A Spectral Index Study of the Jets in MOJAVE

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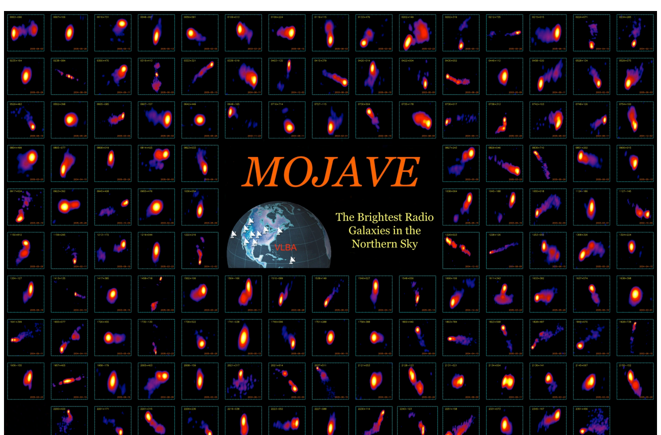

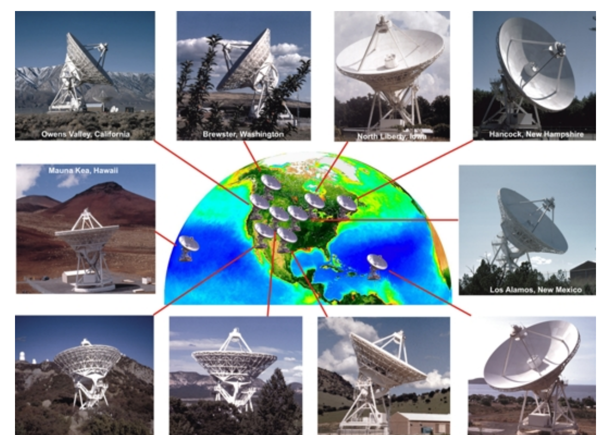

MOJAVE Collaboration

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- M. and H. Aller (Michigan)
- M. Cohen (Caltech)
- D. Homan (Denison)
- T. Hovatta, T. Savolainen (Aalto U.)
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- P. Kharb (Indian Institute of Astrophysics)
- K. Kellermann (NRAO)
- Y. Kovalev (ASC Lebedev)
- A. Pushkarev (Crimean Astrophysical Observatory)

Monitoring
Of
Jets in
Active Galaxies with
VLBA
Experiments

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Outline

- Motivation
- Sample and data
- Spectral index in the cores
- Spectral index in the jets
- Spectral evolution along the jets
- Summary

