Extragalactic Radio Sources

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It all began in the 1940s...

- Galaxies=condensations of gas, dust and stars held together by their own gravitational potential

M 87

M 51 (Keel, 1995)

Seyfert Galaxies: The First AGN

- 1943
  - Nuclei of many spirals display strong, broad emission-line spectra
  - Doppler widths correspond to gas velocities of several thousand km s^{-1}
    - (most galaxies ~ hundreds of km s^{-1})
  - "Active Galactic Nuclei"

NGC 2997

"Radio Stars" in our Galaxy (?)

- Discrete radio sources (Hey et al. 1946)
- Very luminous ($>10^{40}$ erg s^{-1})
- Variability on the order of months or even days limits physical size of source

Not quite!

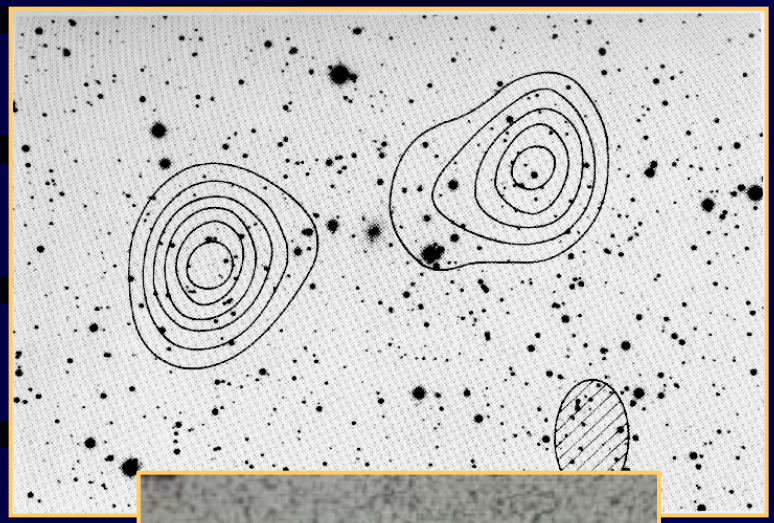
- Three years later, two radio stars were identified with nearby galaxies, i.e. these small, bright sources are extragalactic! (Bolton & Stanley, 1949).

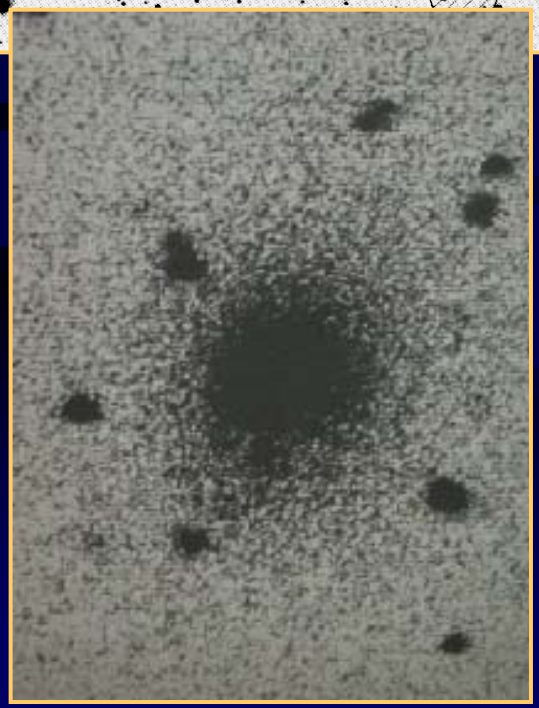
M 87

(35 million ly)

Cygnus A

Ryle et al. 1965





Thompson 1984

- A double radio source (Jennison & Das Gupta, 1953)
- Identified with a 15th magnitude galaxy (Baade & Minkowski, 1954)
  - ~ 720 million light years away (z=0.06)
  - Greater than 600,000 light years across

Technology is wonderful...

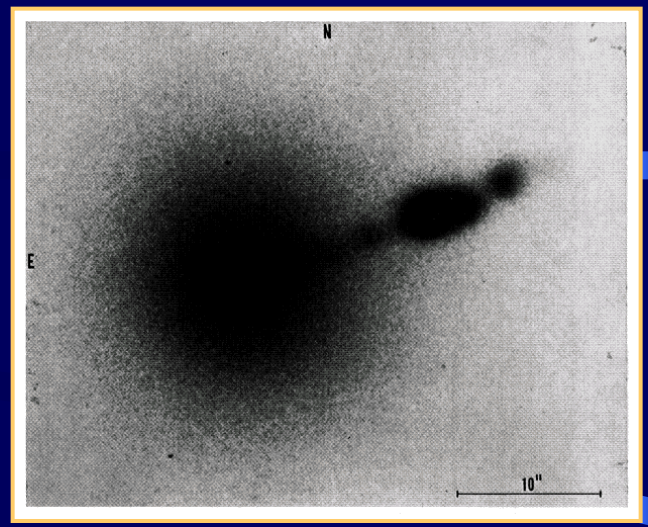
- In the 1960s, use of interferometers resulted in positional accuracies of a few arcseconds
- Optical/radio correlations abound
- Small, strong radio source 3C295 identified with faint, 20th magnitude galaxy
  - z=0.46 (Minkowski, 1960)
  - ~ 8 billion light years away!

…but it raises many questions.

- Radio source 3C48 associated with a 16th magnitude "star" (Sandage, 1961)
  - Unidentifiable emission-line spectrum for a star
  - "Quasi-Stellar Object" (QSO) or "quasar"

The mystery is solved!

- Quasar 3C273 appears as a 13th magnitude "star" having a faint optical jet extending from one side (Schmidt) associated with a radio jet (Hazard)



M87-Arp & Lorre 1976

- 3C273's emission-line spectrum finally identified in 1963
  - discovered to be a redshifted Balmer series of H, plus redshifted MgII
  - z=0.158 (~3 billion light years away)
  - L ~ 10^{47} erg s^{-1}, angular size < 1 kpc

Q: What are AGN?

