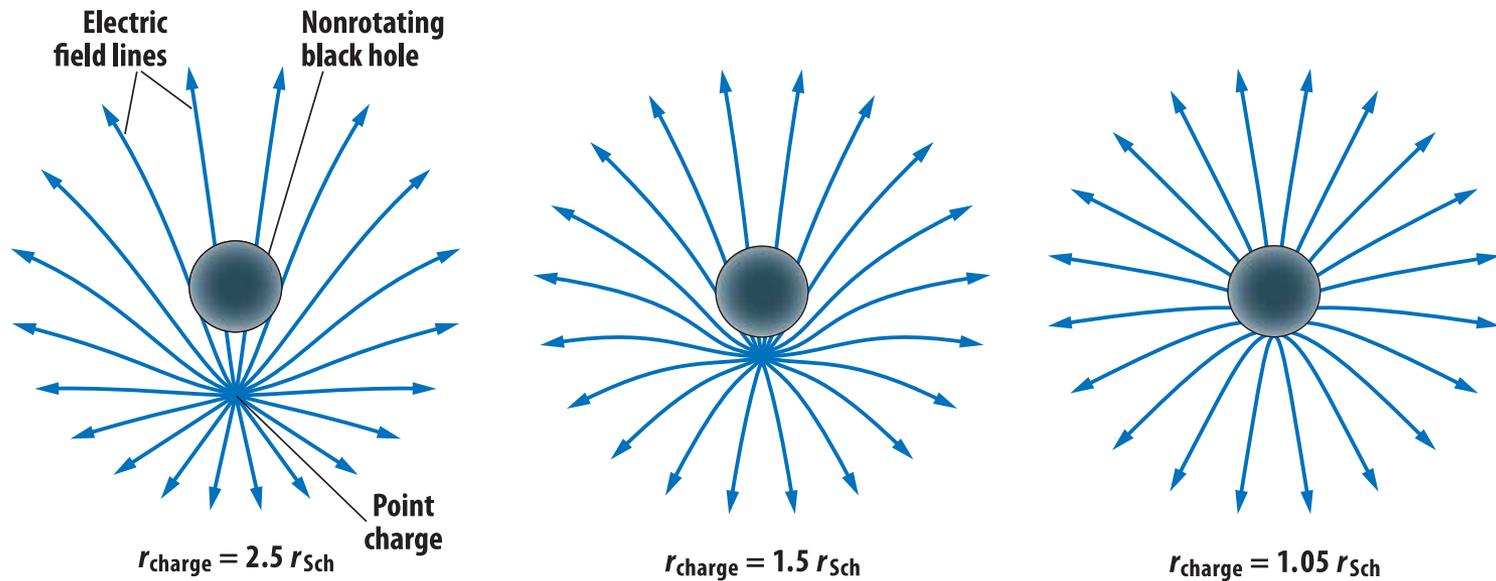
Where does the energy needed to accelerate jets come from?



One jet model uses the **analogy between a black hole and an electrical conductor**.

As a charge approaches the event horizon the field lines appear to emanate from the center. **It is as though the horizon is a conducting sphere** with the charge spread uniformly over it.

Where does the energy needed to accelerate jets come from?



A spinning spherical conductor in a magnetic field develops a voltage difference between its pole and equator.

In a similar fashion a spinning black hole in a magnetic field develops a voltage between its pole and disk (it behaves like a battery with a voltage of about 10^{15} volts).

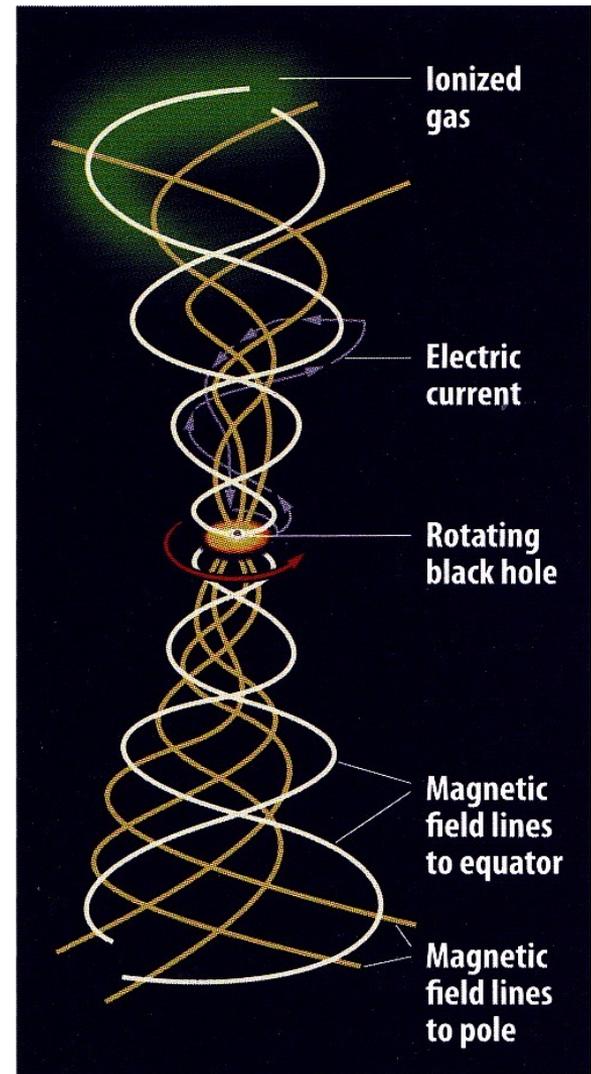
Where does the energy needed to accelerate jets come from?