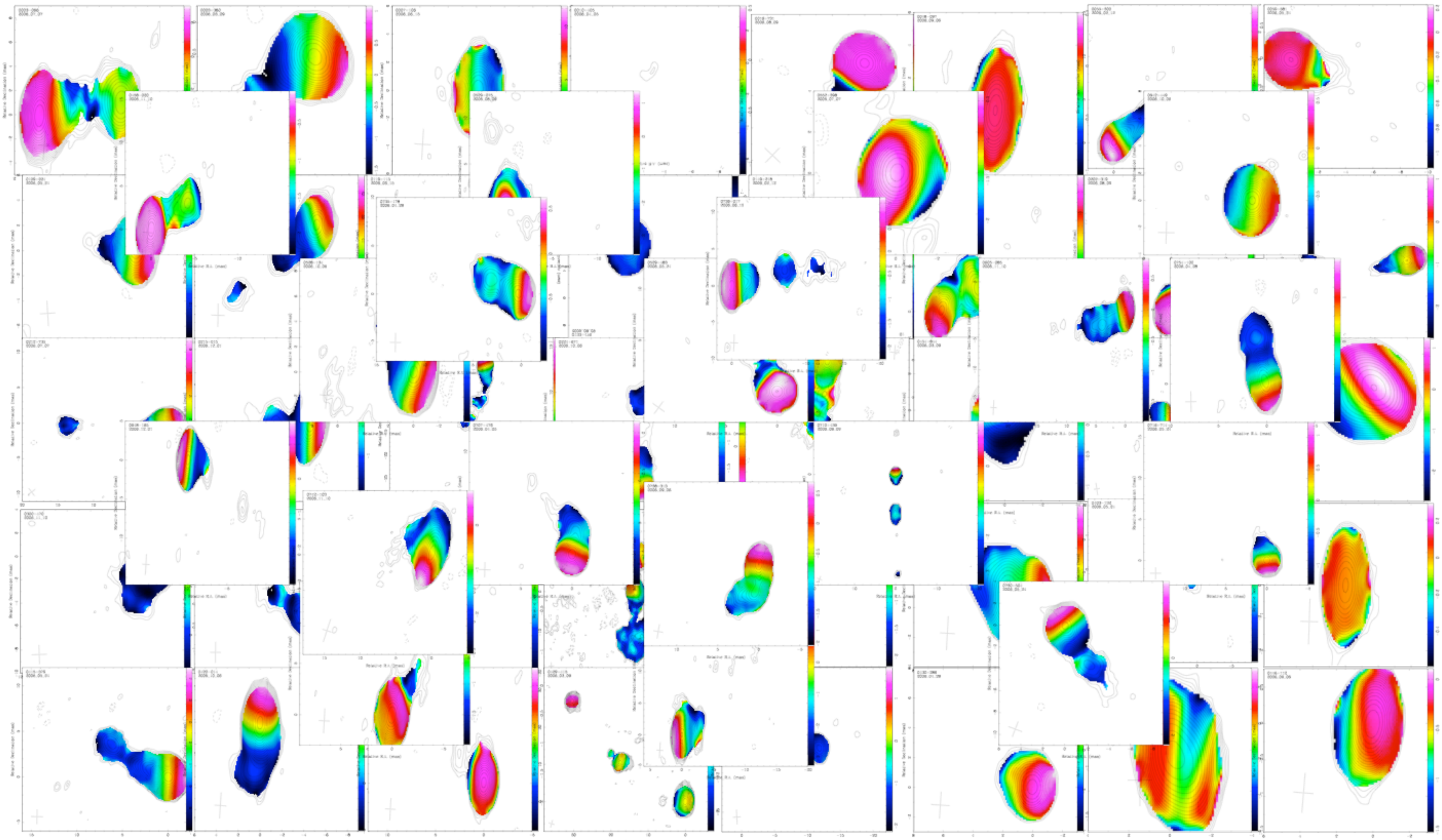
Motivation

- Studying the spectral distributions in AGN jets can tell us about the physical conditions in the jets
  - If the emission is produced by a power-law distribution of electrons $N(E) = N_0E^{-p}$, the optically thin spectrum can be described as $I_\nu \propto \nu^\alpha$, where $\alpha=(1-p)/2$
- Despite numerous studies of the spectra of (mainly) individual AGN since the 1960's, there are not many systematical studies using VLBA images of the parsec-scale jets
- MOJAVE multiwavelength dataset from 2006 is ideal for this

