An Introduction to Radio Galaxies and Radio Loud Quasars

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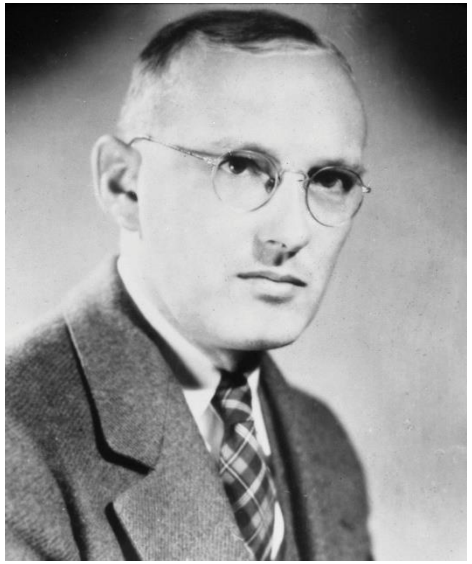
NRAO

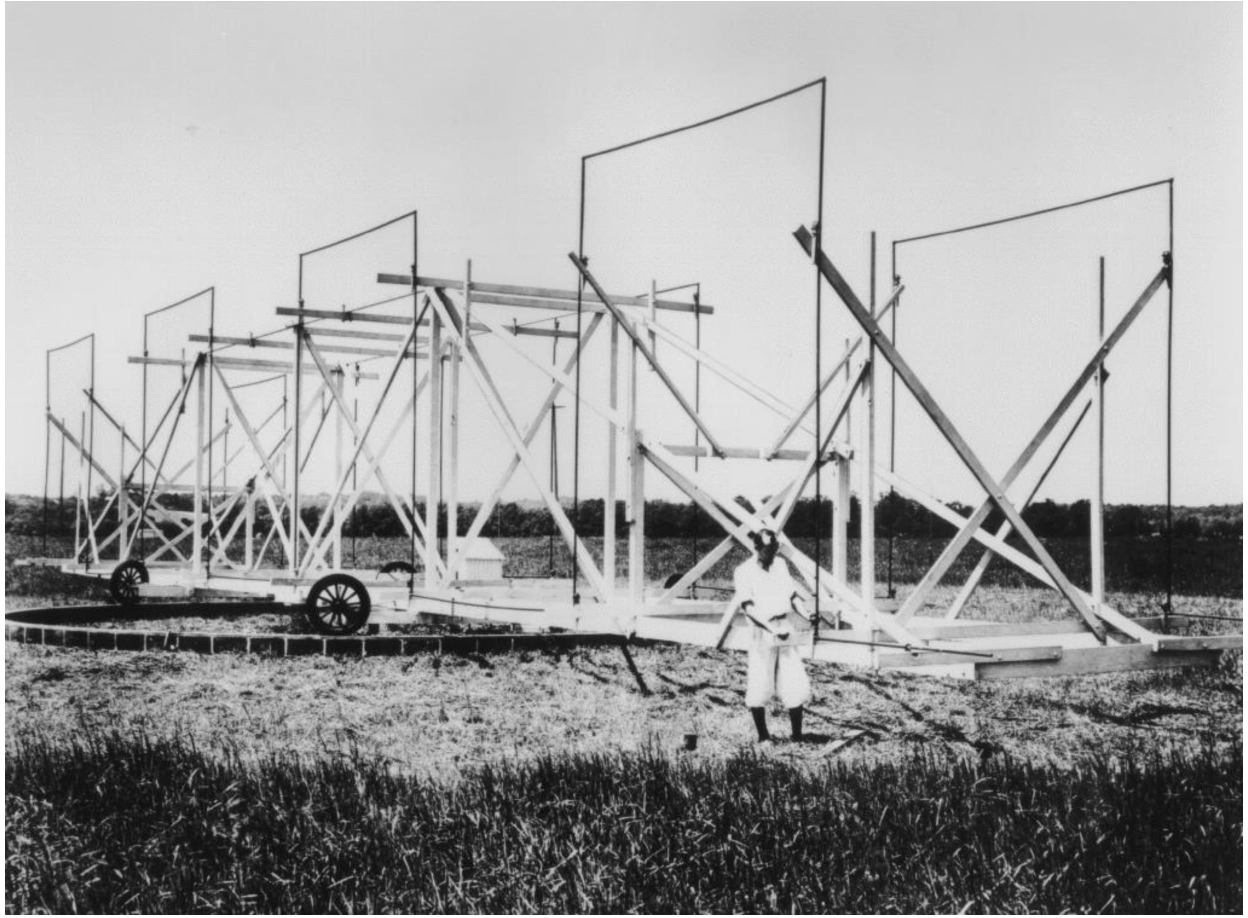
A Brief History of Discovery

- Radio Astronomy is a relatively new science.
- Development of radio technology in the 1920s – 1950s led to remarkable and surprising discoveries.
  - A good exemplar of how new technologies leads to new insights.
- The story starts with Karl Jansky (1905 – 1950).
- Tasked by Bell Telephone in early 1930s to understand origin of radio static.
- To do this, he built an unusual radio antenna.



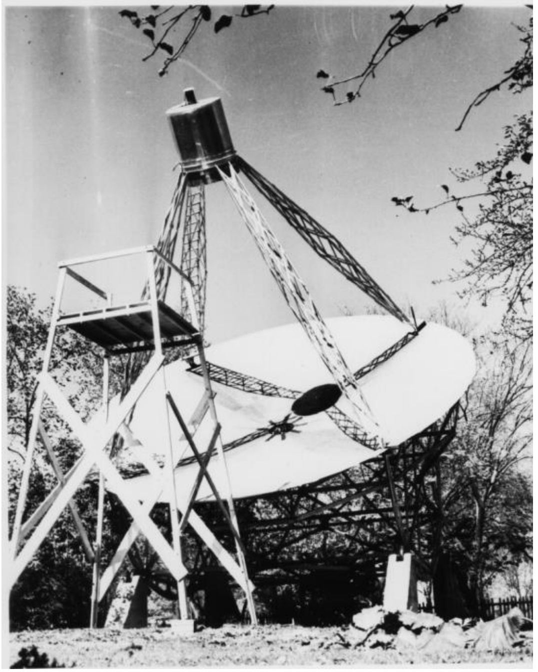
Jansky's Original 20.5 MHz antenna

- 100 x 20 ft antenna could determine direction of radio static by rotation.
- Starting in 1931, he found a steady background signal which repeated each day, but with a 23h 56m period – not 24 hours.
- He correctly deduced this was due to an extrasolar source – the Milky Way
- His discovery made the NY Times on May 5, 1933
- His attempts to further study this source with a parabolic antenna were denied, and he moved on to other work.
- The thread was picked up by Grote Reber, who built a 10 meter parabolic reflector antenna in 1937.



Reber’s original antenna

- Reber was unable to get any funding to pursue radio astronomy, so he did it on his own time, in his backyard, with a 9-meter antenna, in 1937.
- If Jansky’s discovered emission was from thermal sources, then it will be stronger at high frequency.
- So Reber first tried 3300 MHz. Found nothing.
- Next he tried 900 MHz, found nothing.
- Then tried 160 MHz – Yes!!! And later at 480 MHz.
- Published his work in Ap.J. in 1944.
- Big Mystery: Why could he not see this emission at higher frequency? If thermal it should be ~35 times stronger – but it isn’t there at such a level.
- Then comes WWII – no further astronomy, but a lot of wartime development of radio (radar, etc.)



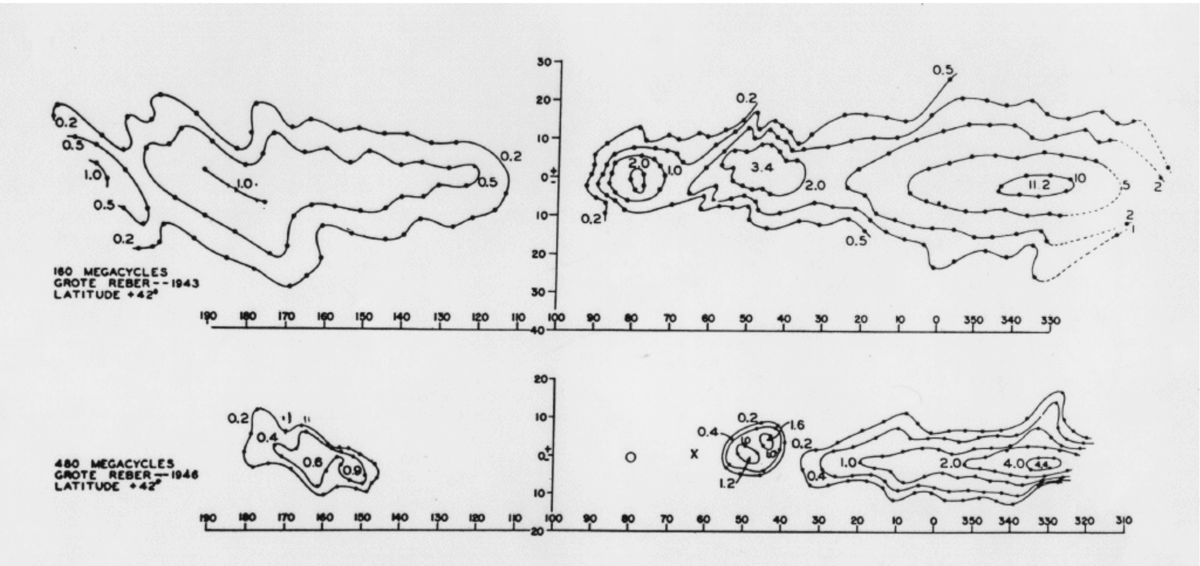


FIG. 7—Contours of constant intensity at 160 MHz and 480 MHz, taken at Wheaton, Illinois.

Developments in the 1950s.

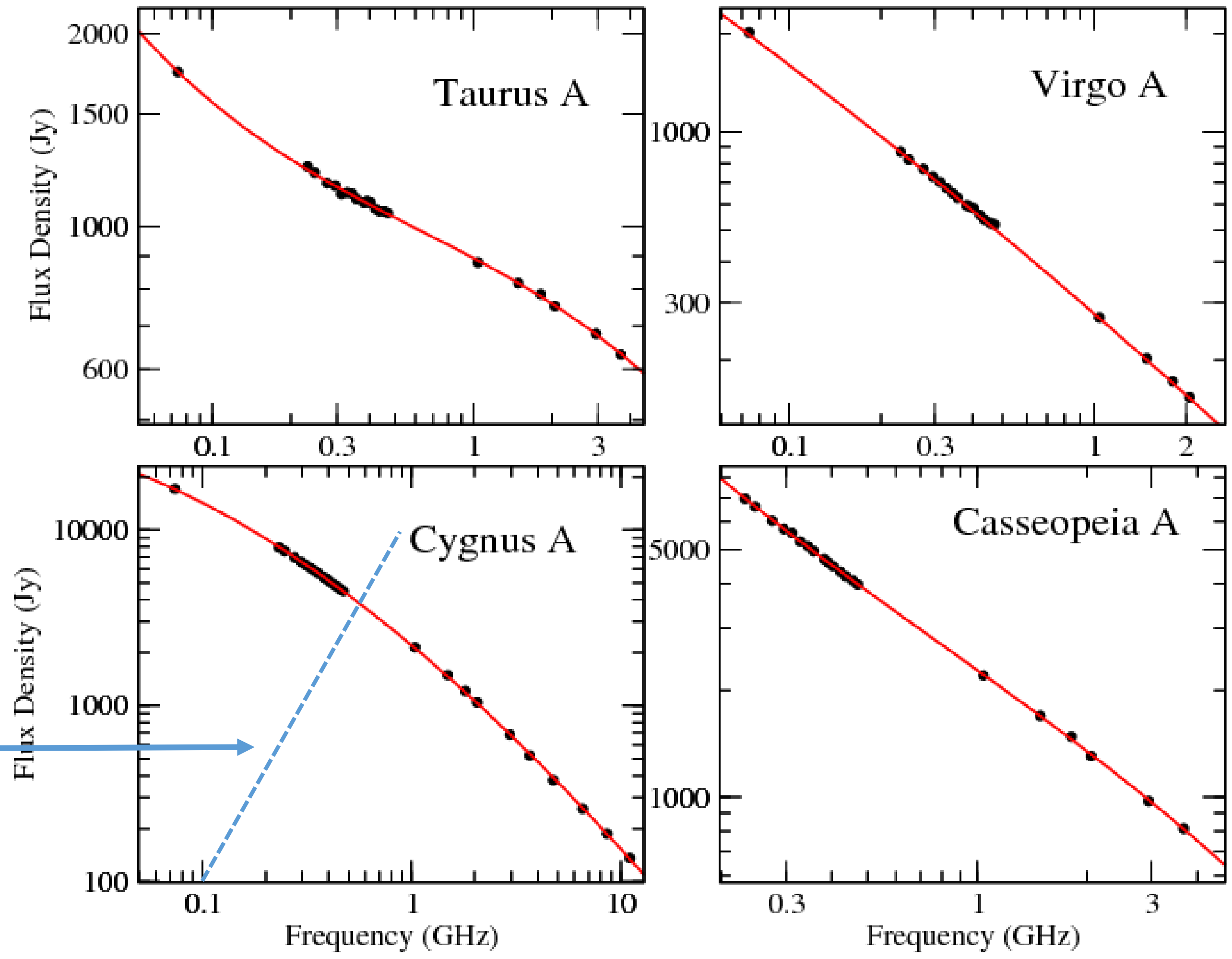
- After WWII, engineers and scientists put the newly developed technology to scientific use – larger antennas, better receivers, more sensitivity.
- With Reber's discoveries known, groups in England, Australia, the Netherlands, Russia, and the US developed larger antennas and interferometers to further study this new source of radiation.
- By early to mid 1950s, maps appeared showing the galactic plane emission (same as Reber), but also found hundreds of isolated 'radio stars'.
- But the positions of these 'stars' did not align with any notable galactic stars.
- Also, the spectra from these 'stars' were very unusual – a smooth power law:

$$S(\upsilon) = S_0 \upsilon^{-\alpha} \qquad \text{with } \alpha \sim 0.7$$

- This is very different than the expected thermal spectrum for a star: $S(\upsilon) = S_0 \upsilon^{+2}$
- Furthermore – the emission was significantly linearly polarized.
- The emission mechanism was a great mystery in the early 1950s…

Typical spectra from four discrete sources.