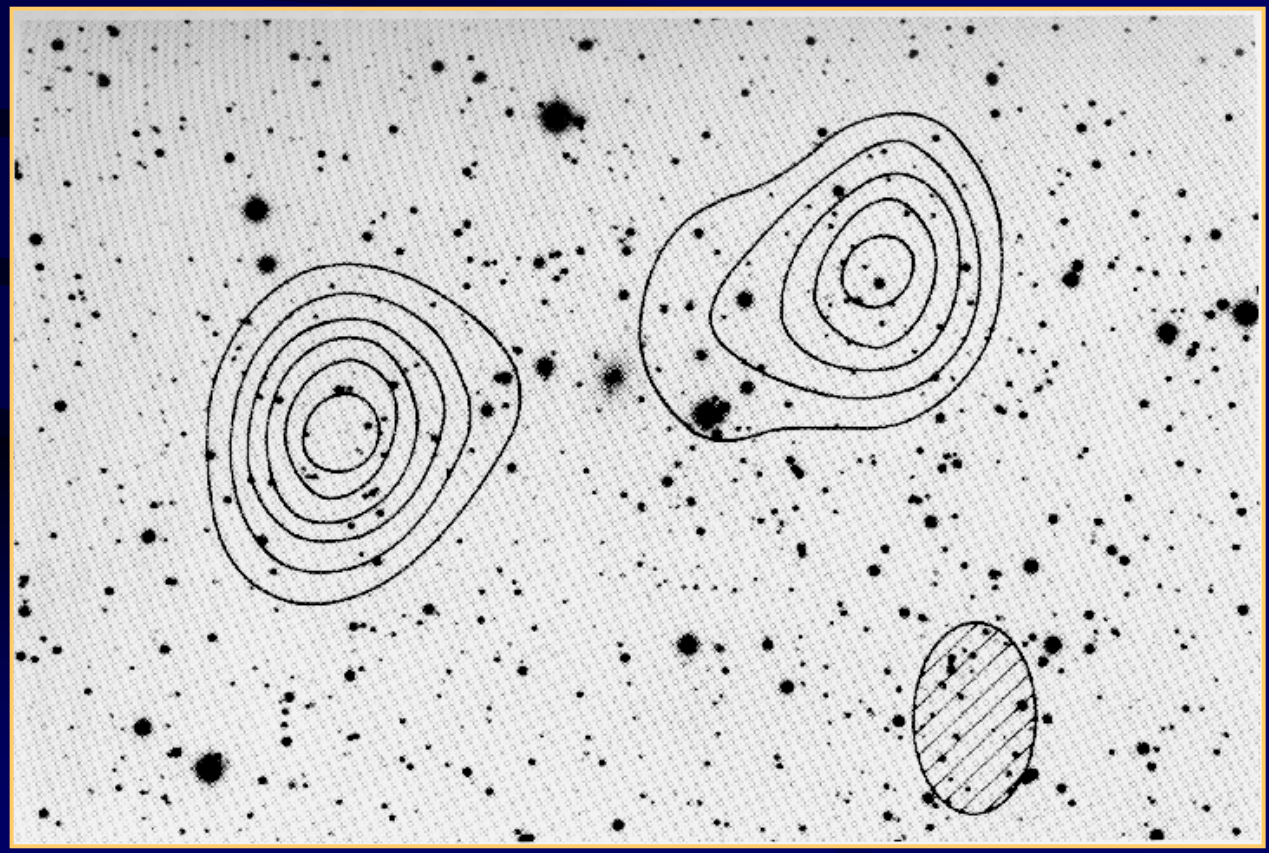
A: The most energetic sources in the Universe!

- $\sim 10^{43}$ erg s^{-1}, primarily from nucleus
  - $\sim 10^{12}$ times the Luminosity of the Sun
  - Cores are very small (recall intraday variability)
  - Continuum emission=synchrotron radiation (Shklovskii, 1953)

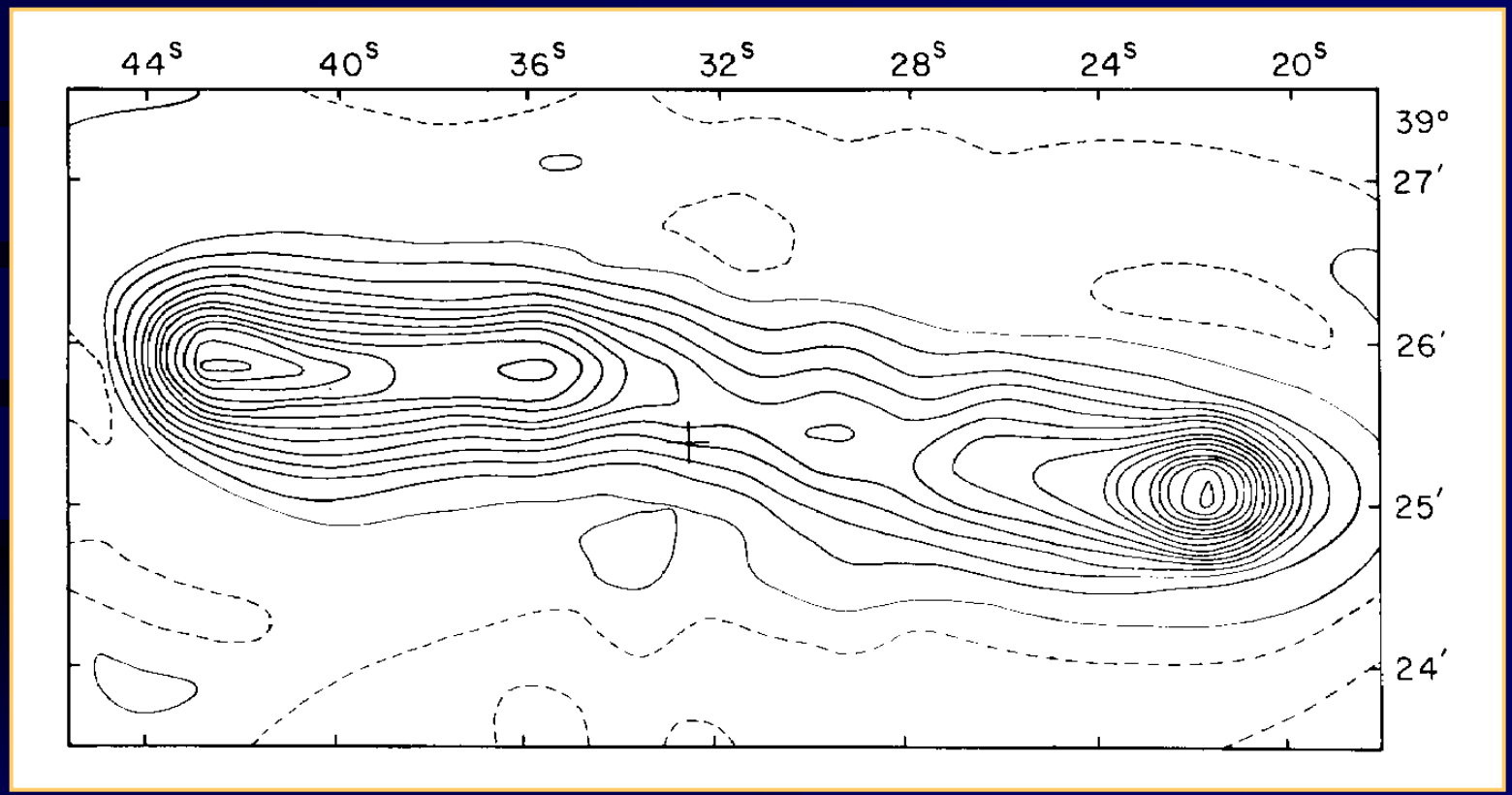
- This can only be a gravitational energy release from an accretion disk feeding a supermassive rotating black hole!
  - Some matter falls in and imparts angular momentum to the black hole
  - Some matter is converted into radiation or fast particles

The Double-lobed Structure of Cygnus A

•Cambridge 3 element, 5 km interferometer used to make first detailed pictures of double radio sources at 1.4 GHz (Ryle et al. 1965)