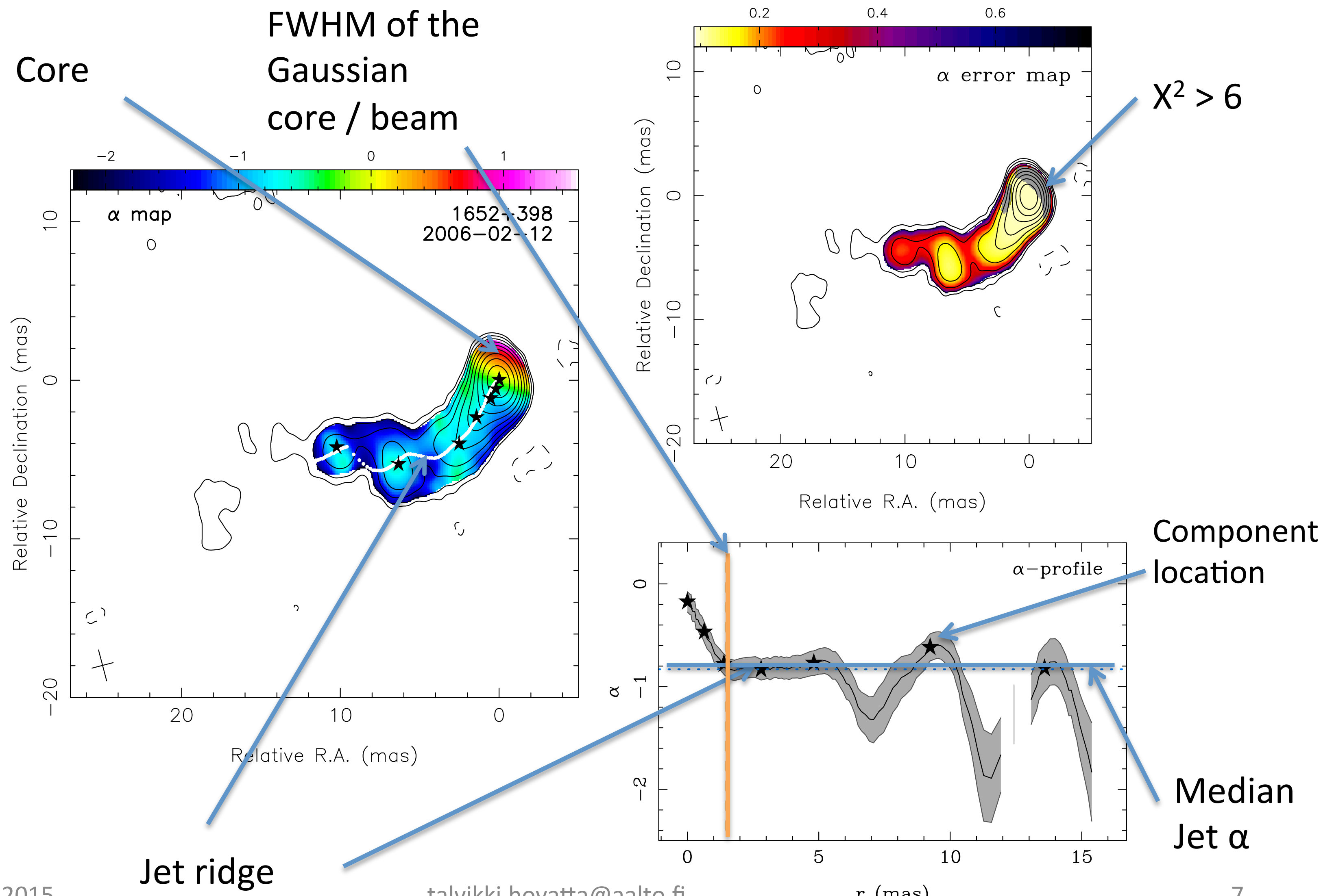
Sample and data

- Observations in 2006 with the VLBA within the MOJAVE program
- 191 objects in total
  - 133 flat-spectrum radio quasars (FSRQs)
  - 33 BL Lac objects
  - 21 radio galaxies
  - 4 optically un-identified objects
- Four frequency bands 8.1, 8.4, 12.1 and 15.4 GHz
- Spectra are calculated by fitting a power law to the total intensity data
- All of the following results are presented in Hovatta et al. 2014 (MOJAVE XI, AJ, 147, 143)
  - Same dataset has been used to study Faraday rotation (Hovatta et al. 2012) and core-shift effect (Pushkarev et al. 2012)

Spectral index maps



Some definitions



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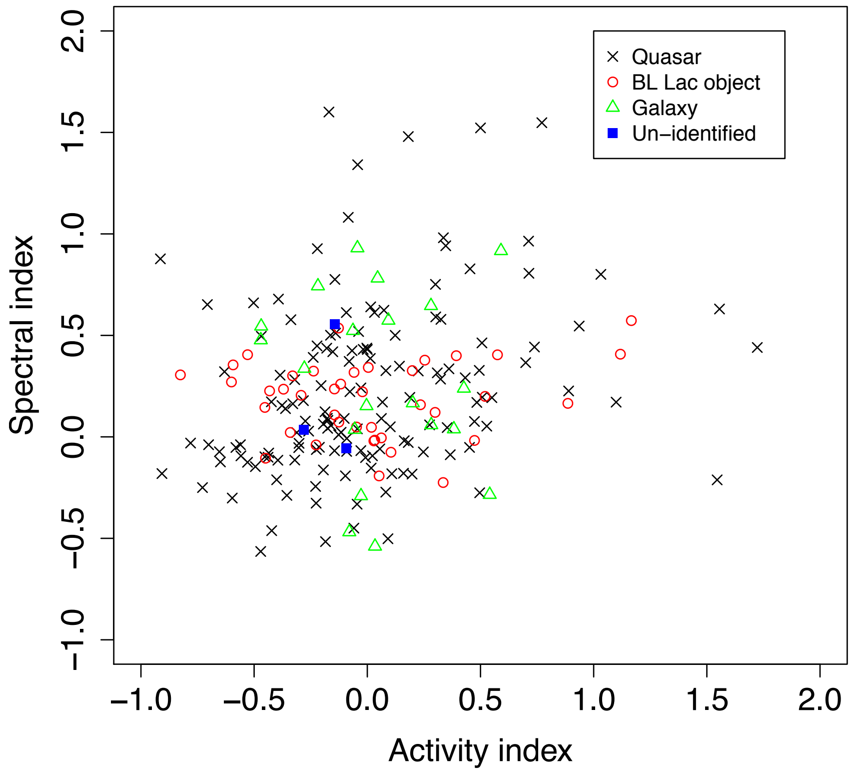
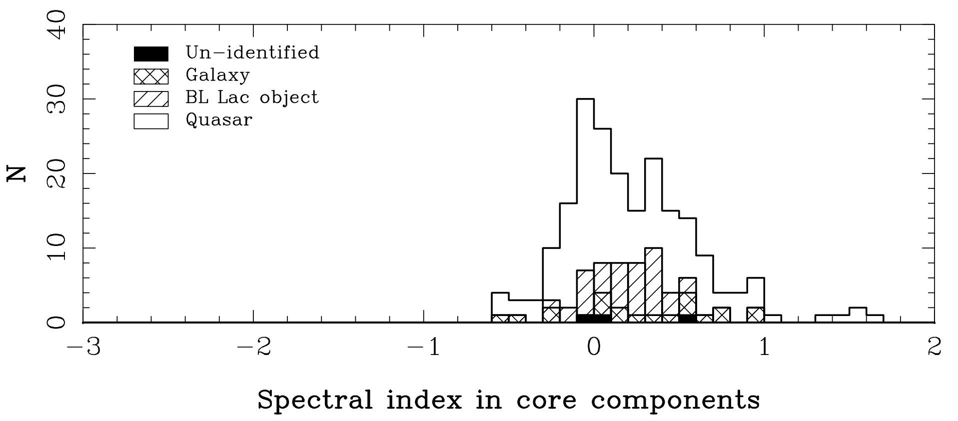
Spectra of the cores



$$V = \frac{S - <S>}{<S>},$$

- Spectra of most core components are flat with a mean at 0.2
- More inverted spectra are in objects that are flaring