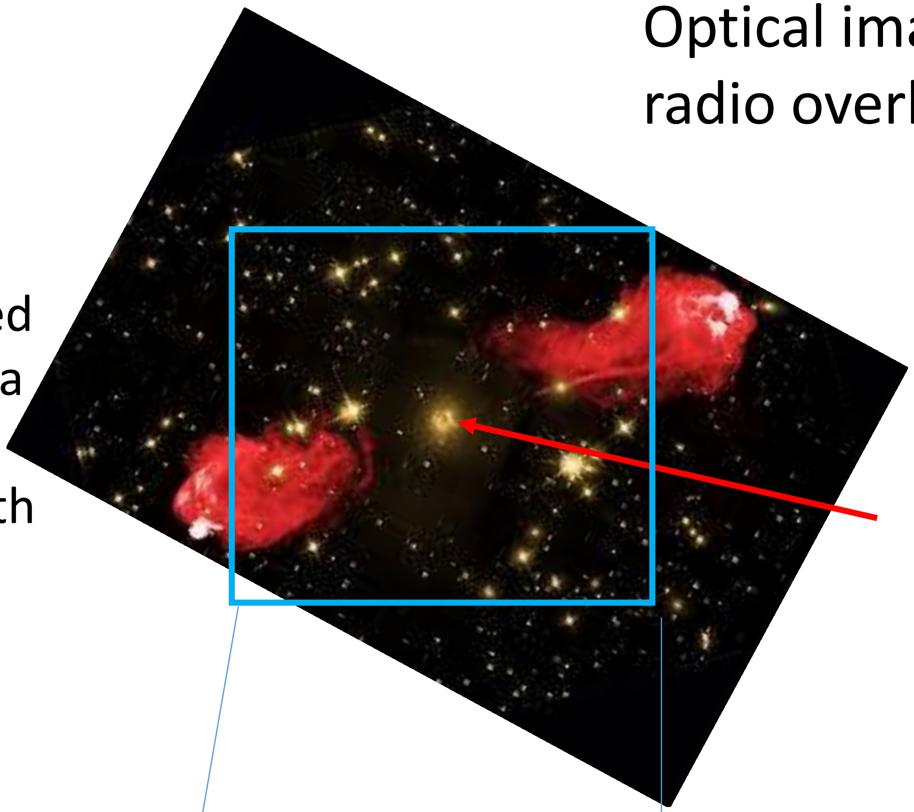
- Note: These spectra are typical in their slope and shape, but not in the flux density.
- These are the four strongest sources in the sky.
- Two of these are radio galaxies, the other two are supernova remnants.
- Both types of source have same spectral characteristics – which is not that of a thermal source.
- If the emitting mechanism were thermal (like a star) the spectrum would look like this …
- Clearly, these are 'non-thermal' sources. But then, what is the emitting mechanism…? We return to this later.



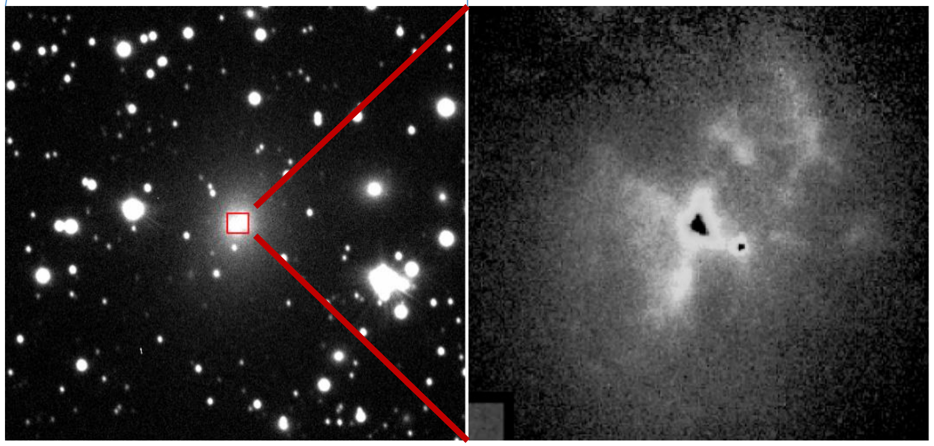
Cygnus A –
the first identification.

- The first discrete radio source to be identified with an optical object was Cygnus A – using a simple interferometer, in 1951.
- To everybody's surprise, it was identified with a rather non-descript galaxy (!)
- Radio emission ws found (in 1953) to comprise two components (lobes), each of which was far outside the galaxy stellar component.
- The galaxy redshift is z = 0.056, so D = 232 Mpc. (1" ~ 1 Kpc).
- Size ~ 120 kpc.
- The radio flux then resulted in:
- Spectral luminosity ~ 6 x 10^{27} Watt/Hz.
- Total luminosity ~ 10^{38} watts (10^{12} x the sun)
- Total energy content ~ 10^{53} Joules.
- Timescale ~ 10^{8} years.

Optical image, with radio overlay in red



Cygnus A optical galaxy



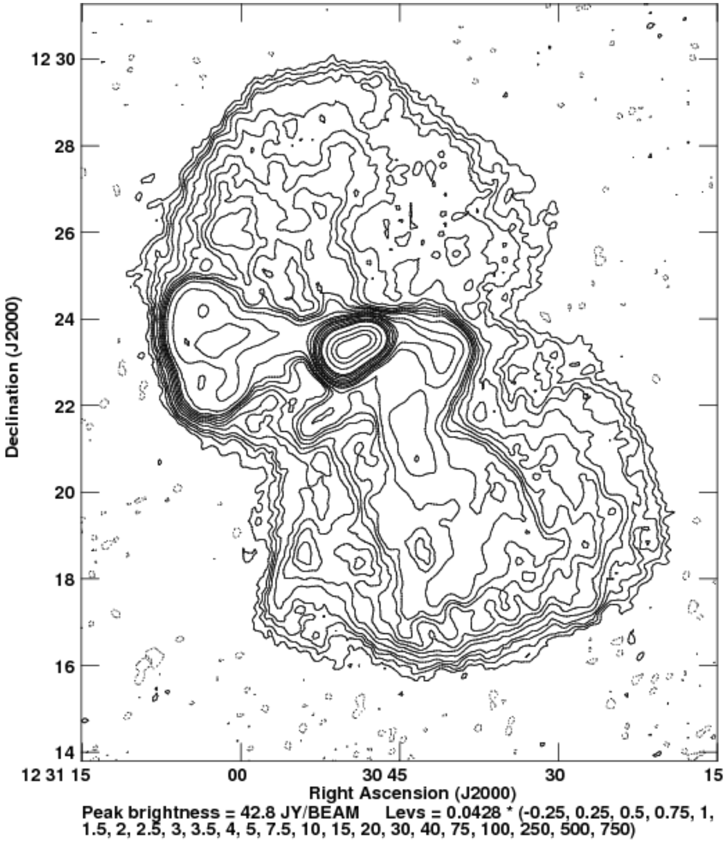
Gemini i-band 0.8 µm   Keck K-band 2 µm

Surveys, surveys, surveys

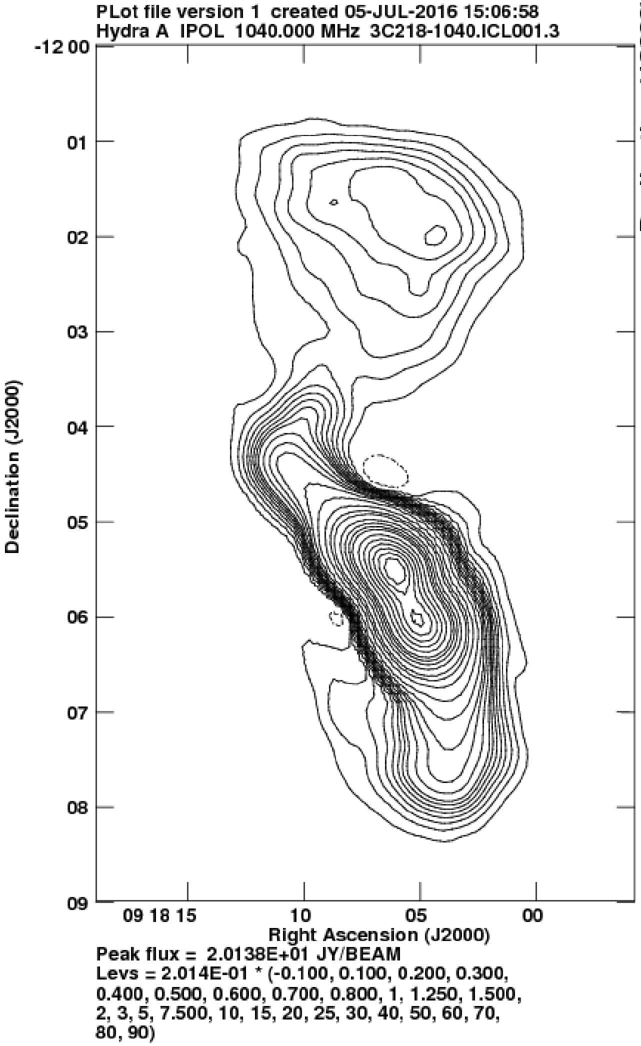
- These exciting discoveries encouraged the development of radio telescopes around the world, which undertook all-sky surveys.
- The most famous catalog is the 3C catalog, (Cambridge, England) with almost 500 sources. Published in 1959.
  - It has been revised twice – the latest is the 3CRR catalog, (1983) with 179 discreet sources, with $S > 10.9$ Jy at 178 MHz, $\delta > 10$, and $|l| > 10$.
  - All of these are identified with galaxies or quasars.
  - This classification (galaxy or quasar) is based on the optical properties. Quasar optical images are dominated by a bright point-like emission.
- Meanwhile, radio interferometers were busy making resolved images of all these newly discovered sources.
- These provided a wondrous diversity of results.