Hints of Jet Structure in 3C452

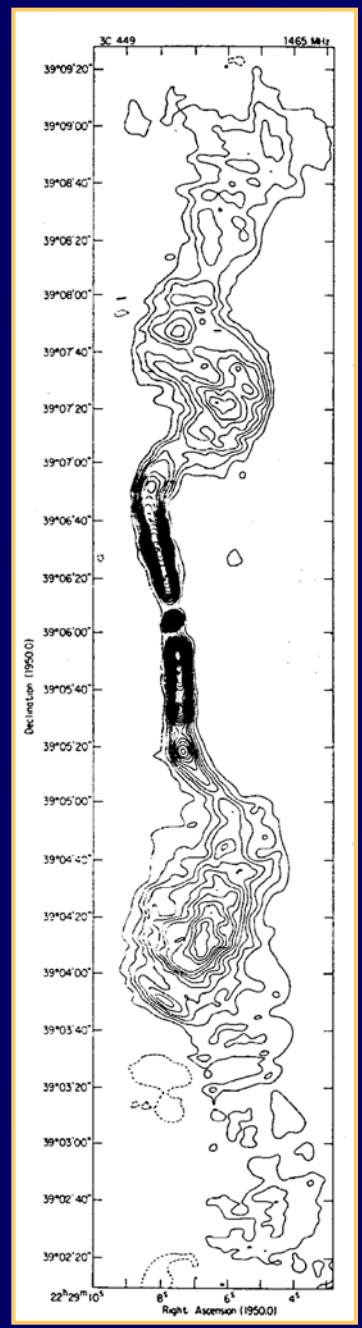


Ryle 1965

Here comes technology again!

- Increased resolution and better instrumentation leads to new source morphologies
- Focus turns to JETS!