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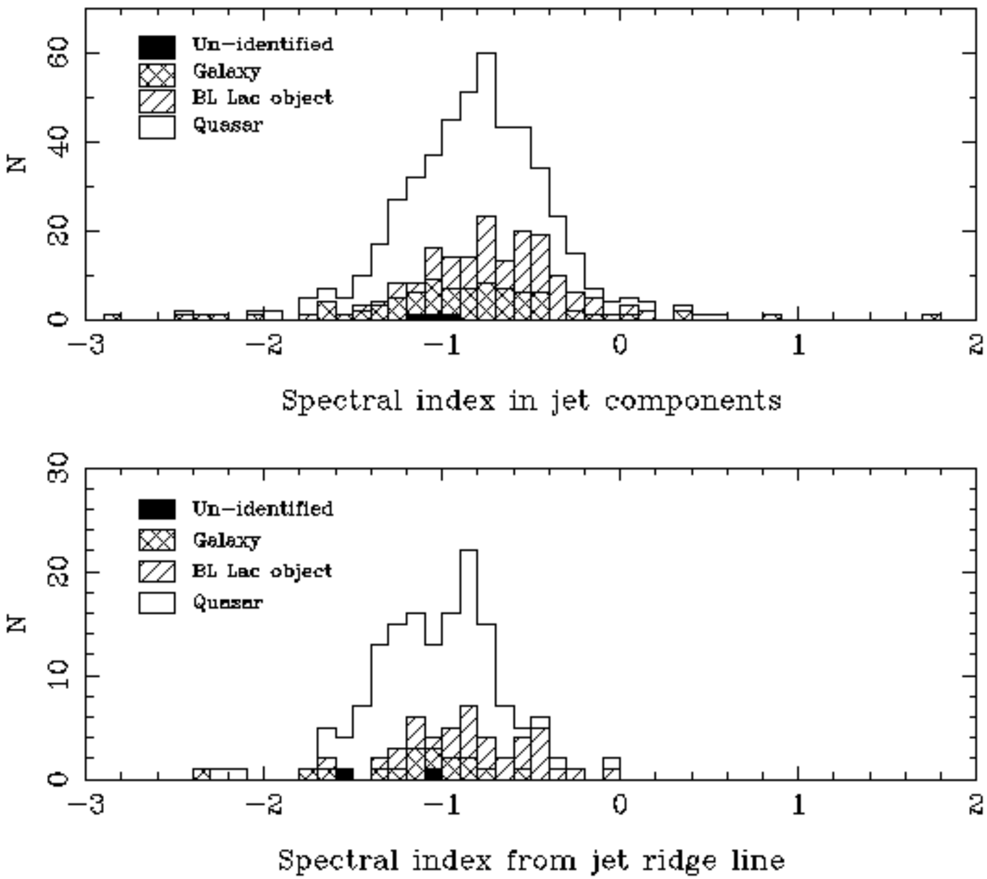
Distribution of spectral index in the jets

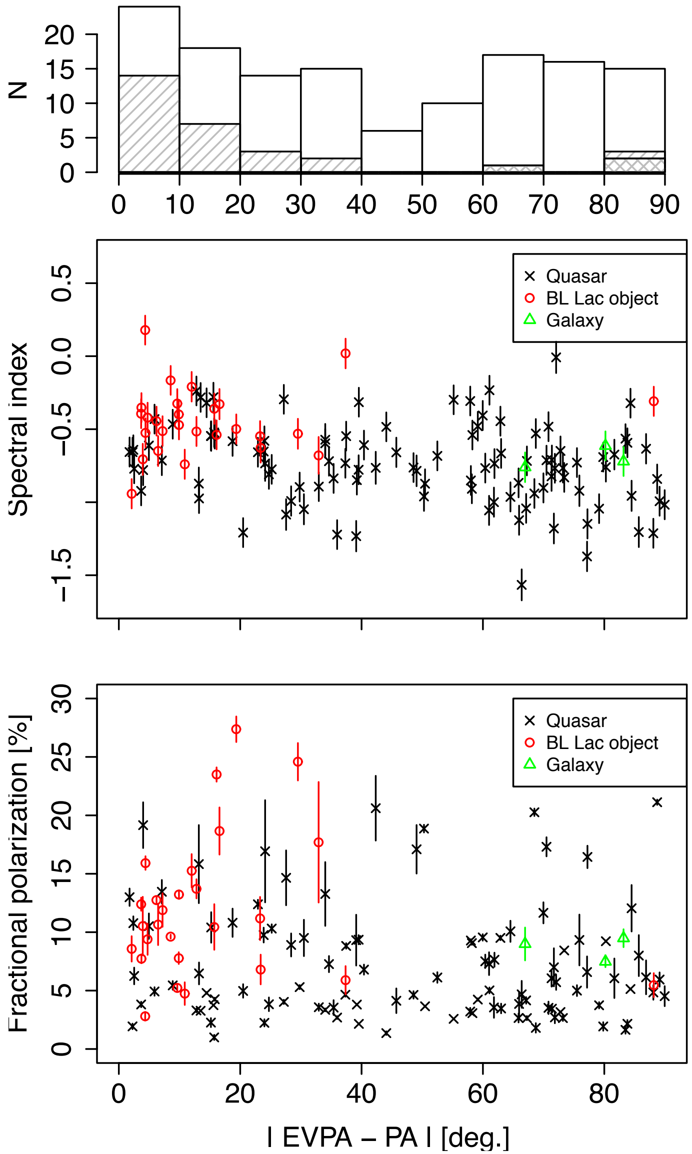


- Power law works for > 90% of the jet components
- Two interesting notes:

1. The spectra is flatter at component locations (mean -0.81) than the median value on the jet ridge (mean -1.04)

2. BL Lacs have on average flatter spectra (mean -0.64) compared to FSRQs (mean -0.85)

Difference between FSRQs and BL Lacs



- In BL Lacs the polarization of the components is more aligned with the local jet direction than in the FSRQs
- The overall trend of flatter spectra with smaller alignment is consistent with shocks in jets
- BL Lac components have higher polarization fractions, indicative of jets with more shocks
- Our results are consistent with single-dish observations by the UMRAO group (Aller et al. 1999, Hughes 2005, Aller et al. 2003)

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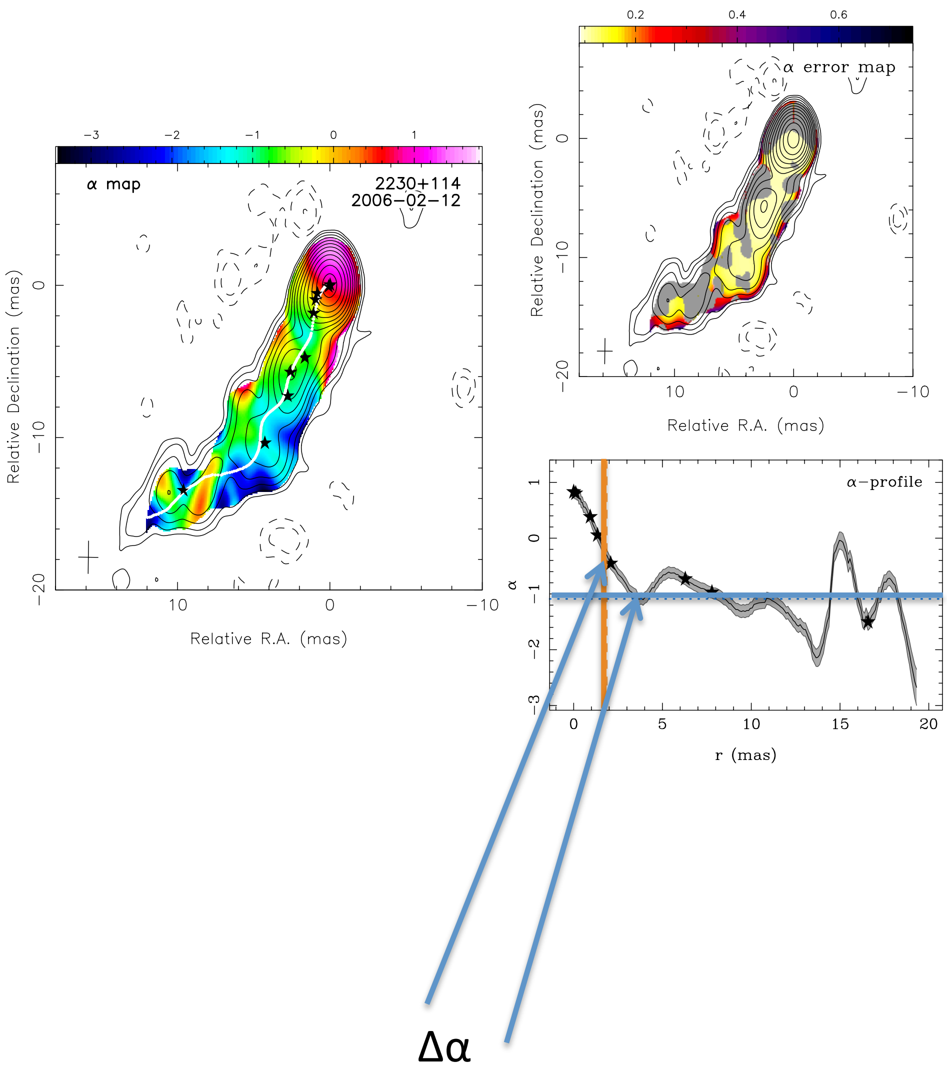
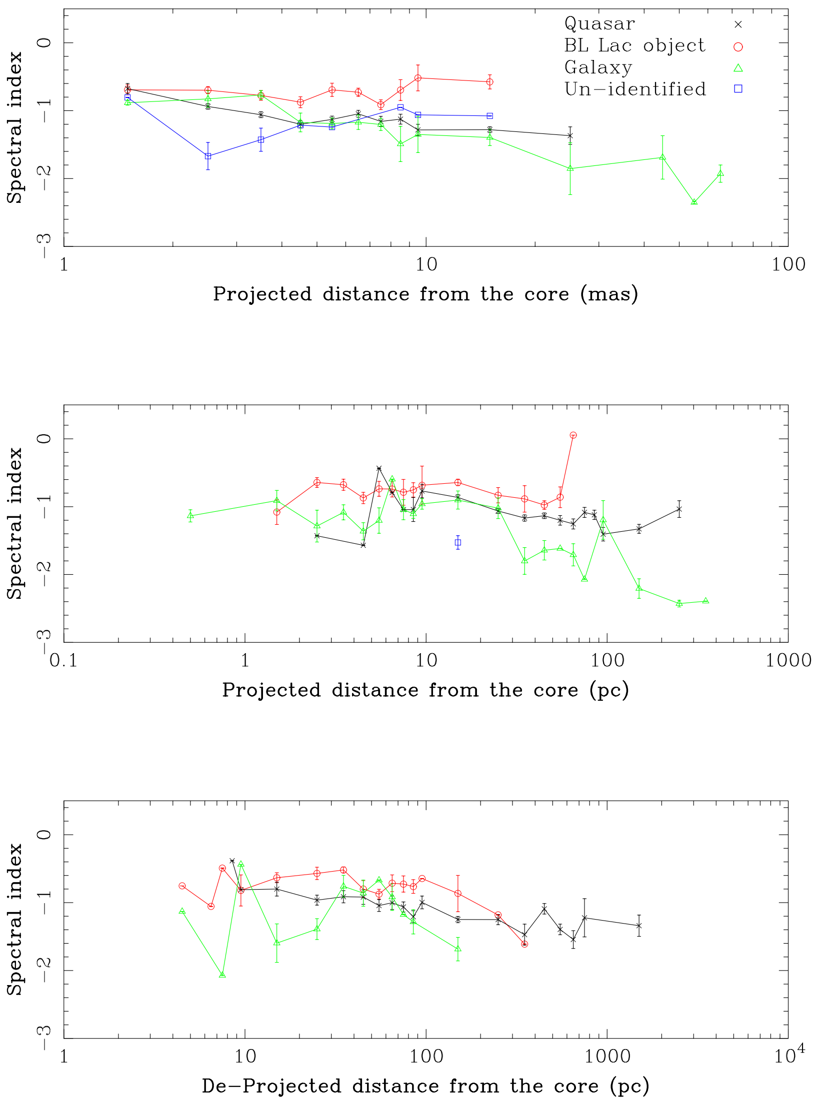
Spectral evolution