Some examples

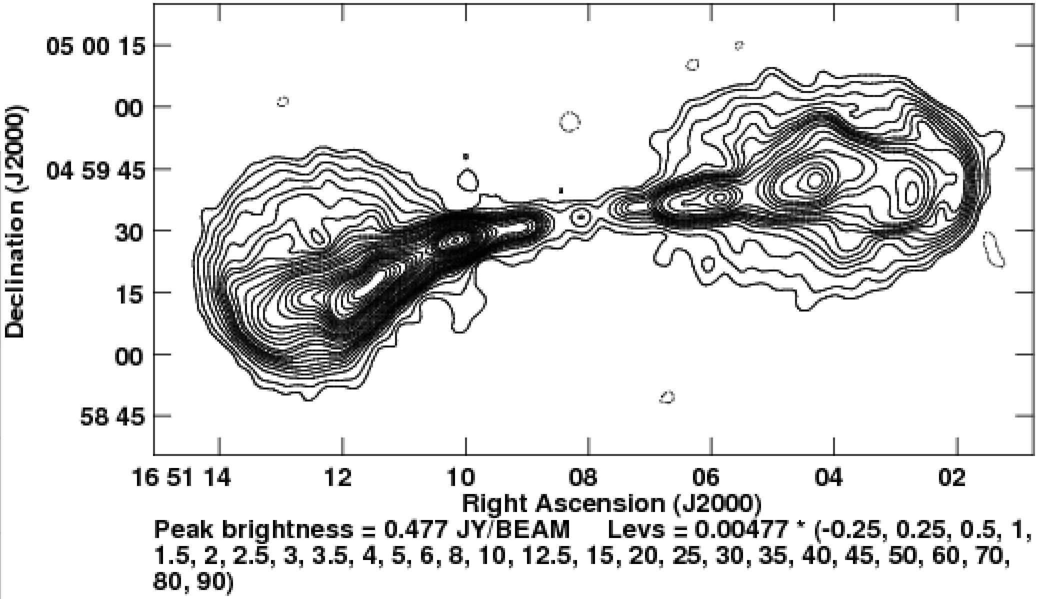
3C274 = Virgo A



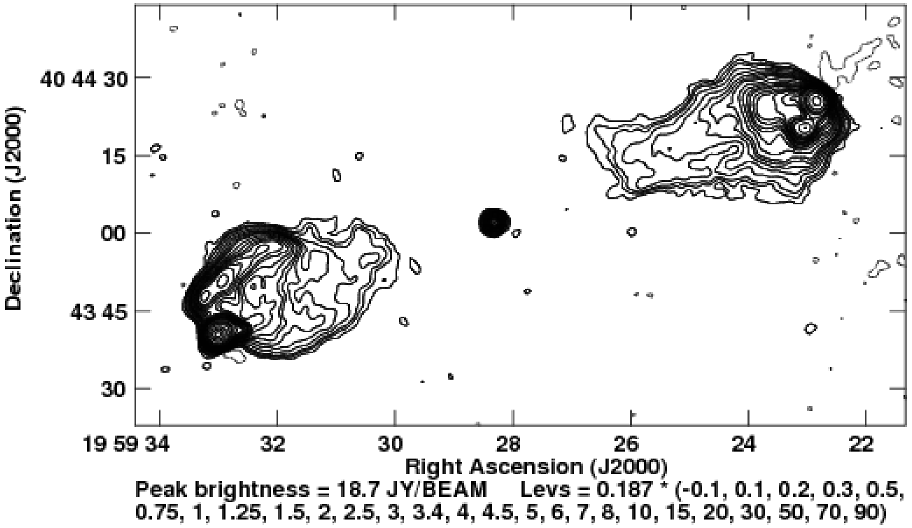
3C218 = Hydra A



3C348 = Hercules A



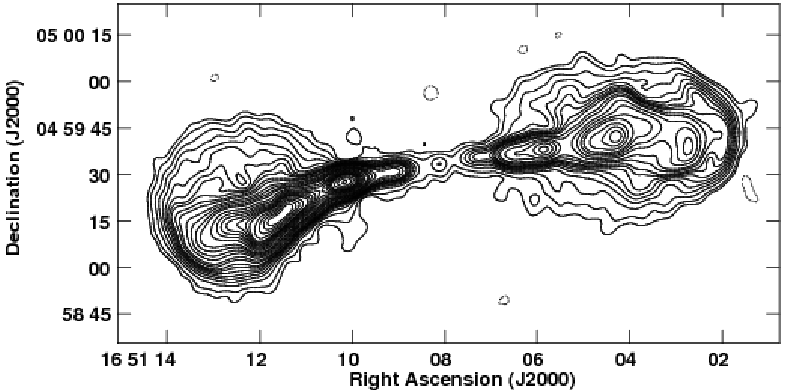
3C405 = Cygnus A



These are all nearby (few hundred Mpc), of similar sizes (Kpc).

Diversity and Commonalities in structures

- The imaging showed a great variation in structures. But there are (almost) always some common themes:
  - The structure is nearly always two-sided, normally with two ‘lobes’ straddling the optical galaxy.
  - In many sources, there is bright, compact structure at the extreme ends.
  - In others, the brightest structures are near the middle, while the lobes trail away.
  - There is almost always unresolved (‘point’) emission identified with the nucleus of a galaxy.
  - High resolution, high sensitivity observations usually show thin ‘jets’ of emission extending out from the galaxy nucleus, leading to the lobes and hotspots.
  - These ‘jets’ are seen at all scales – from Mpc to sub-parsec.

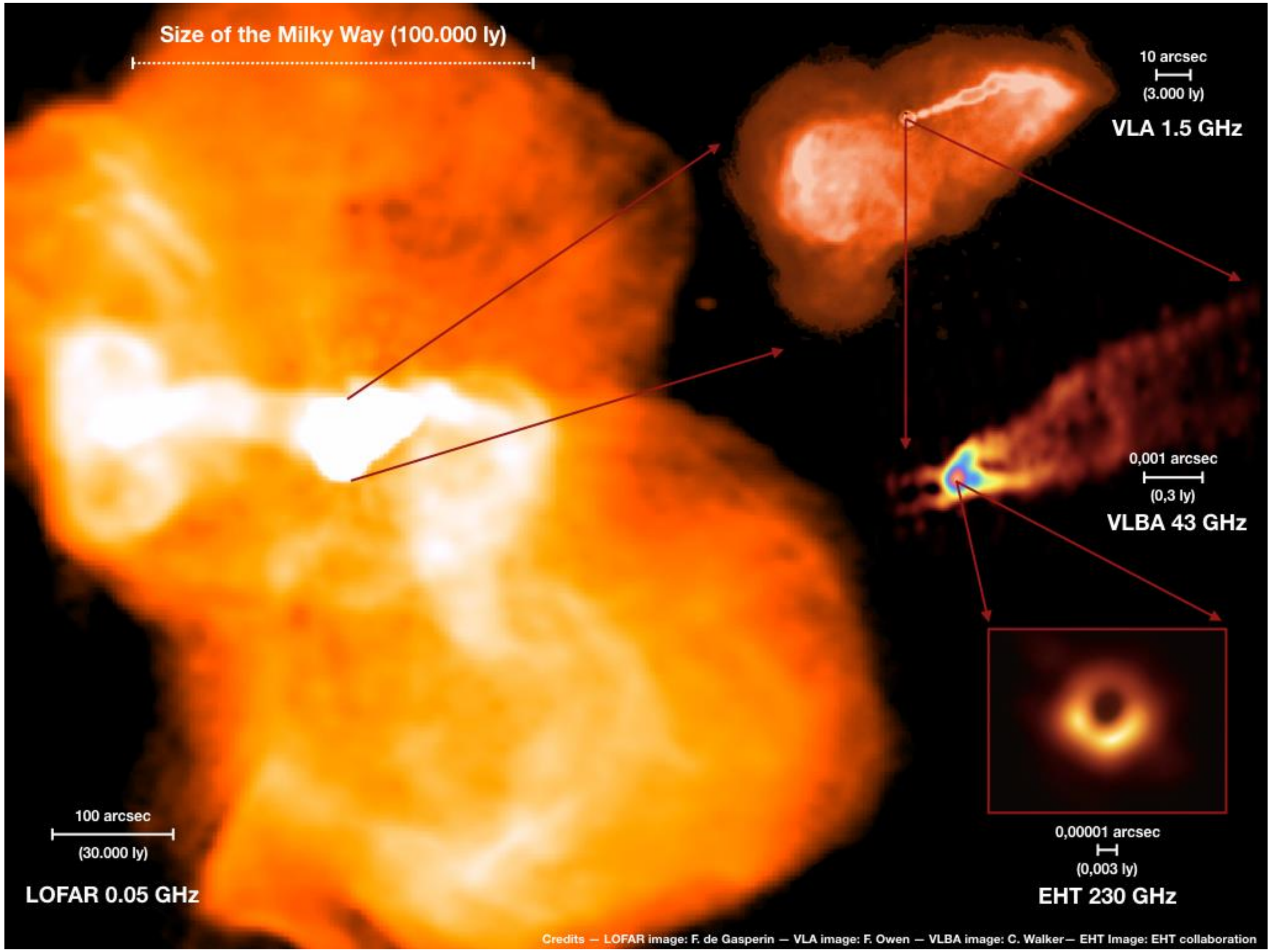


Peak brightness = 0.477 JY/BEAM Levs = 0.00477 * (-0.25, 0.25, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 6, 8, 10, 12.5, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90)

Hercules A = 3C348
Z = 0.144, D = 644 Mpc

Virgo A – a good example of vast range of scales

- Shown here is Virgo A = 3C274 = M87.
- A nearby 'radio galaxy', D = 16 Mpc.
- Large scale structure 100 Kpc across.
- Images here made with four different telescopes (LOFAR, VLA, VLBA, EHT) at four different frequencies (50 MHz, 1.5 GHz, 43 GHz, 230 GHz), and different resolutions.
- The EHT image is the very famous black hole image released a year or so ago.

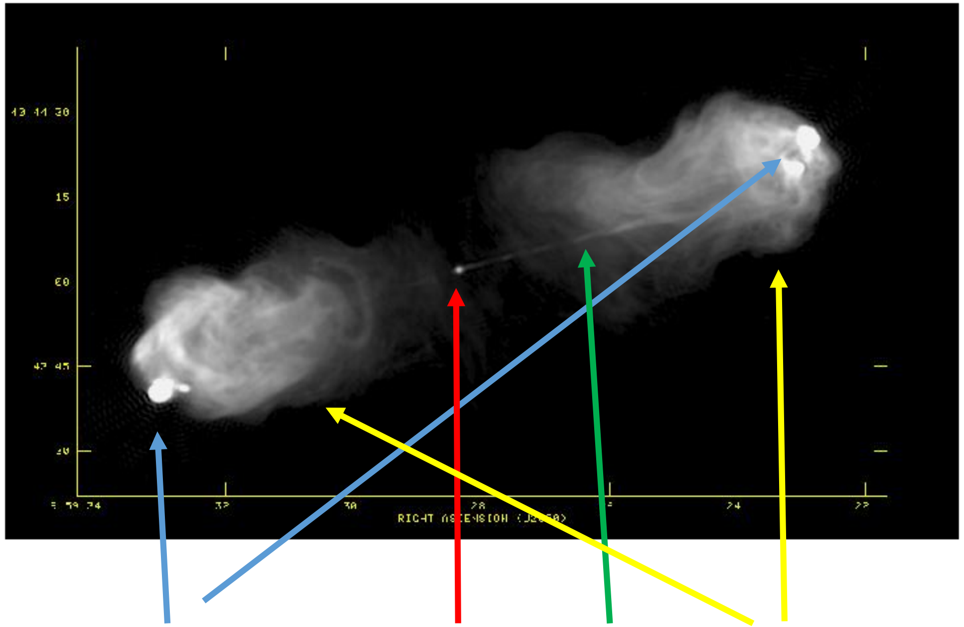


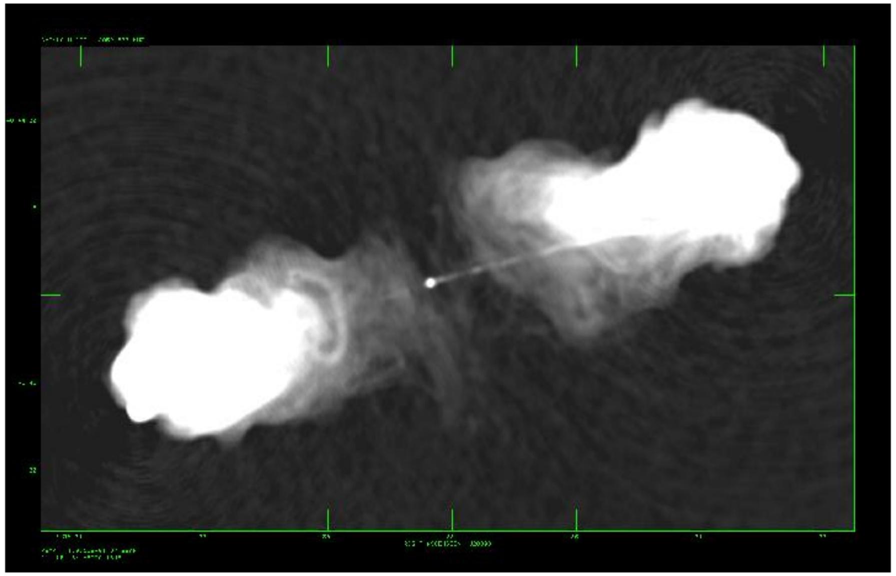
Ratio of physical scales is ~10^8! What physical processes are at work here?

Structure Variations

- The images of these sources (most from the VLA) show an amazing range of structures.
- An early and important result (Fanaroff and Riley, 1974) was the relation between structure and luminosity.
  - Weaker sources have structures which are brightest near the nucleus, and trail way into the distance. They look like (and probably are) plumes of light gas rising up through an enveloping gaseous galactic, or cluster, medium.
  - Stronger sources have brightness maxima at the edges, and are sharply bounded, commonly containing very bright `hot spots' near the extrema. They look like (and probably are) supersonically expanding gas bags.
  - There are (of course) intermediate cases.
- The weaker, fuzzier variety are called 'FRI', the stronger, sharper, are 'FRII'.