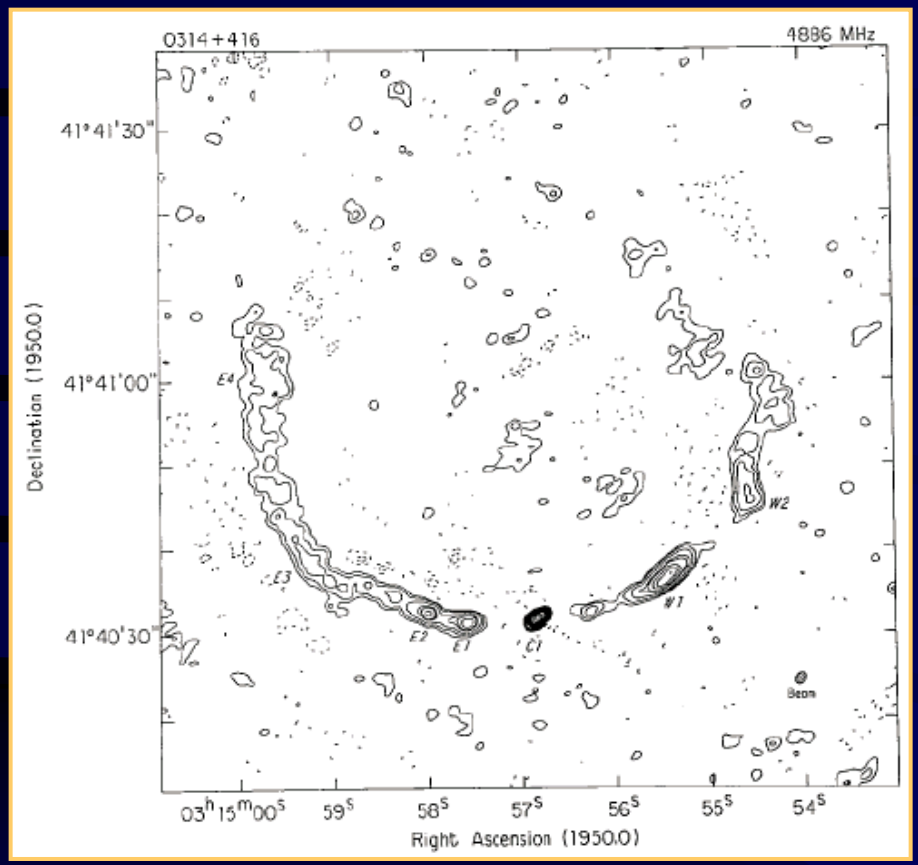
Triple jet structure



3C449 - 1.4 GHz

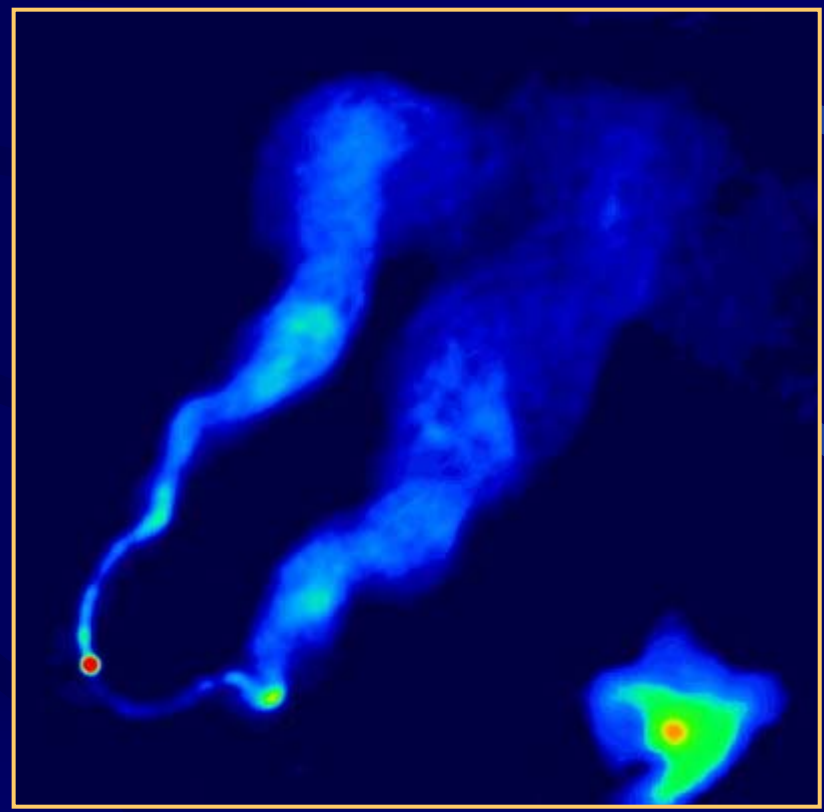
Perley et al. 1979

Highly distorted jets, bent jets

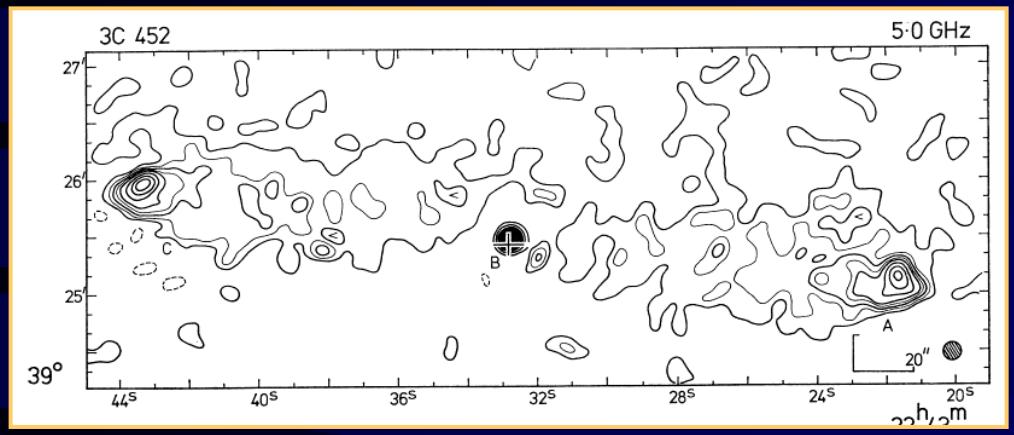


NGC 1265 - Owens et al. 1978

4C26.42 - Taylor



Hot spots discovered within lobes

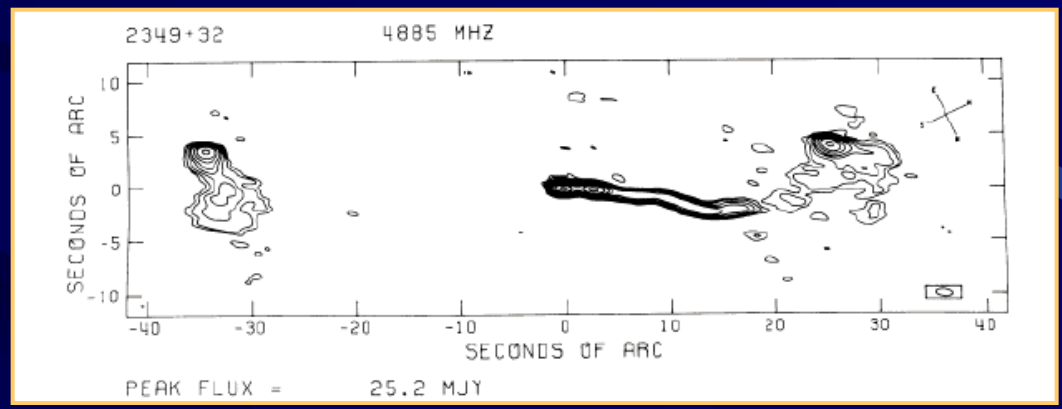


3C452

Riley & Branson 1973

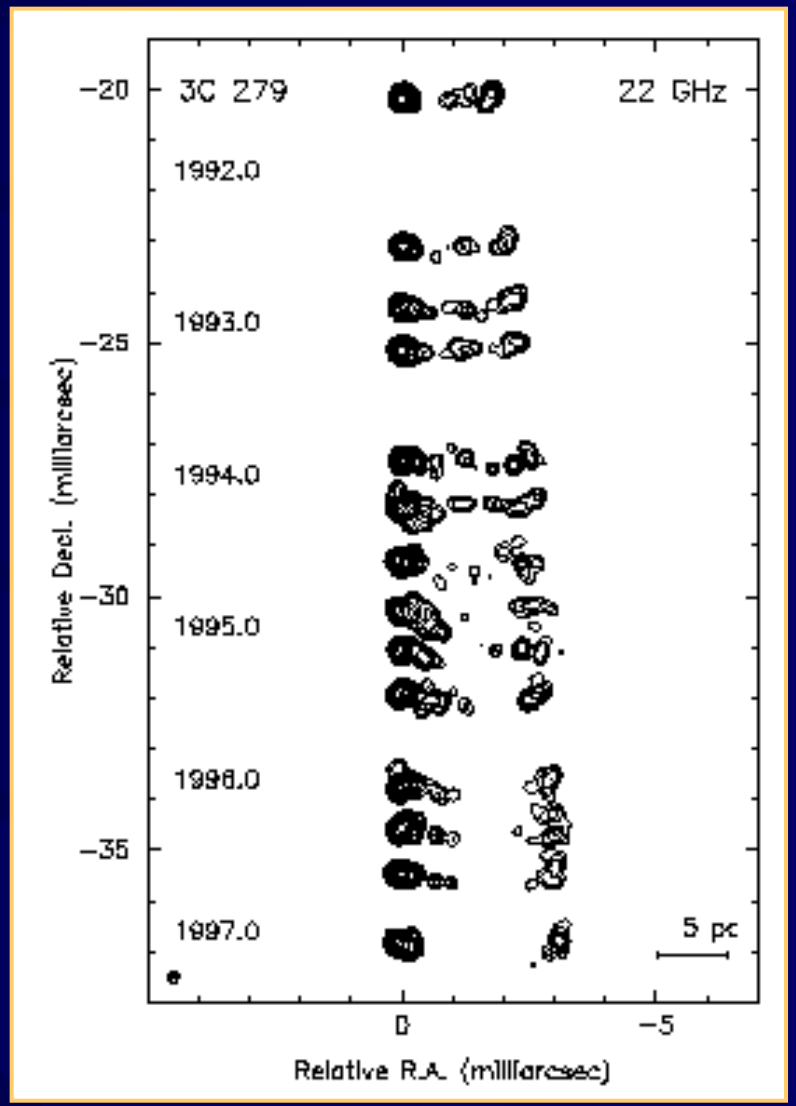
4C32.69

Potash & Wardle 1980



Single sided jets

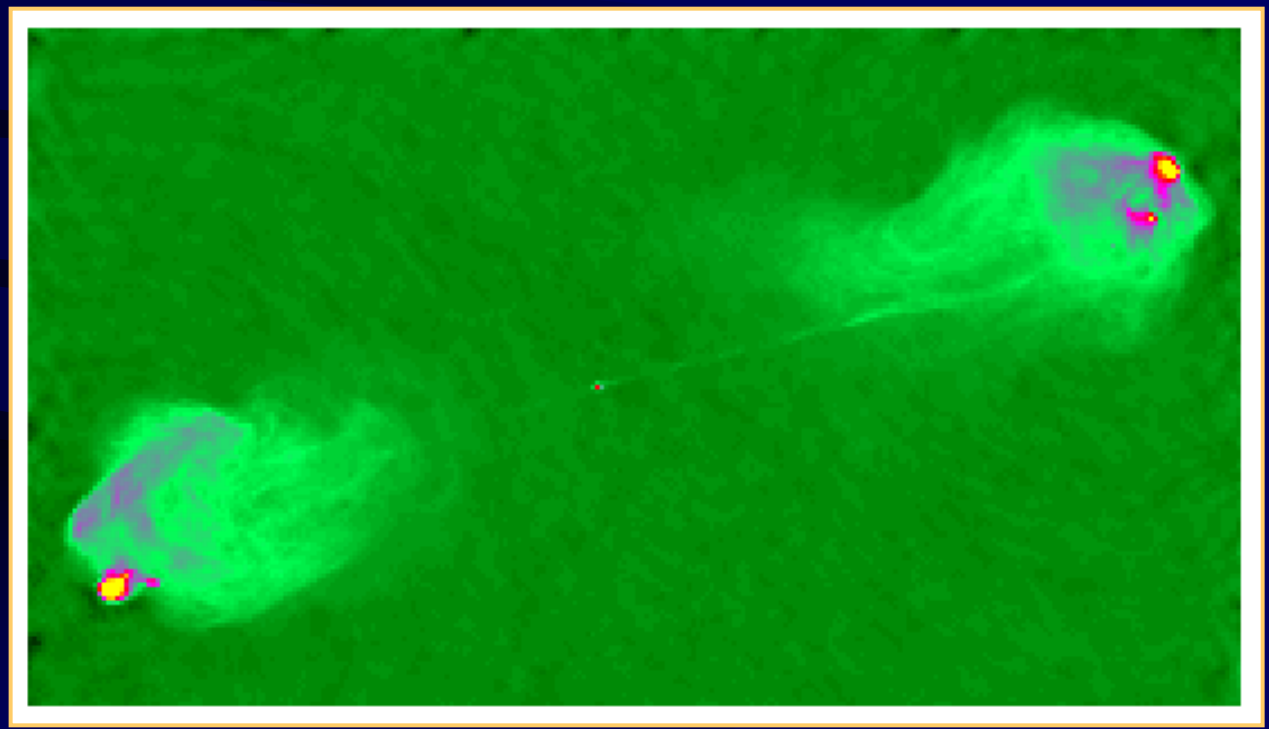
- Superluminal motion - apparent faster than light speeds of components
  - Angle to line of sight - projection effects
  - Relativistic beaming



Unwin 1998

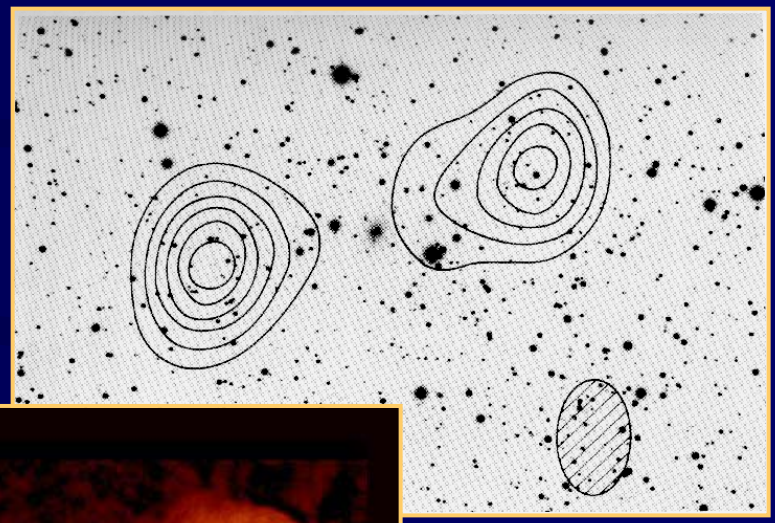
We can do better than this...

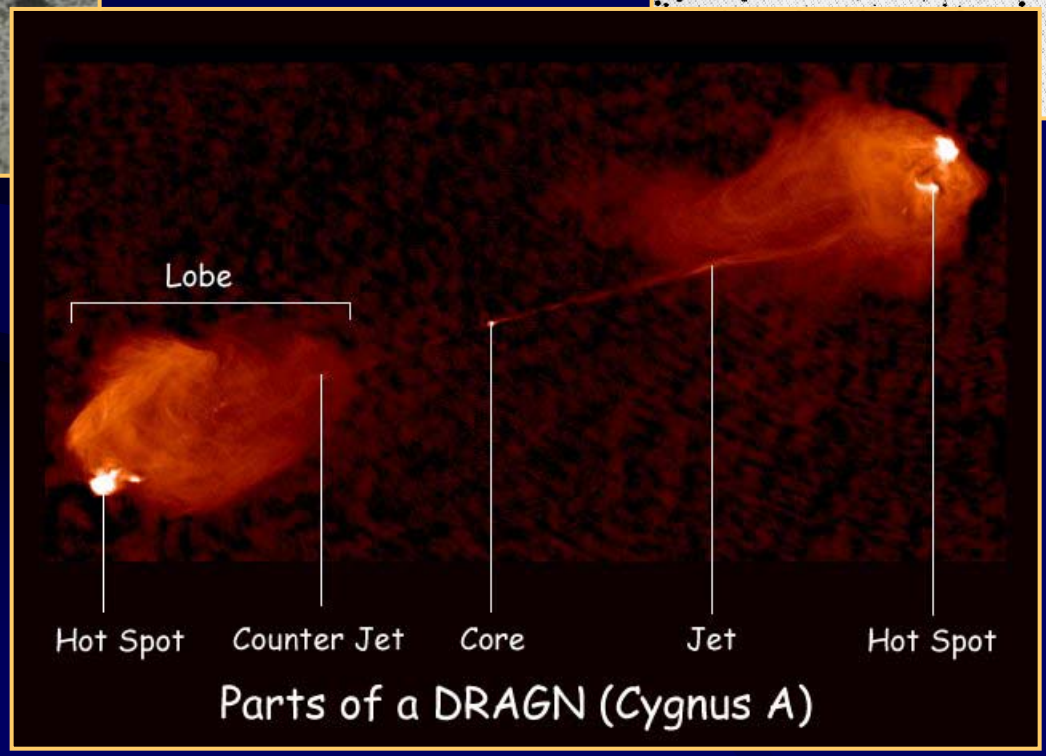
- Imaging gets even better - VLA Cygnus A



Perley et al. 1984

Cygnus A revisited





Double Radio Source Associated with a Galactic Nucleus

Are the sources related?

Optical Classifications

- Seyferts = spiral galaxies (Sey 1s - broad and narrow emission lines; Sey 2s - narrow lines only)
- Radio galaxies (NLRG like Sey 2; BLRGs like Sey 1)
- Quasars are QSOs that emit in the radio (radio-quiet; radio-loud)
- Radio-loud (90% of quasars)
  - OVV variable optical continuum
  - HPQs are OVVs with optical polarization > 3%
  - BL Lacs are HPQs with weak or no emission lines
  - OVVs and BL Lacs are often grouped as Blazars

Radio Classifications

- Core dominated
- Lobe dominated
- Fanaroff-Riley
  - FR I - Diffuse extended structure
  - FR II - Clear hotspots far from the core