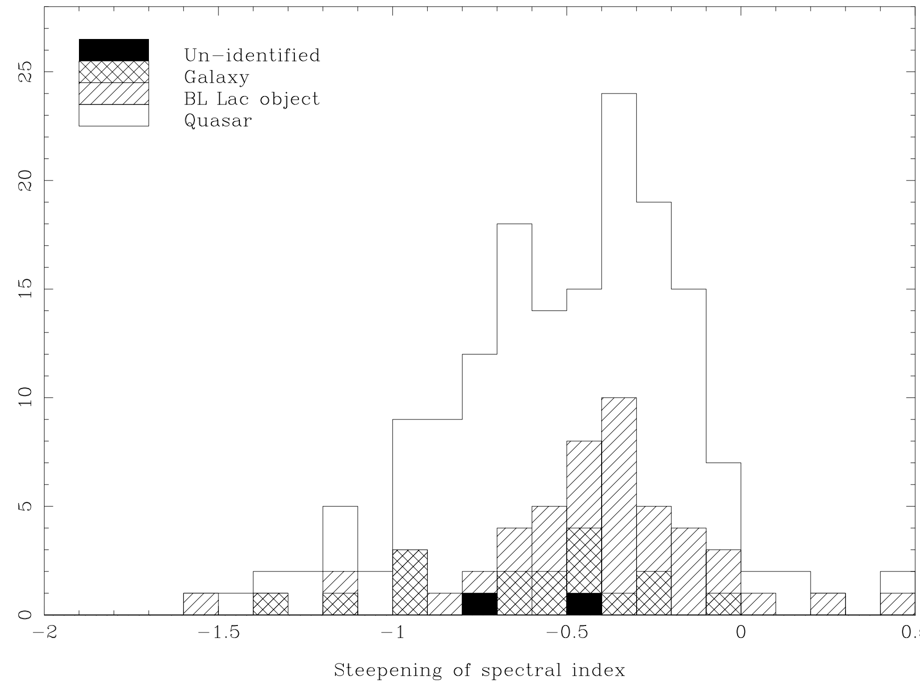


- There are several ways to study the evolution of the spectral index

1. Study the spectral index as a function of distance along the ridge
2. Compare spectral index close to the core and the median of the jet
3. Study the spectral index as a function of age (unique to MOJAVE-type monitoring)