Prototypical FRII is Cygnus A:





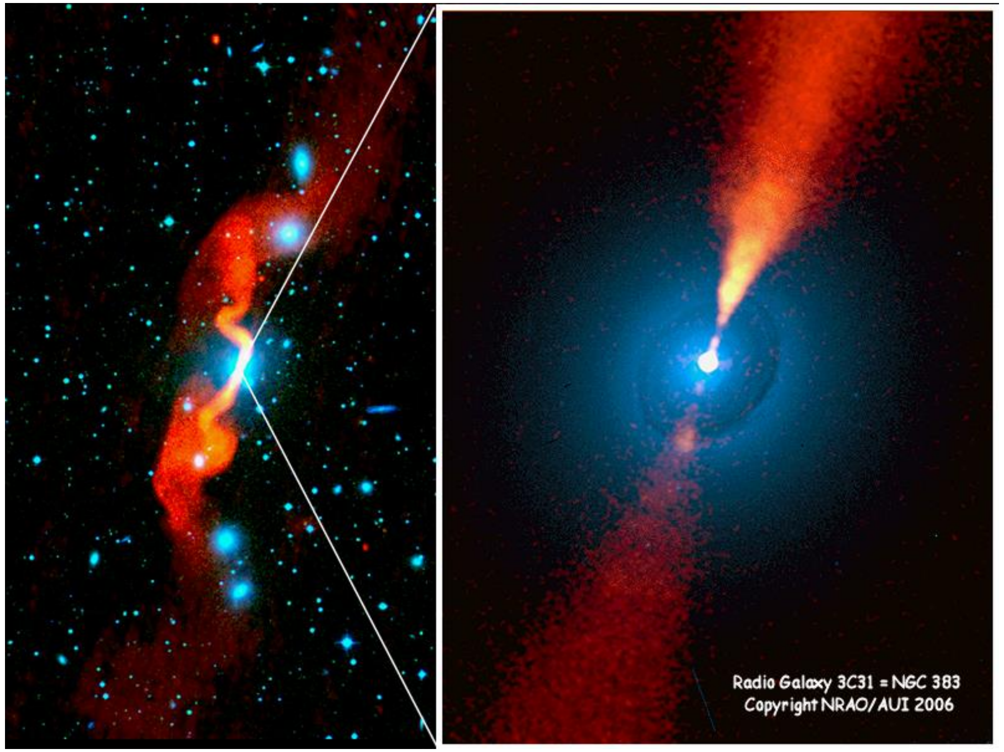
These are VLA images, made at 2 GHz frequency (15 cm wavelength), with 1 arcsecond resolution.
The `jet’ is very weak, and must be efficiently transporting the needed power to illuminate the lobes.
The radio emission is highly polarized, especially at high frequencies.

Prototypical FRI – 3C31

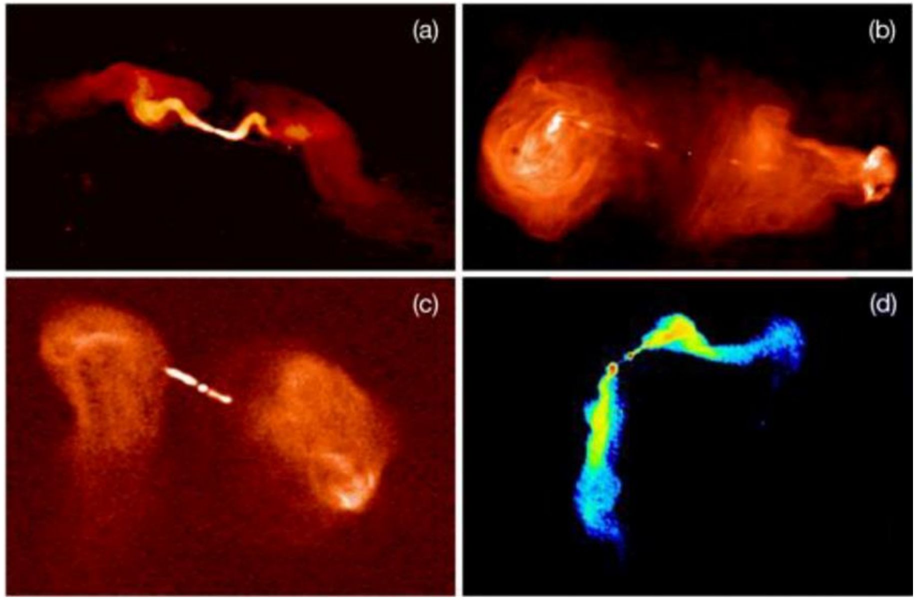
Radio-Optical Overlay: Radio in red/yellow, optical in blue

Z = .014, D = 64 Mpc.

Note the large-scale emission trails away, with no clear boundary.
Inner jets go through numerous changes in scale and structure.
Jets are two-sided, but one side much brighter.



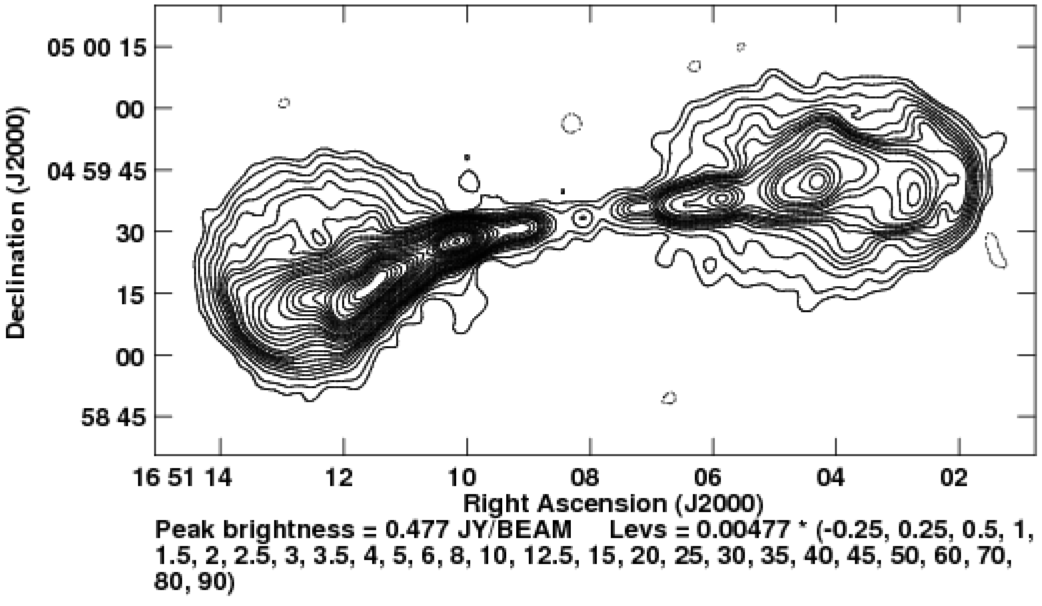
Blue `fuzz' is the optical galaxy – an elliptical.



Four other examples, showing variation in structure.

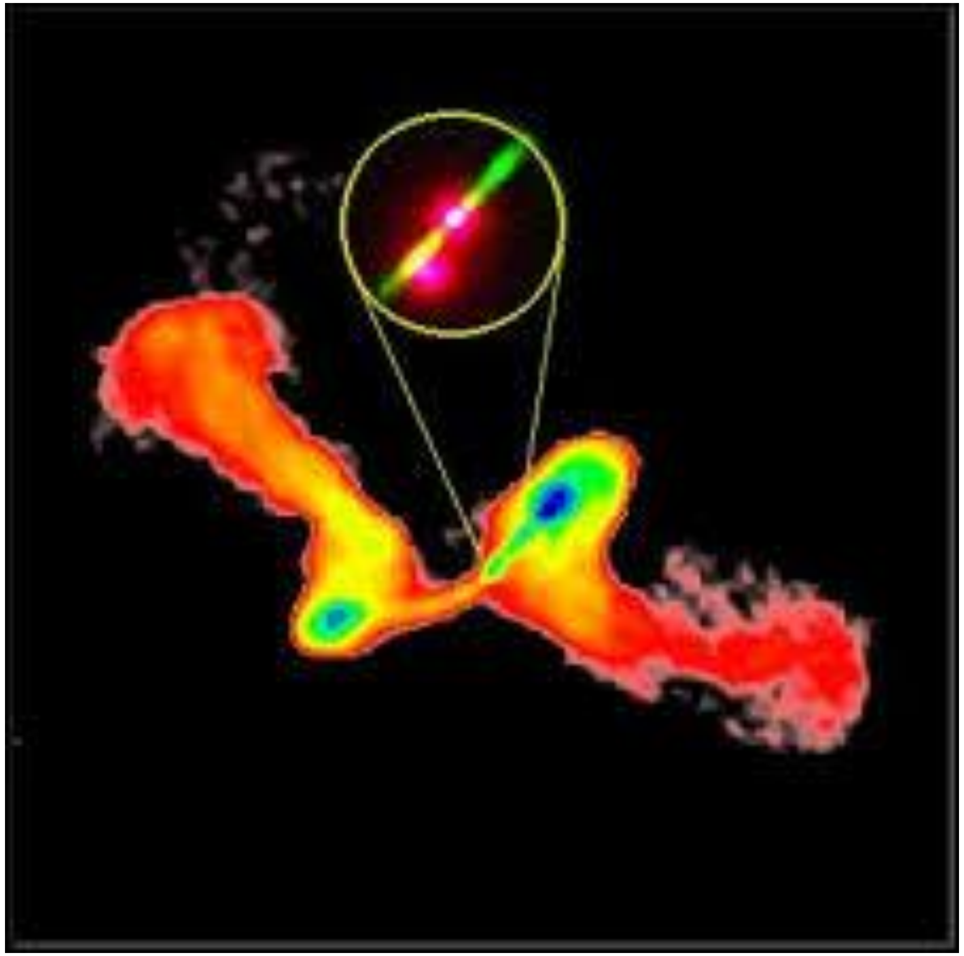
An intermediate case – 3C348 = Herc A

The ‘FRI – FRII’ classification is not clean. People like to show the obvious cases, but there are many examples of intermediate types, like t his one.

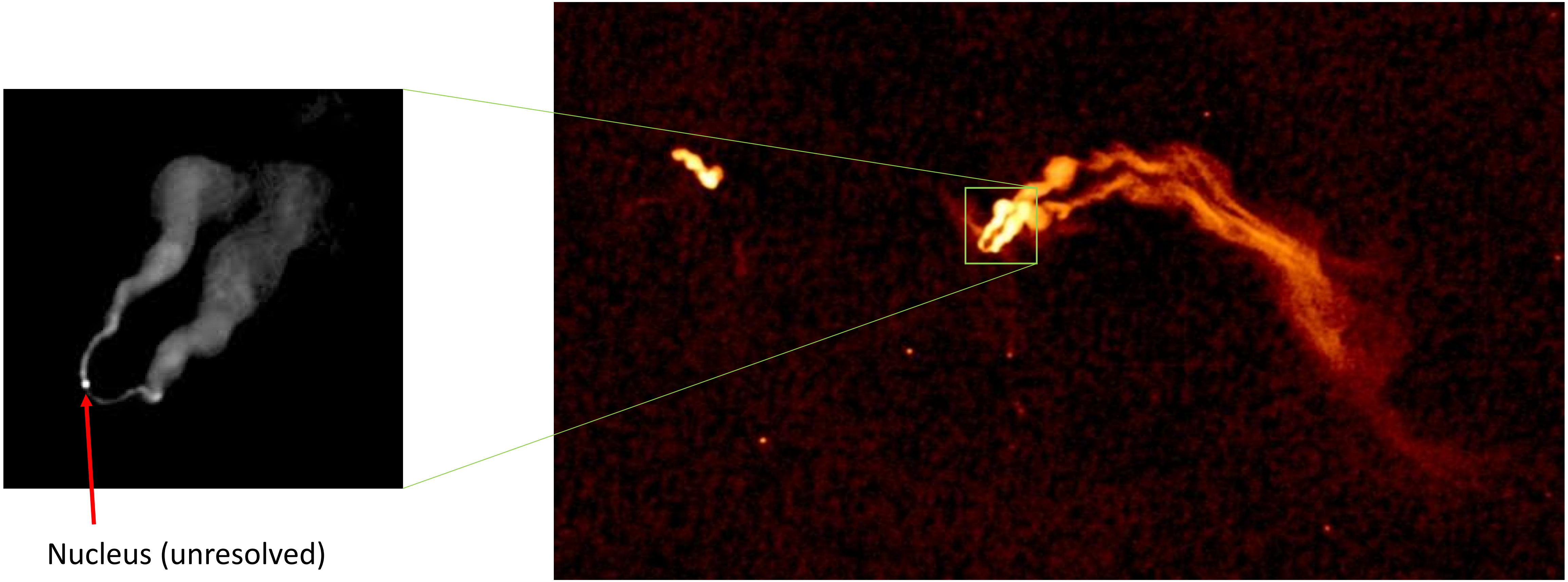


Other interesting structures – X-shaped.

- Although the radio emission is nearly always two-sided, it is common to see the two sides have different directions on different scales.
- Suggests the outflow is now along a different axis than it was in the past.
- Or, backflow from active lobe is rising in a plume-like structure.