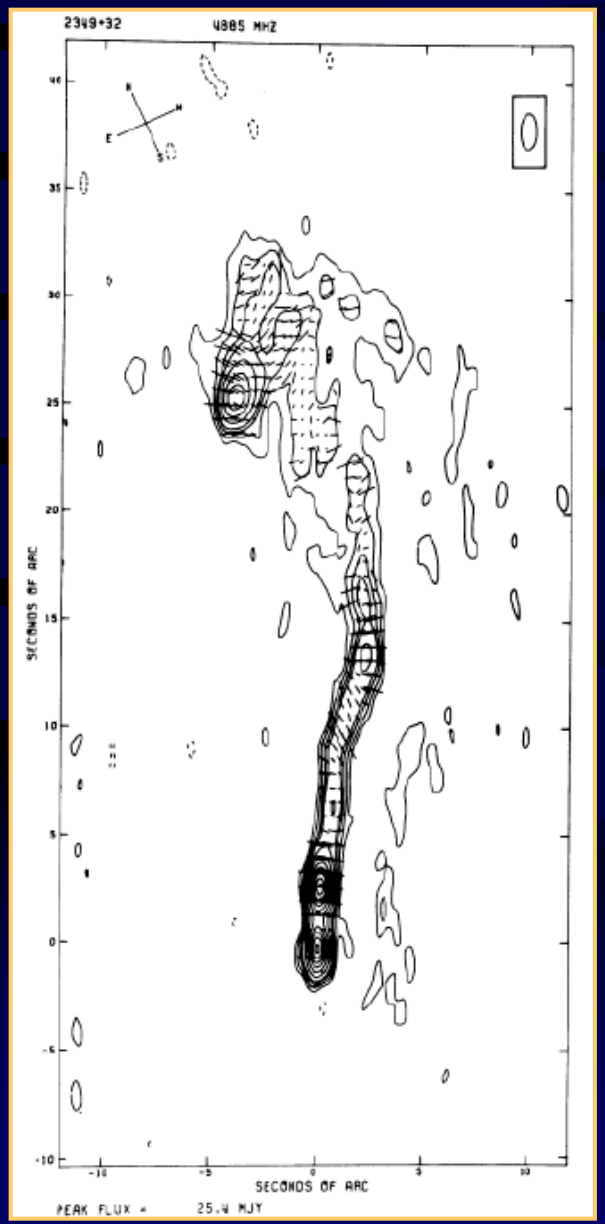
How can we explain all of this?

- Models develop
  - Single outburst creates symmetric lobes
  - Multiple outbursts over time
  - Constant flow
- What about the knots in the jets?

Shocking Models!

- Changing plasma velocities in jets cause internal shocks (Rees)
- Obstacles in jet flow cause shocks (Blandford & Königl)
    - Internal forces such as velocity variations
    - External forces such as clouds of matter which enter the jet
- Quasi-stationary shocks travel at a different velocity than the underlying relativistic jet (Lind & Blandford)
- Irregularities are illuminated by highly relativistic shocks moving down the jet (Qian)
- Shocks originate in AGN cores and propagate down the jet as superluminal components (Zhang)
- "Shock-pair" = a forward and reverse shock exist (Marscher)
- "Piston-driven" shock = knots move through areas of different optical depths causing shocks (Hughes, Aller & Aller)

Can polarization mapping help?

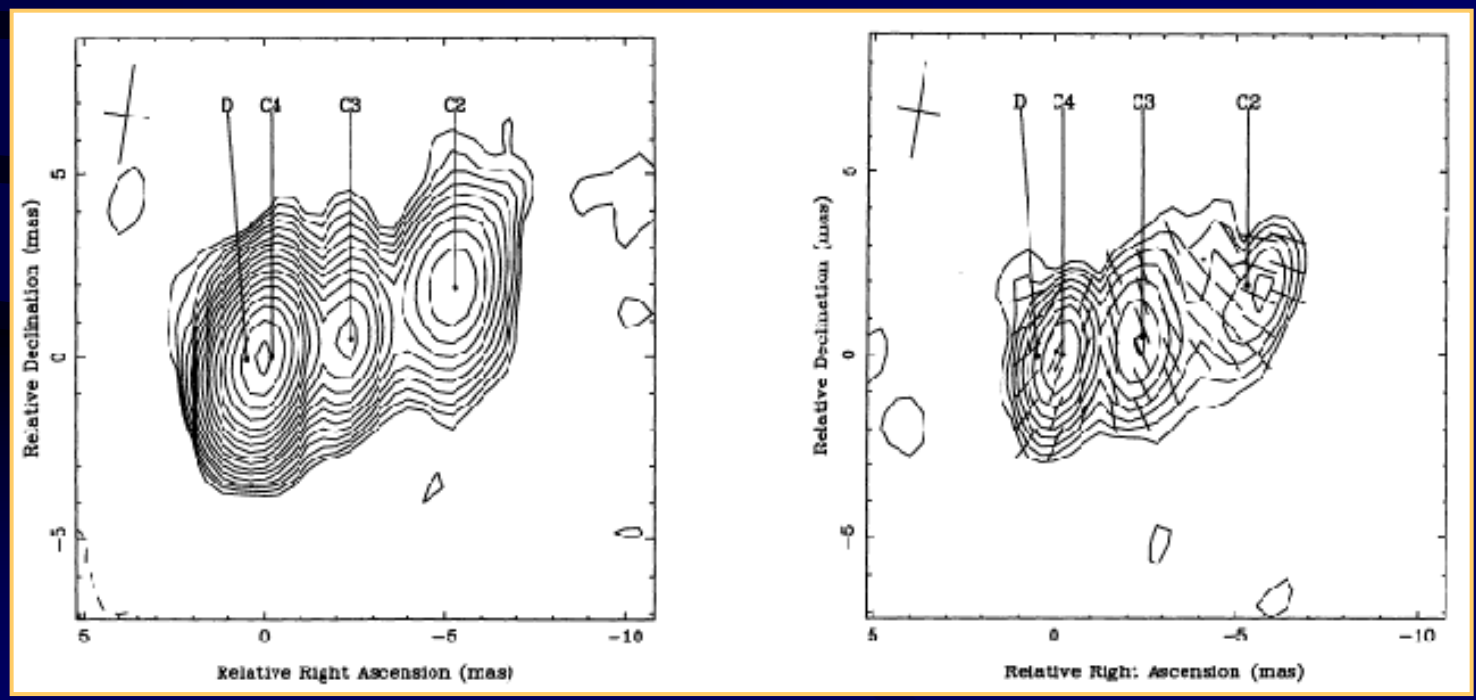


- Polarization imaging traces the jet flow
- Modeling begins in the 1990s
  - Witzel - Variable emission is caused by **B** field compression and particle acceleration produced by a passing shock
  - Aller, Aller & Hughes - Piston-driven shocks compress an initially tangled **B** field transverse to jet axis