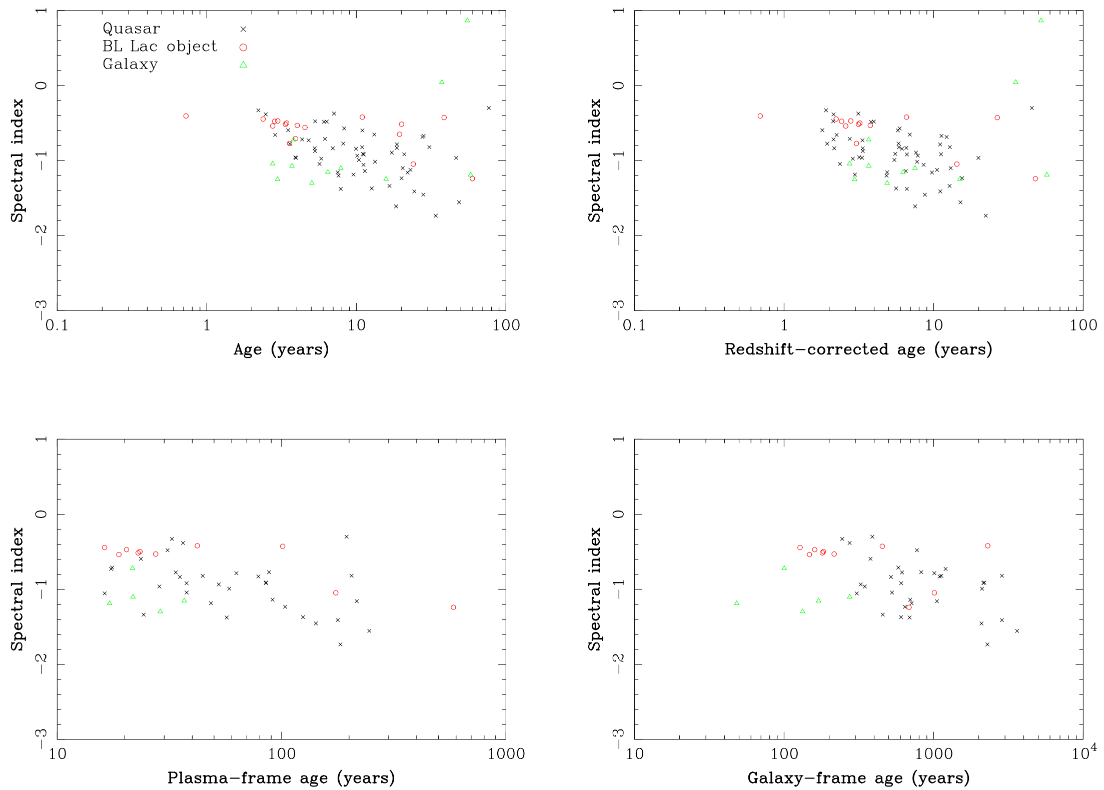
Spectral index steepening





- There is a significant negative trend in the binned ridge line spectral index vs. the distance along the jet
- Spectra steepen on average by -0.45 when comparing values at the edge of the core and end of the jet

Spectral index vs. age



- Age of the component calculated from the ejection epoch determined from MOJAVE monitoring data
- Older components have steeper spectra

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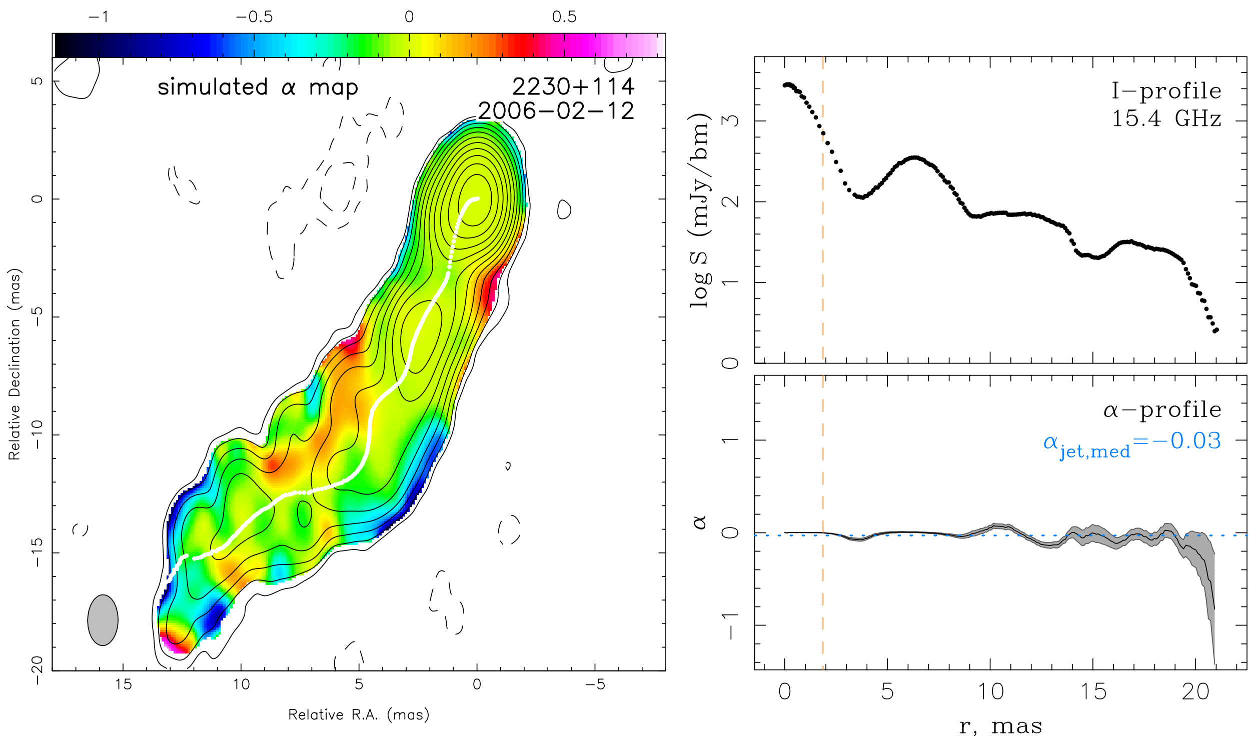
Interpretation of the steepening