Ionized gas between the pole and disk acts as a conducting “wire” allowing current to flow through the gas.

Energy can thus be extracted from this black-hole battery and accelerate charged particles and eventually propel the jet.

As energy is extracted there is a drag on the spin of the hole, slowing it down.

The huge voltage may also create some of the matter that flows along a jet through pair-production, the creation of electron-positron pairs.



How is a black hole spun up?

- Accretion of material over millions of years.
- Black holes may be formed with considerable spin during core collapse of a massive star.
- Merging of black holes. Some of the angular momentum ends up in the spin of the black hole.

Extracting Energy from Spinning Black Holes

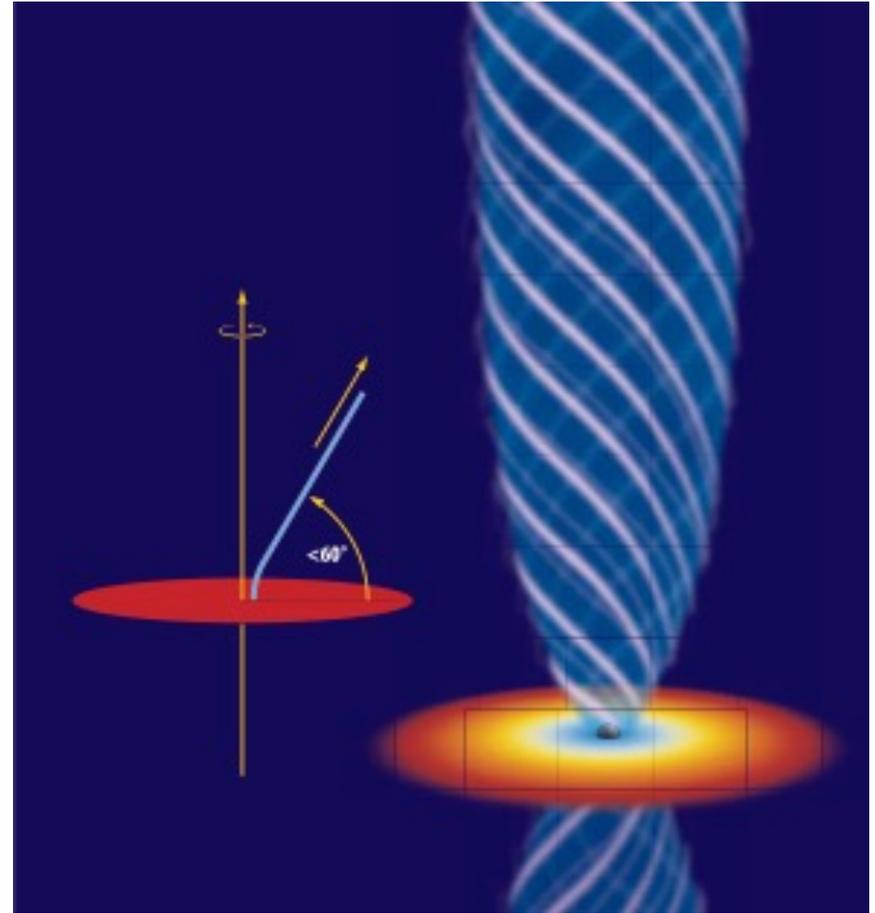
Remaining Puzzles:

- Why do most AGN with jets (**radio-loud AGN**) reside in elliptical galaxies and radio-quiet AGN typically reside in spiral galaxies.
- We think of whether or not a jet is formed is decided on scales not much larger than the event horizon of the black hole, whereas, somehow the host galaxy properties seem to depend on the radio loudness of the nucleus.
- Preliminary estimates of the spins of black holes of Seyfert's (radio-quiet AGN) point to large values of the spin parameter. This seems to contradict models that posit that energy to power jets is extracted from the spin of a black hole.
- AGN with large accretion rates ($L/L_{\text{Edd}} \sim 1$) in general do not have radio jets.

Jets: The Magnetocentrifugal Mechanism

Magnetic field lines rotate with the accretion disk. If the field lines make an angle of less than about 60° with the disk, gas moving with the field is flung out by the centrifugal force.

When the gas flung out is fast enough it twists the magnetic field lines into a helix which then exerts a pinching force that focuses the gas into a collimated jet.



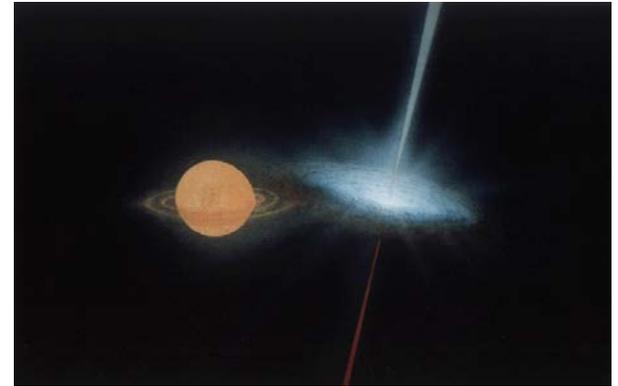
Jets in Microquasars

A **microquasar** can be considered a scaled down version of a quasar.

Microquasars have some common characteristics with quasars: **strong and variable radio emission**, often resolvable as radio jets, and an accretion disk surrounding a compact object which is either a black hole or a neutron star.

In quasars, the black hole is supermassive ($\sim 10^6$); in microquasars, the mass of the compact object is only a few solar masses.

Circinus X-1 is a microquasar with **the compact object being a neutron star**. So in this case the formation of relativistic jets does not require the peculiar “black-hole-battery” model proposed to explain jets in black hole systems.



Artist's impression of SS 433