4C32.69 - 4.8 GHz E-vectors

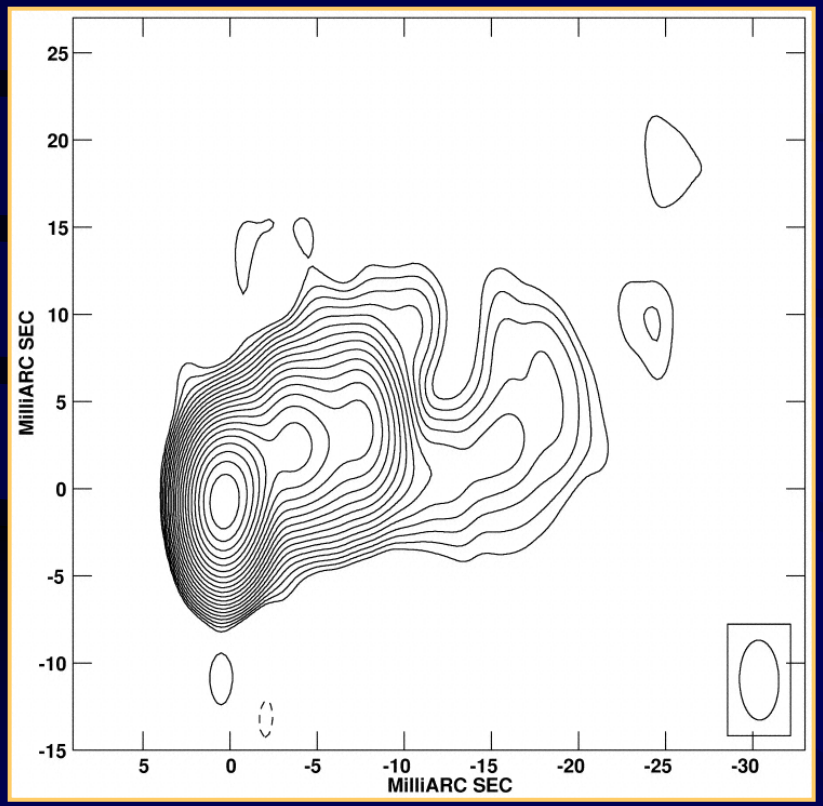
Potash & Wardle 1980

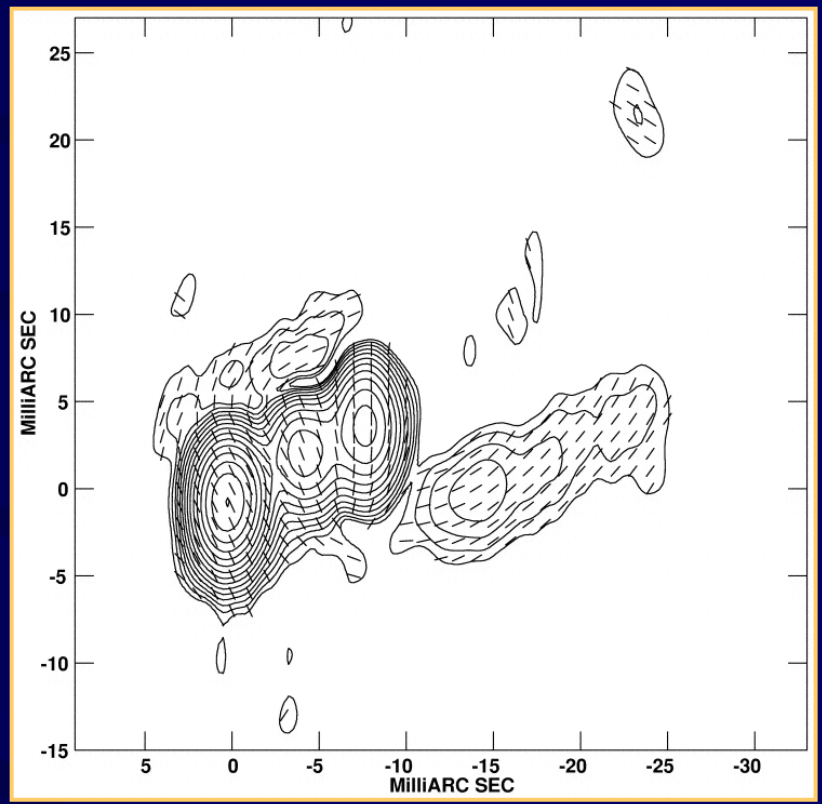
- Brandeis VLBP group
  - Strong-lined sources have magnetic fields oriented longitudinally with jet axis (e.g. 3C345)
    - Shear stretches the field, weak shocks add transverse component to longitudinal jet
    - Electric vectors shown



4.8 GHz - *Brown et al. 1994*

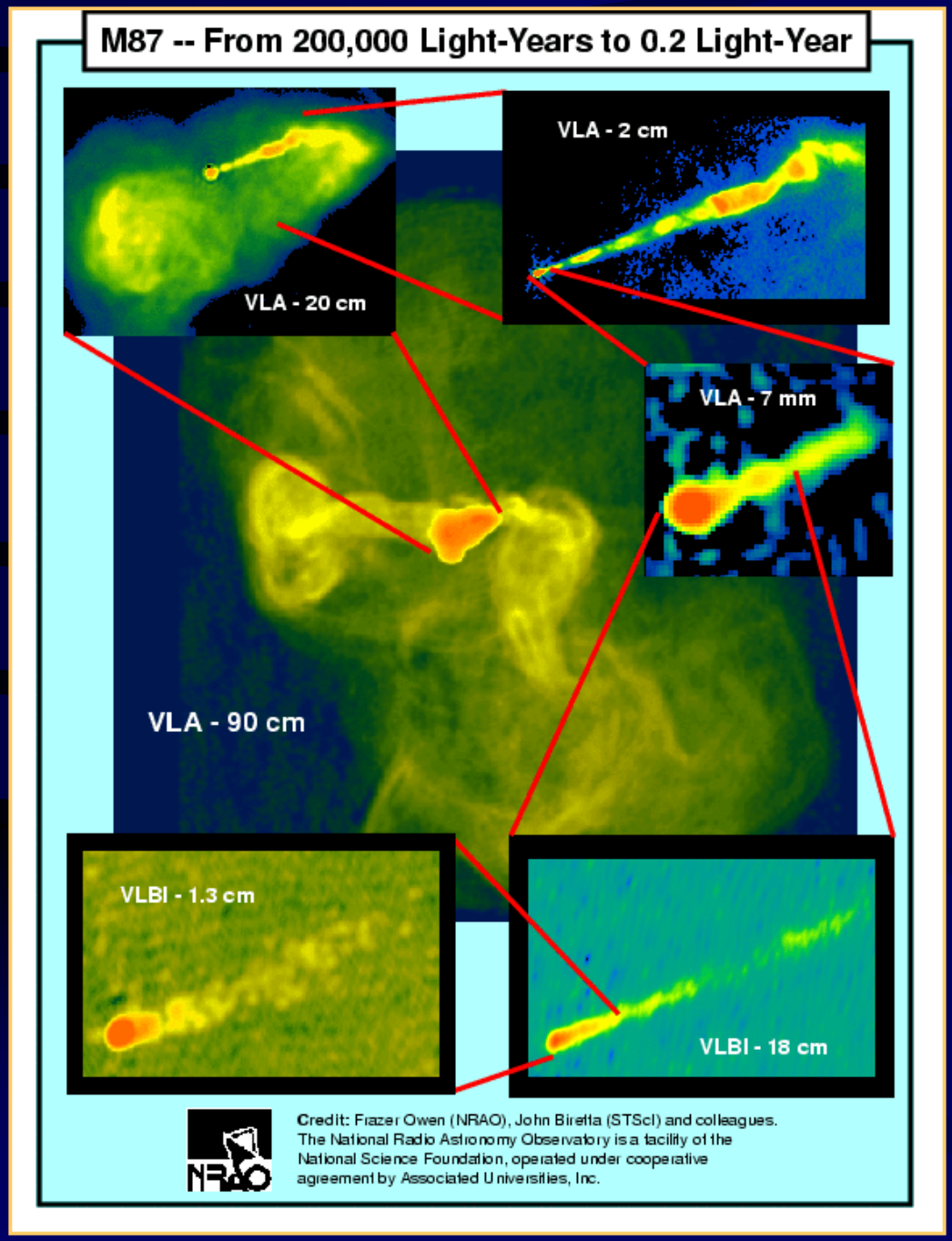
- Weak-lined sources have magnetic fields oriented transverse to jet axis (e.g. 1055+018)
  - Strong shocks compress field
  - Magnetic vectors shown





4.8 GHz - *Attridge et al. 1999*

…so polarimetry simply added another layer of questions.