- Several alternatives can explain the steepening of the spectra as a function of distance and/or age:

1. Observational effects, such as the (u,v) coverage
2. Radiative losses i.e. a synchrotron cooling break (Kardashev 1962)
3. Evolution of the maximum Lorentz factor of the electron distribution γ_{max}
4. Changes in the particle acceleration process

1. Observational effects



- Detailed simulations show that changes in the (u,v) coverage between the frequency bands can only explain a steepening of -0.1

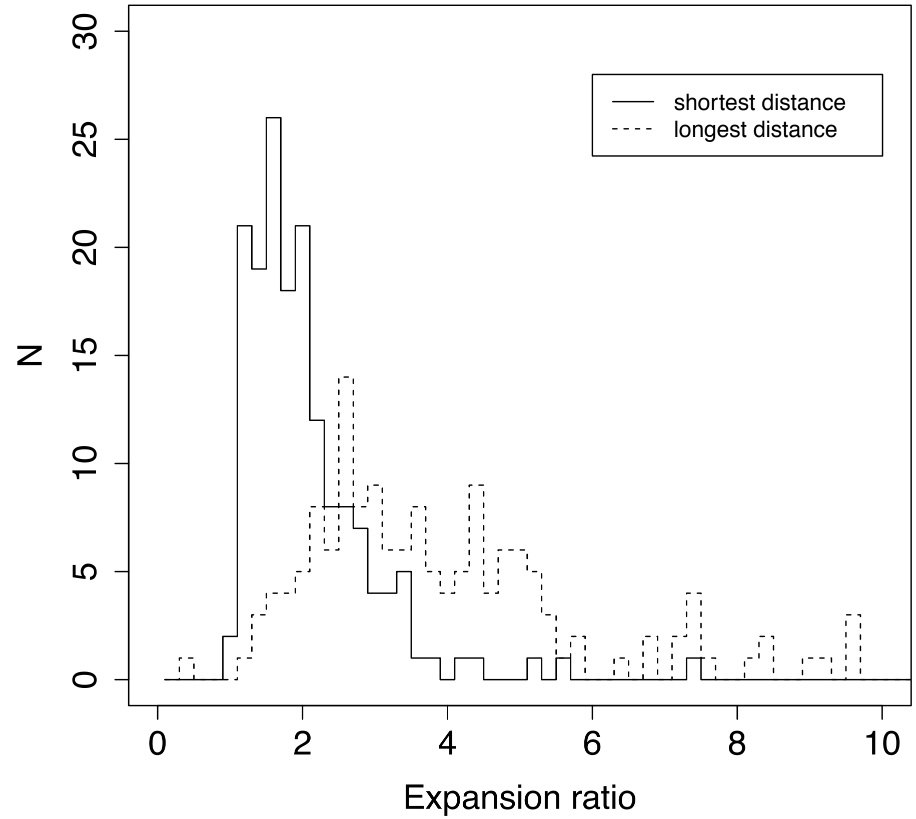
=> The steepening is mostly intrinsic to the jets

2. Radiative losses

- Synchrotron losses introduce a break of -0.5 in the spectrum (Kardashev 1962)
- If the jet is *collimating,* the break frequency moves to a *lower* frequency as the component ages, steepening the spectra by -0.5
- If the jet is *conical,* the break frequency moves to a *higher* frequency and cannot explain the steepening we see
- Several recent studies indicate that jets on parsec-scales are conical (Jorstad et al. 2005, Pushkarev et al. 2009, Clausen-Brown et al. 2013), but collimating jets cannot be ruled out.

3. Evolution of γ_{max}

- *If no injection occur*, γ_{max} decreases in time due to radiative and adiabatic losses
- Steepening of -0.5 can be explained if the components expand by a modest factor as they move down the jet
- This works for conical jets



4. Change in particle acceleration

- If the power-law index of the underlying electron distribution changes, so does the observed spectrum
  - This could be due to time evolution of the distribution of the pre-accelerated particles
  - Due to the particle acceleration process itself
  - Or some other acceleration related process
- None of these are easily testable and cannot be ruled out

Summary

- Spectra of the cores is nearly flat with a spectral index of 0.22. Flaring sources show more inverted spectra.
- The jet spectral index in FSRQs (mean -0.85) is significantly steeper than in the BL Lacs (-0.64), which can be explained with BL Lac jets having more shocks
- The spectra flattens at component locations and there is a significant correlation between the polarization direction and spectra, further indicating shocks in jets
- The jet spectra steepen on average by -0.45, which can be explained with radiative losses if the jets are collimating or with time evolution of γ_{max} if the jets are conical