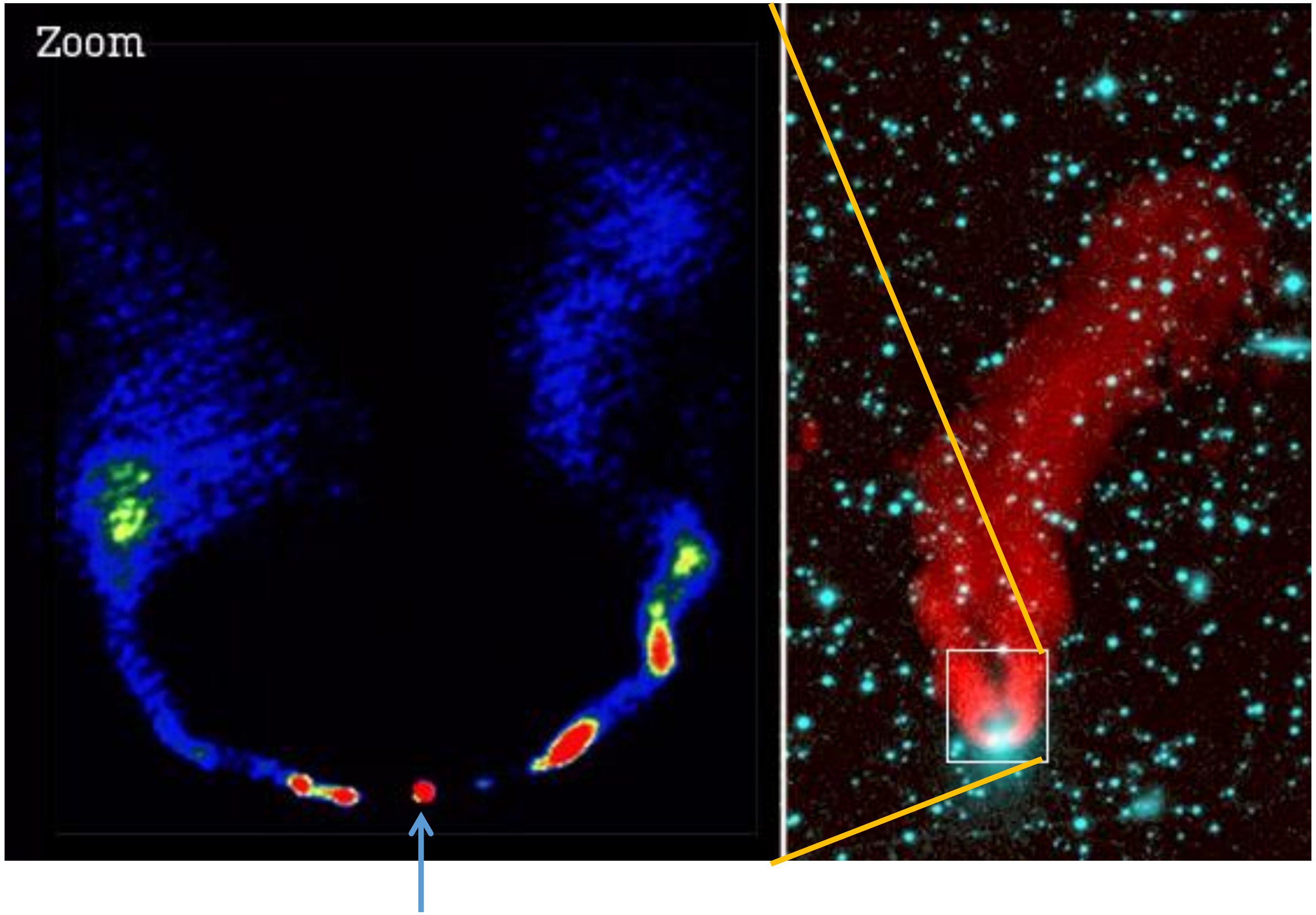
Radio tail sources – 3C129.



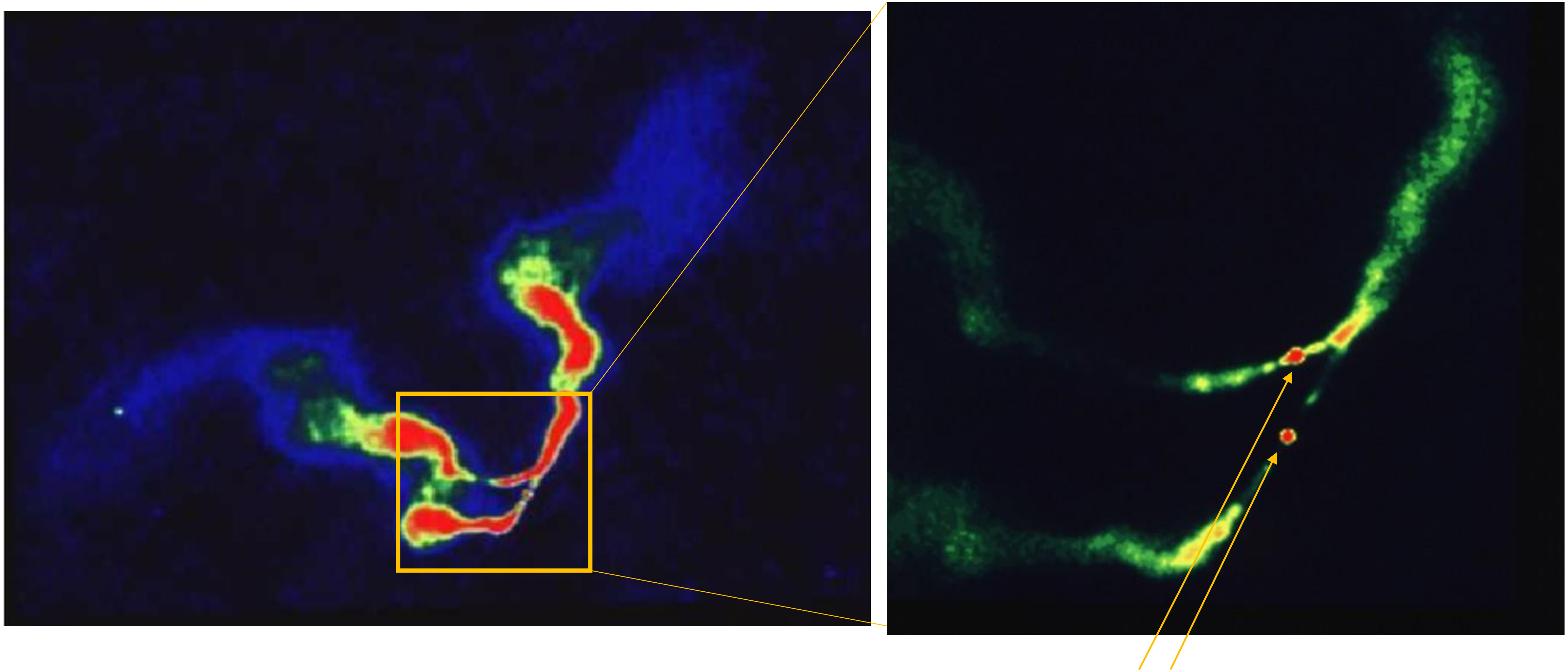
Suggests a galaxy moving through some gaseous medium.
Note the high resolution image shows two ‘jets’.

Another famous radio tail – 3C83.1B

- Jets emitted horizontally, swept back by motion through the external medium.
- Jets trails are left behind as the galaxy moves through the external medium.



3C75 – two nuclei, each active, and orbiting



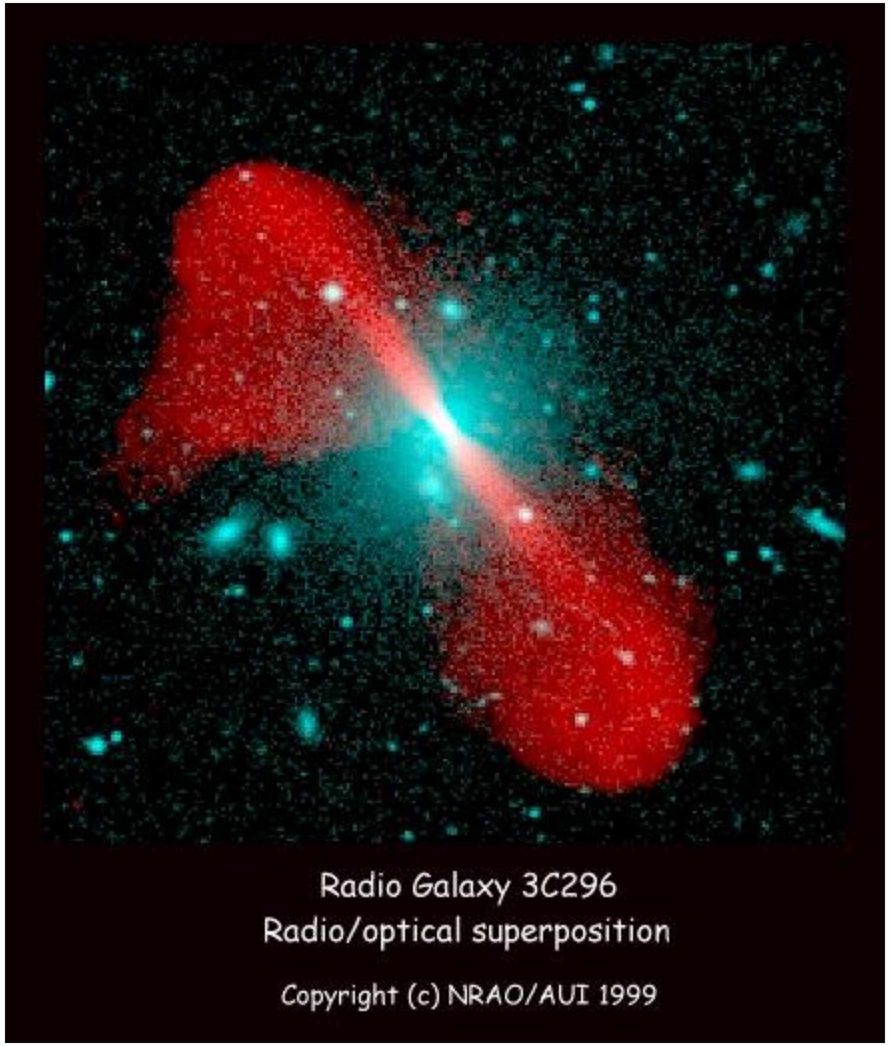
Two Nuclei – a binary black hole system

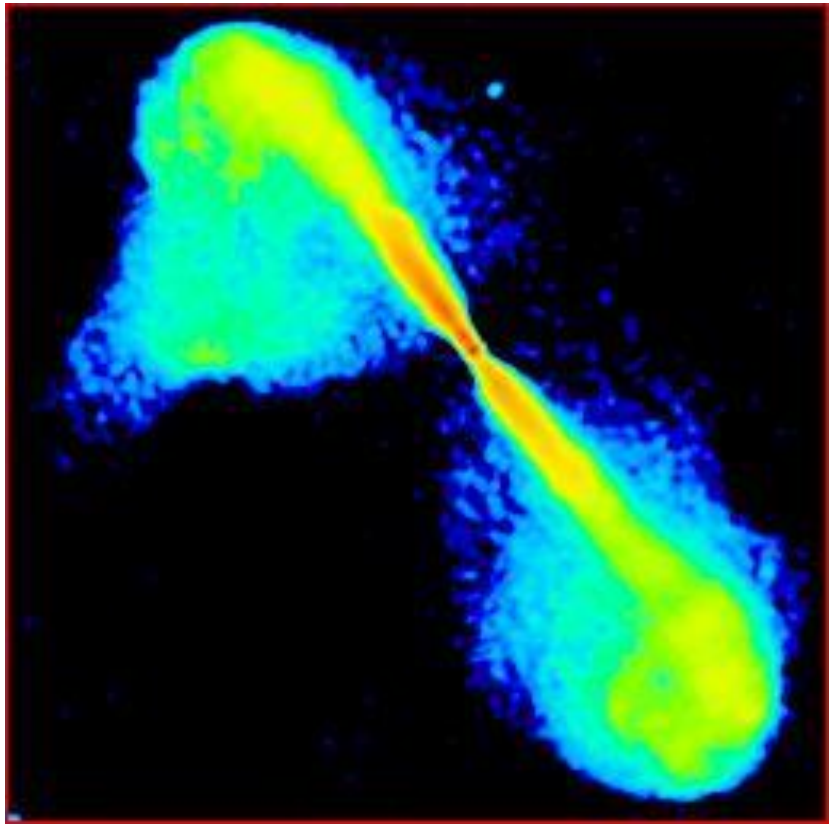
A big fuzzy source – Fornax A.

- Very close (19 Mpc), very weak source.
- Very large in angular size (12 x 9 arcmin).
- This is one of the few radio galaxies with little, or no, nuclear emission.
- It also has no compact structure.
- Many people think it is a ‘dead’ radio galaxy.

Radio-Optical overlay. Optical = white. Radio in orange.

3C296 – another intermediate galaxy.