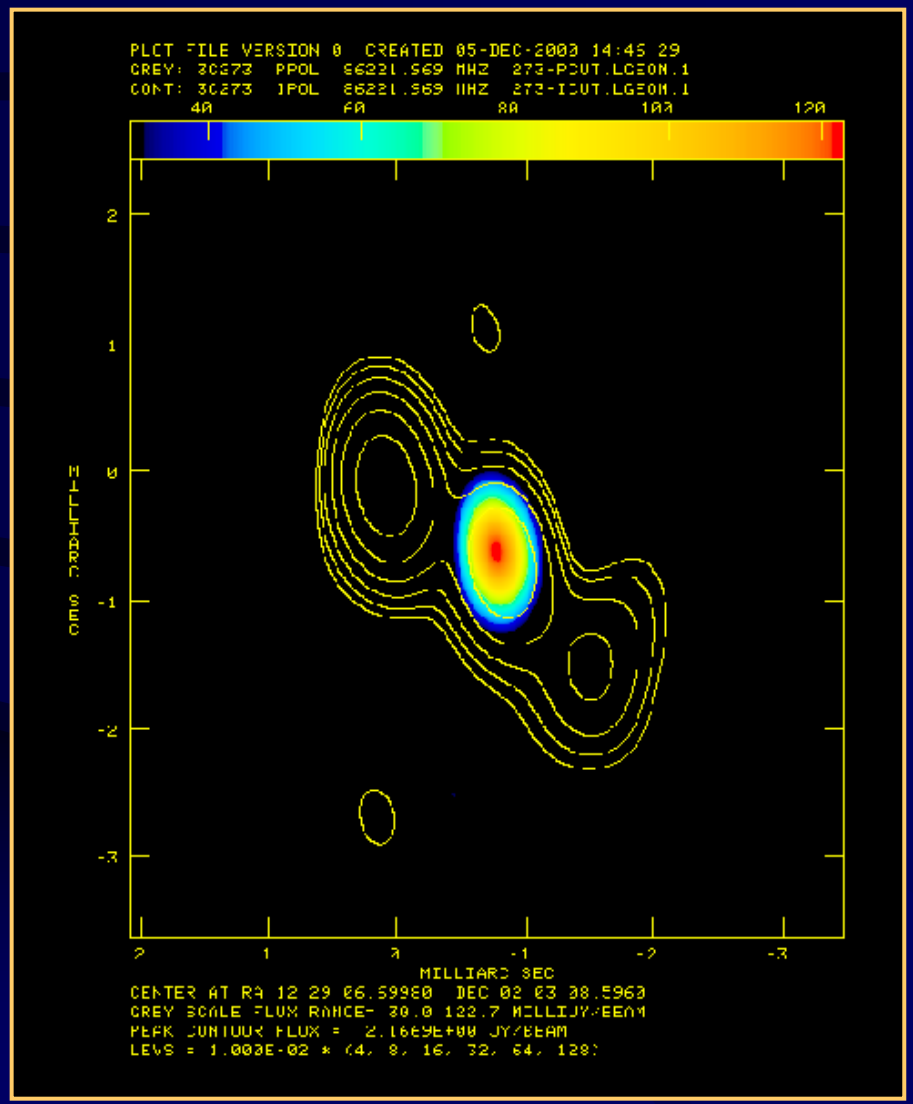


Where do we go from here?

VLBI at higher frequencies!

Don’t forget where we started!

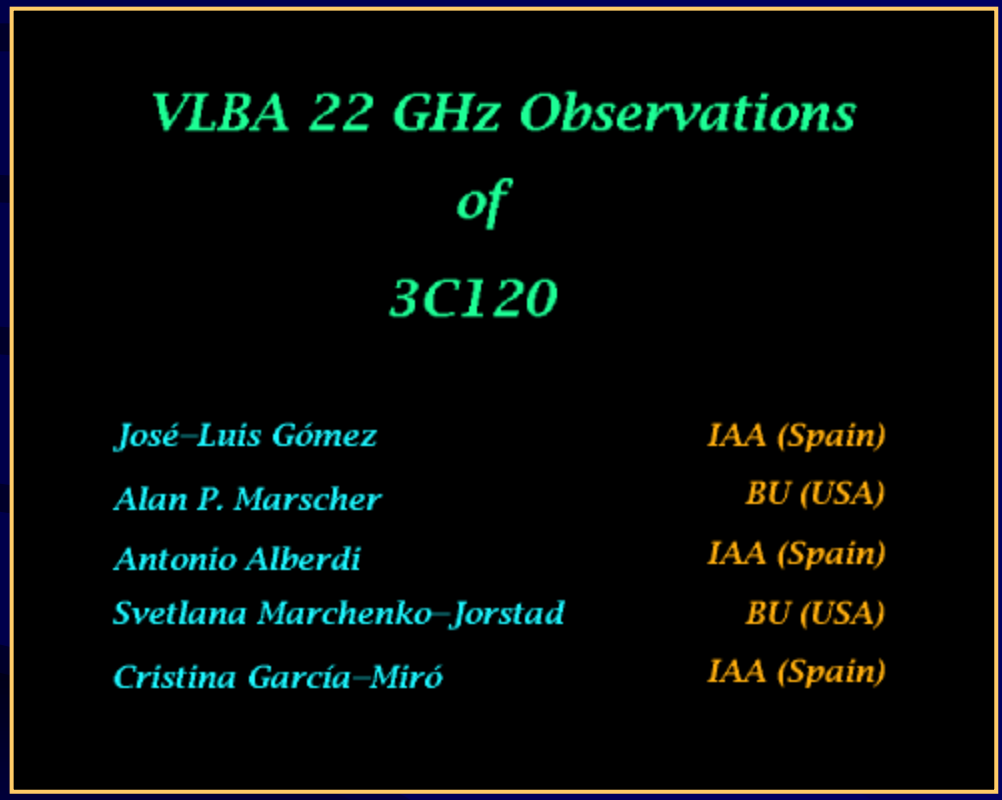
VLBP at High Frequencies



3C273 at 3mm

Attridge 2001

Movies!


VLBA 22 GHz Observations
of
3C120
José–Luis Gómez
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Alan P. Marscher
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