Time for some physics …

- Note: These spectra are typical in their slope and shape, but not in the flux density.
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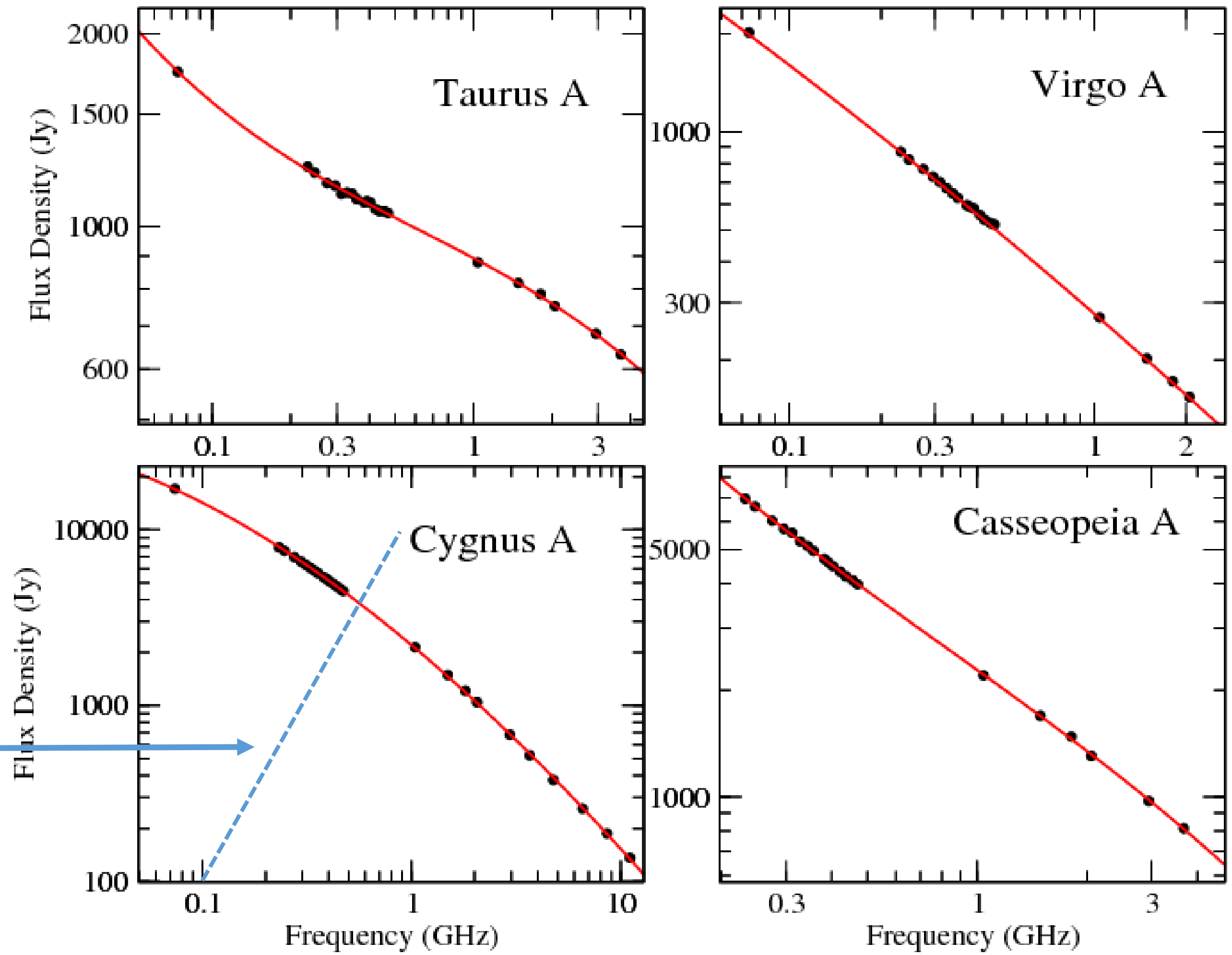
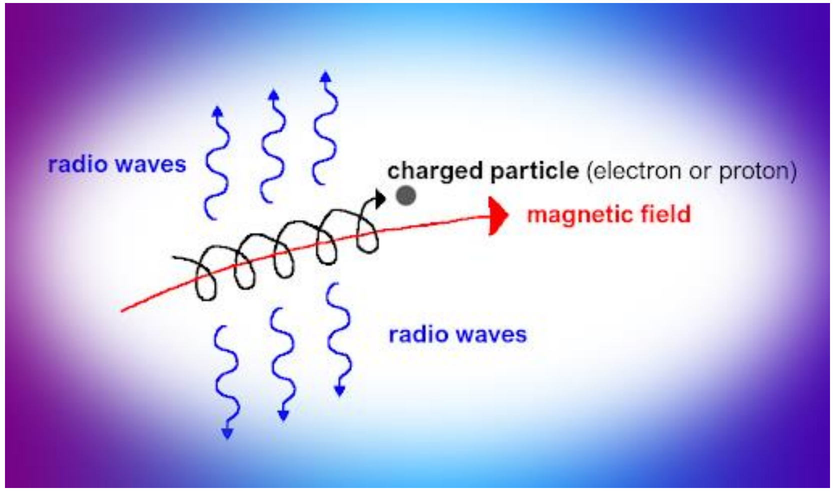


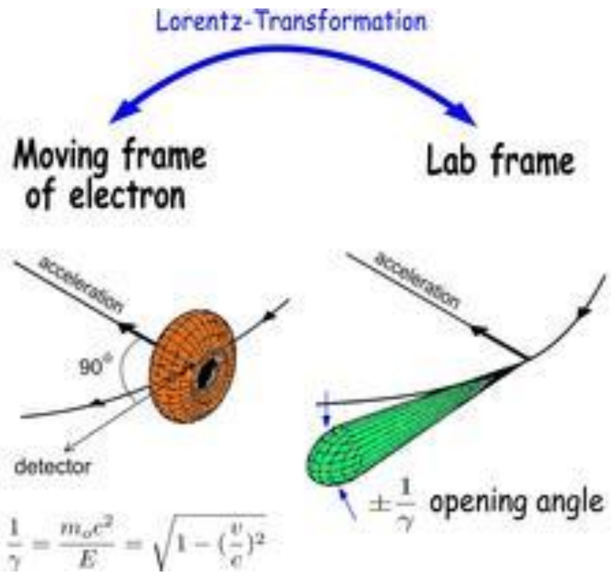
Answer: Synchrotron Radiation

- The mystery of the spectrum was solved in the mid-1950s.
- In general, charged particles emit radiation when accelerated.
  - Example: electrons in an ionized gas emit photons when accelerated by a nearby ion.
  - This is called ‘bremsstrahlung’ – operates in ionized nebulae.
  - A fast-moving (‘relativistic’) electron’s path is curved due to a magnetic field, causing a type of emission now known as ‘synchrotron radiation’.
- This was discovered during the development of cyclotrons and synchrotrons, in the early 1950s. This emission was broad-band, and highly polarized.
- The same process is occurring in these radio galaxies – relativistic particles (primarily electrons) follow curved paths due to embedded magnetic fields.
- Key clue: synchrotron radiation is polarized, thermal radiation is not.
- Hence, there must be both relativistic electrons (and/or positrons), and magnetic fields in these radio sources.
- Knowledge of the radiation mechanism allows estimates of the luminosity and age.

Synchrotron Radiation Basics

- Theory is quite mathematically complex, but the basics are easy.
- An electron's path will be curved in the presence of a magnetic field, causing photon emission.
- But if the electron is very energetic ('relativistic'), the emission, as seen in our `lab' frame, is highly beamed in the direction of motion.
- This results in the emission (from a single electron) as being seen as a train of very short pulses.
- Adding up all the pulses from the 'zillions' of randomly oriented electrons, all whizzing around the magnetic fields, results in an apparent continuum emission.



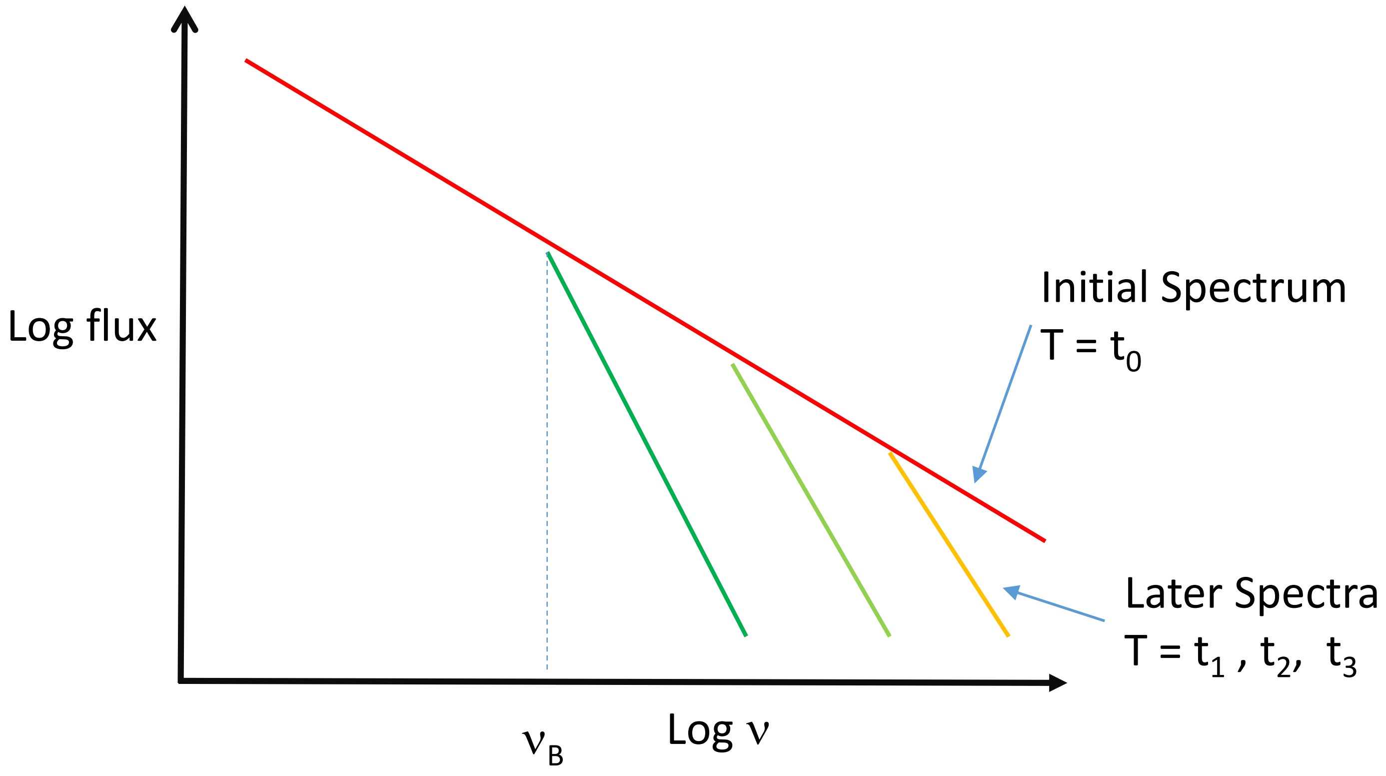


Synchrotron Radiation Basics

- The power emitted for a single electron is: $p = const.B^2E^2\sin^2\theta$.
- The spectrum of the emitted power, for electrons of a given energy, maximizes at a frequency: $\nu_C = const.B.E^2$.
  - In the absence of acceleration, the high energy electrons, which radiate at highest frequencies, lose energy the fastest, resulting in an evolution of the spectrum to lower frequencies.
  - This spectral slope change can be used to estimate the age of the source.
- If the energy spectrum of the electrons is power-law: $N(E)= KE^{-\gamma}$, then the resulting spectrum is also power law: $S(\nu) = S_0\nu^{-(\gamma-1)/2}$.
  - So if a source has spectral index = 0.7, then the electron energy spectrum has index 2.4.
  - The measured spectral index gives us information on the electron acceleration process.
- The emission is linearly polarized, with the observed electric vector orthogonal to the direction of the magnetic field.

Synchrotron Evolution

- Initial spectrum a pure power law. (A result of the acceleration mechanism).
- As time goes by, the high frequency emission declines, low frequency stays the same.
- The `break frequency' ν_B is a function of the age of the source (and other things).
- High frequency spectrum rarely power-law – shape depends on many details.

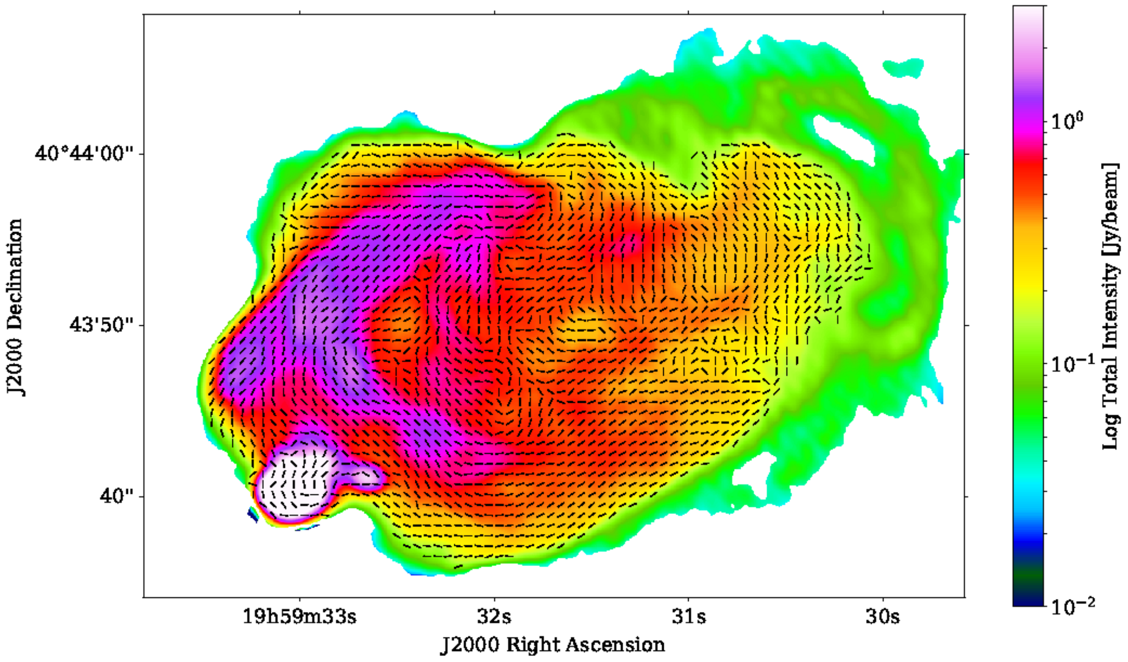


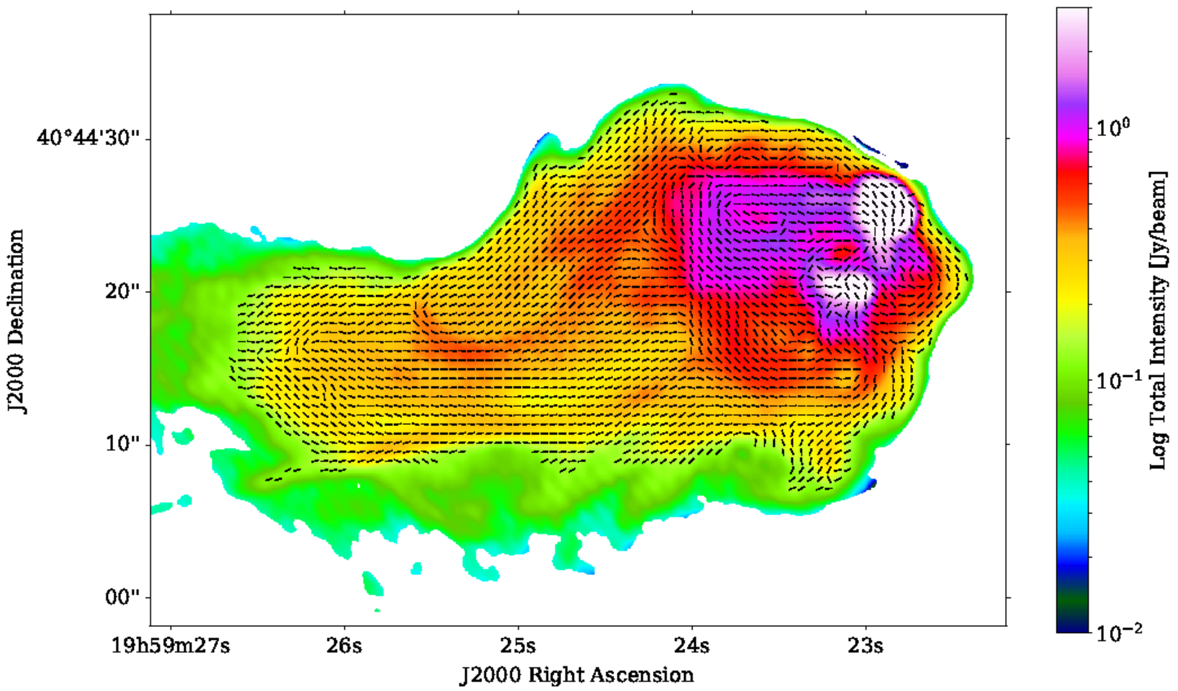
Results from Synchrotron Theory

- The brightness of the emission gives us estimates of the electron energy and magnetic field strength.
- Because both B (magnetic field intensity) and E (electron energy) are involved, we need an independent measure of one to derive the other.
  - In the absence of such a measure, the usual procedure is to assume there is equal energy in fields and particles.
- For super-bright 'hotspots', the magnetic fields are ~ 300 μGauss
- For the much dimmer lobes, magnetic fields are ~50 μGauss.
- For other, much weaker (and dimmer) sources, field of a few μGauss.
- The polarimetric images show the magnetic fields are well ordered, and follow the radio lobe boundaries.
- The change in spectral slope over frequency is used to generate age and velocity maps. Ages of $10^7 – 10^8$ years are common.

Magnetic Fields in Cygnus A

Shown here are two lovely images made by Lerato Sebokolodi, my graduate student. These show the intensity (brightness) of Cygnus A (colors), with the magnetic fields superposed in dark lines.

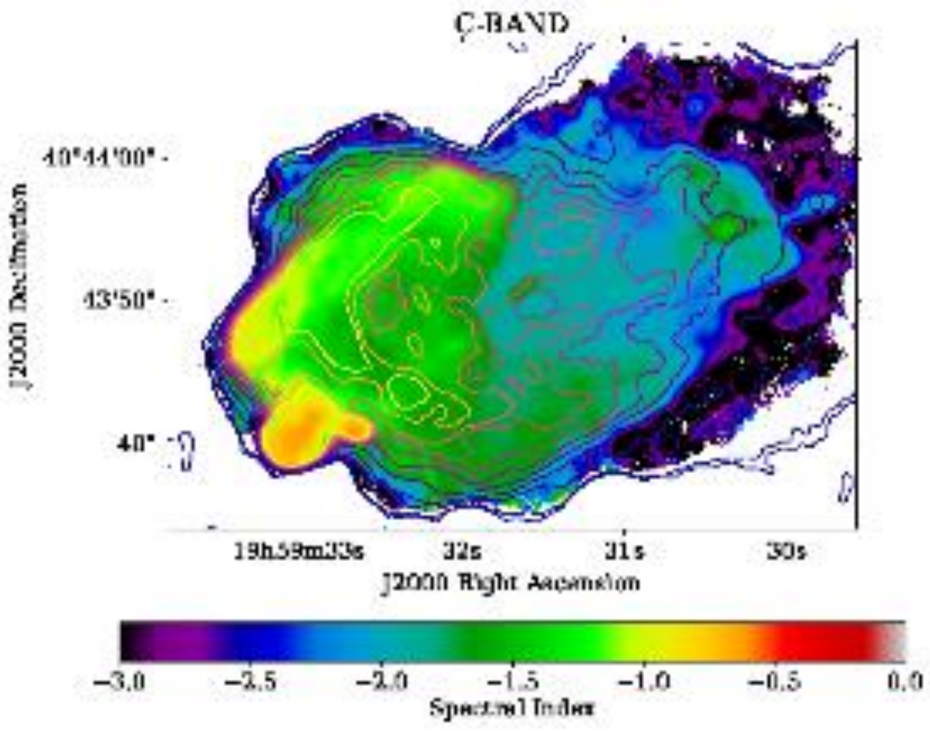


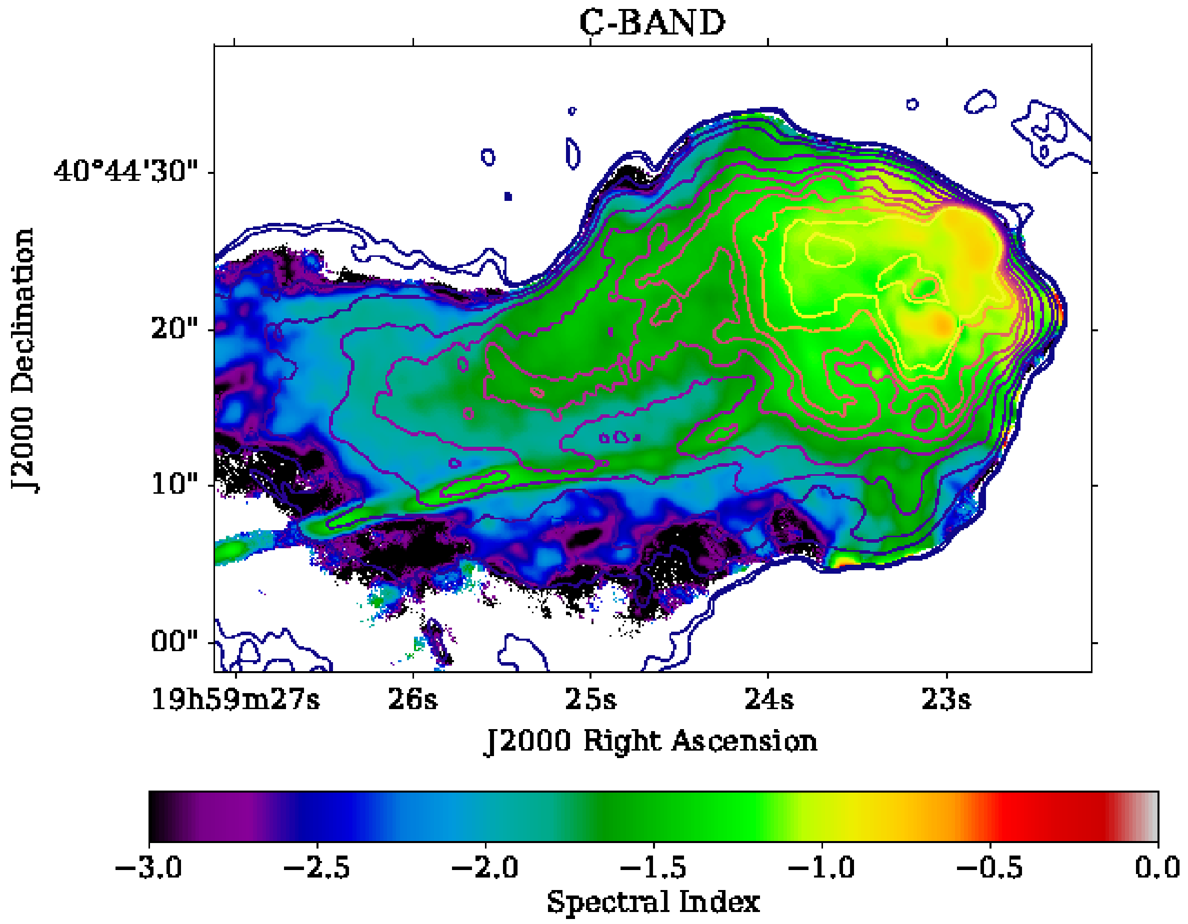


Note the magnetic field orientations are not random, and tend to follow the source boundaries.

Spectral Index – source ages

- The slope in the spectrum gives information on age:
  - Steep slope (dark colors -- high frequencies dim) means old electrons, and great age.
  - Flat slope (bright colors -- high frequencies bright) means young electrons – younger regions.



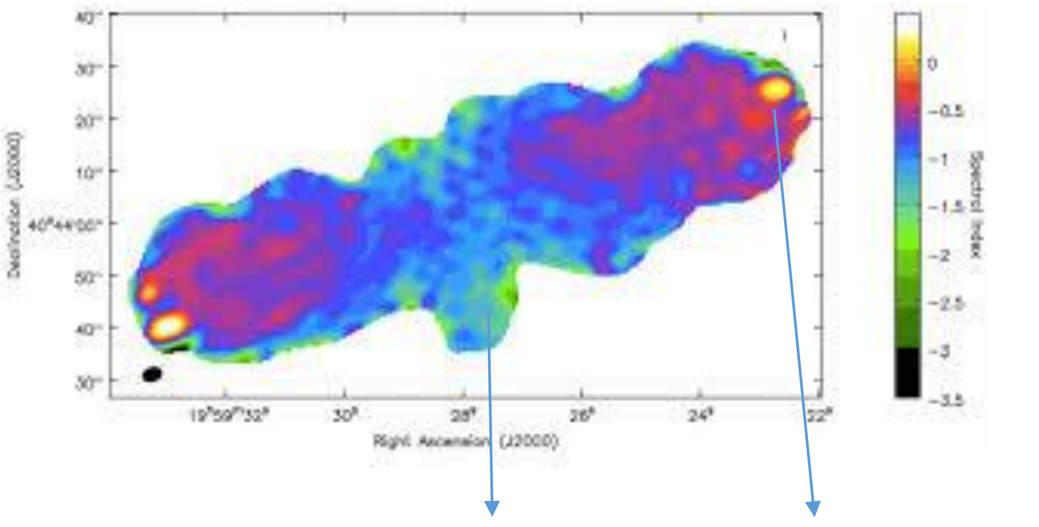


In these figures, made by my student Lerato, the color gives the slope: Purple/blue -> Steep -> Old
Yellow/red -> Flat -> Young.

Towards the Basic Model

- The emitting electrons in the hotspots in FRII sources have very short lifetimes – as short as 1000 years. But they are located hundreds of thousands of light years from the nucleus. Therefore …
- There must a continuous source of acceleration in these hotspots.
- Age studies (using knowledge of synchrotron radiation) show the faint inner parts of FRII sources are old, while the outer parts are young.

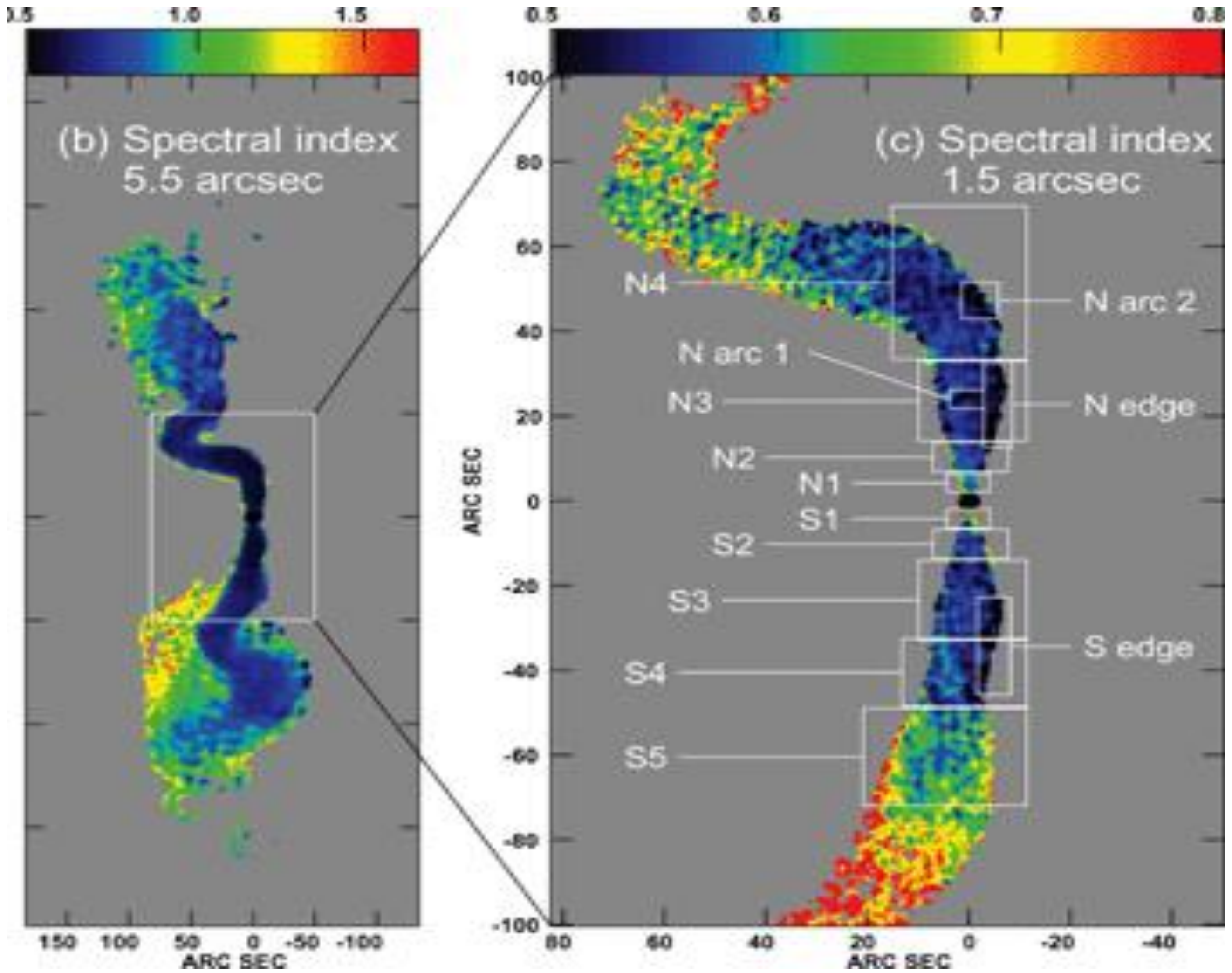
Spectral Slope of Emission in Cygnus A



It is clear that these FRII sources grow outwards, with the 'hotspots' being some sort of 'working surface' where the energy source pushes against the external medium. Power source must be the nucleus (black hole), and the conduit is the jet.

FRI Sources – a different picture. 3C31:

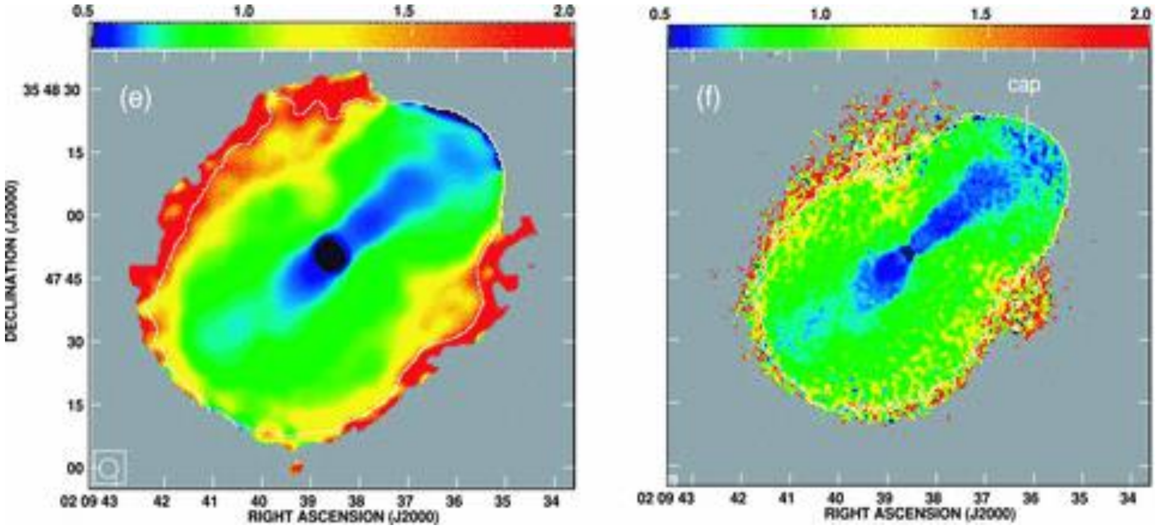
- The classic FRI source 3C31 shows the typical picture for low-power sources.
- Blue = flat = young
- Red = steep = old.
- The picture here is that the jet has entrained gas from the surrounding medium, which has slowed it down to subsonic speed.
- The jets expand out, and slowly rise through the surrounding gaseous cloud.

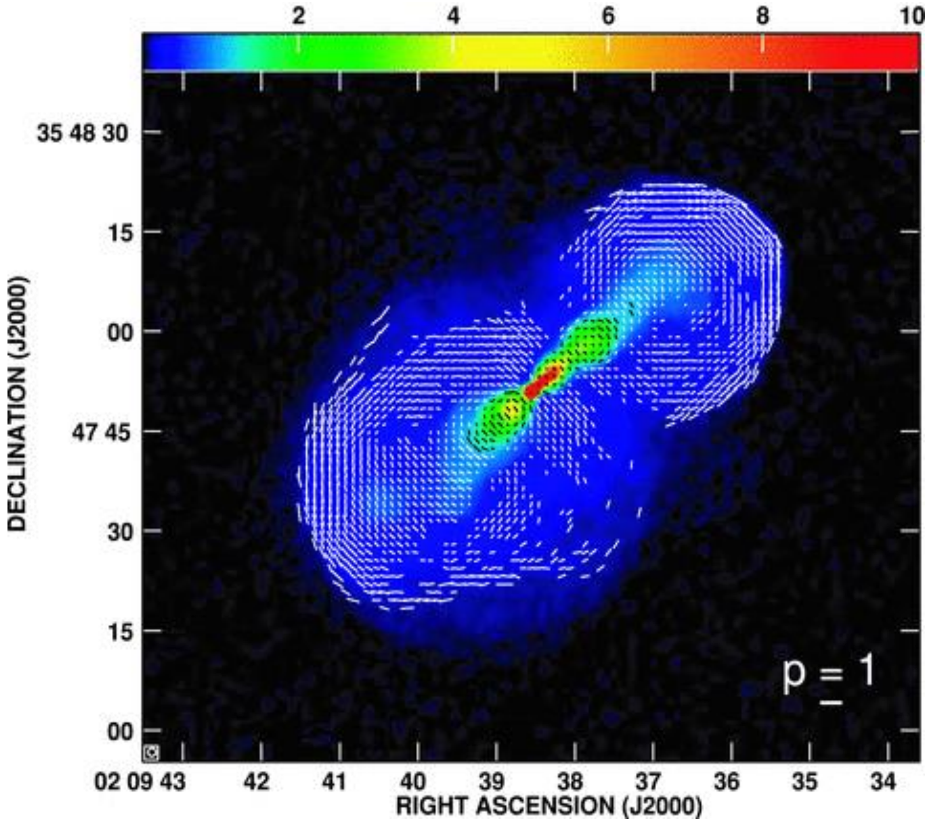


From Laing et al. MNRAS, 386, 657, 2008

Another Example – B0206+35

This low-power source is a real ‘gas-bag’!





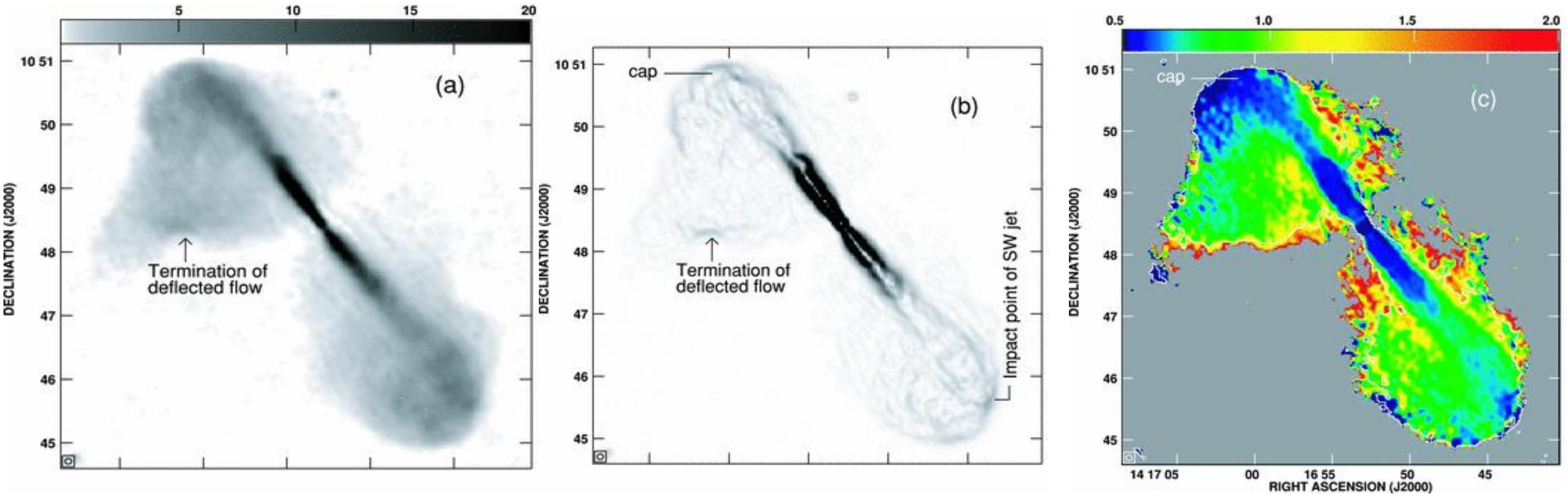
Above: Spectral index: Blue = young, Red = old.

Right: The brightness (color) and magnetic fields (white)

From: Laing et al. MNRAS, 417, 2789, 2011

Mon Not R Astron Soc, Volume 417, Issue 4, November 2011, Pages 2789–2808, https://doi.org/10.1111/j.1365-2966.2011.19436.x

Finally – 3C286 – another FRI source.



Grey-Scale representation | **Contour Plot** | **Spectral Index**

From Laing et al.: MNRAS, 417, 2789, 2011

Mon Not R Astron Soc, Volume 417, Issue 4, November 2011, Pages 2789–2808, https://doi.org/10.1111/j.1365-2966.2011.19436.x

For FRI sources – summary…

- FRI sources (which fade away into the distance …) show a different pattern.
- For these, the flat spectrum gas (= young) is near the nucleus, while the steep spectrum (= old) are those dim regions far away.
- So for these, there is no supersonic growth, no hotspots, and no fast jets.
- The nucleus (black hole) still provides the energy, but it is not conducted to the far end of the sources by an efficient ‘jet’.
- Likely, these sources entrain the gas, which slows them down, and turns them into plumes of gas.

The Basic Model

- These arguments, and many more, lead to this:
- The energy source is a galactic supermassive black hole.
- The BH spin generates a bi-directional relativistic outflow.
  - Content unclear – e+e-, or e-p?
- For FRII, the jet propagates efficiently until it strikes undisturbed medium.
  - A strong shock forms (hot spot), and high energy particles spill out.
  - These push the external medium out – and the cavities are filled mostly with relativistic gas.
  - The lobe gas density is far less than the that of the confining medium.
- For FRI, the jet entrains external medium, slowing it down – resulting in a buoyant plume.

Lot of Uncertainties …

- What is the process which generates the jets?
- Are the basic jets electron/positron, or electron/proton?
- Why are the jets so stable?
- Does the jet carry an electric charge (i.e., is there a current)?
- What is the makeup of the gas in the lobes? Is there any significant thermal gas within?
- Does the gas in the lobes of FRII sources flow back to the nucleus?
- Why do some jets (FRI) entrain gas, while others (FRII) do not?
- What role does the environment play in the RG structures?
- Is there feedback from the energy dumped into the medium?