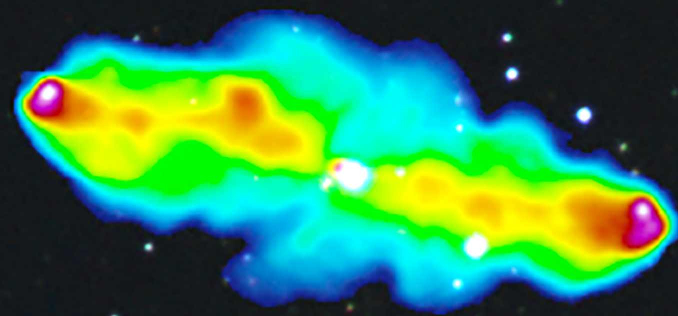
FR II Radio Galaxies at Low Frequencies

Jeremy Harwood



The broad impact of low frequency observing

Bologna, June 2017

Collaborators:

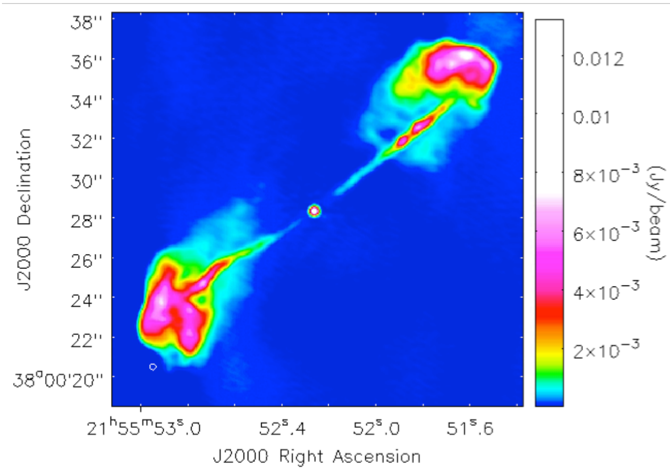
R. Morganti (ASTRON) M. Hardcastle (Hertfordshire) J. Croston (Southampton) E. Orru (ASTRON) A. Stroe (ESO) H. Intema (Leiden)
V. Heesen (Southampton) J. Ineson (Southampton) A. Shulevski (ASTRON) M. Brienza (ASTRON) & the LOFAR nearby AGN KSP team

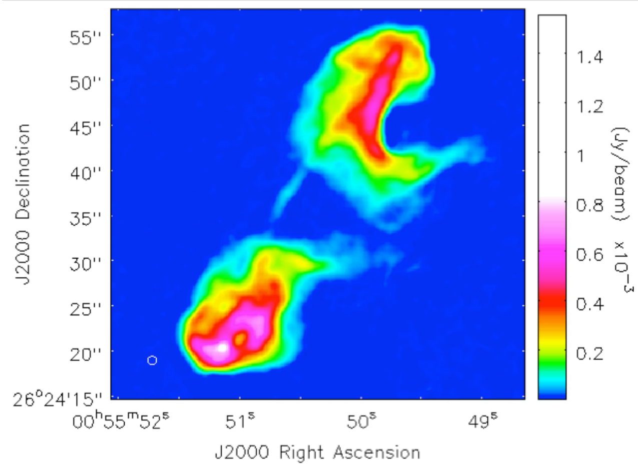
ASTRON
Netherlands Institute for Radio Astronomy

LOFAR

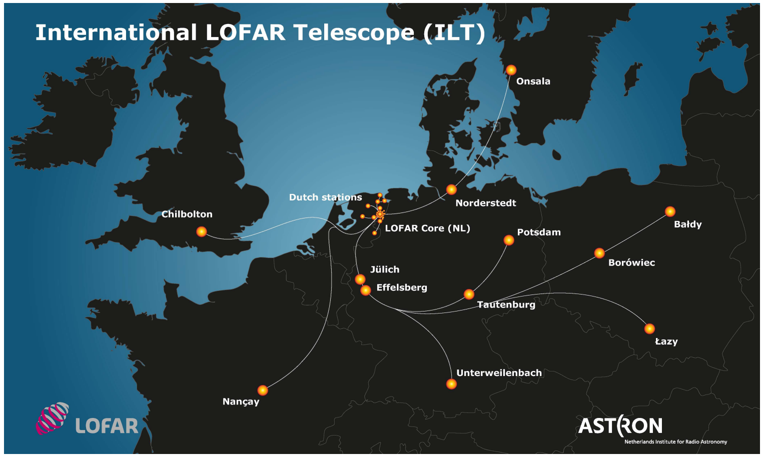
The importance of radio galaxies

- For simulations to reproduce observations, additional energy input is required
- Radio galaxies are an observational keystone for understanding this energy input
- Efficiently transport energy away from the AGN to the surrounding environment in a self regulating manner (i.e. AGN feedback)
- Vital we understand what drives emission from these sources and the timescales on which they operate
- One of the most pressing questions is the total power output of these sources and how it changes over cosmic time (life expectancy, duty-cycle)





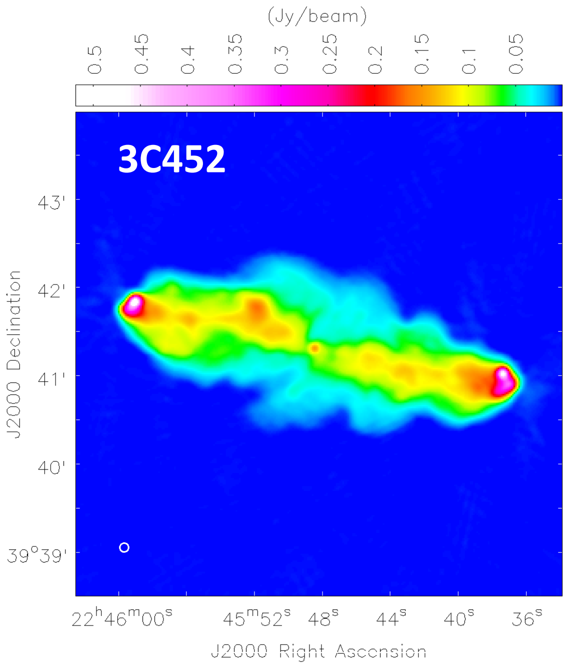
Why low frequencies?

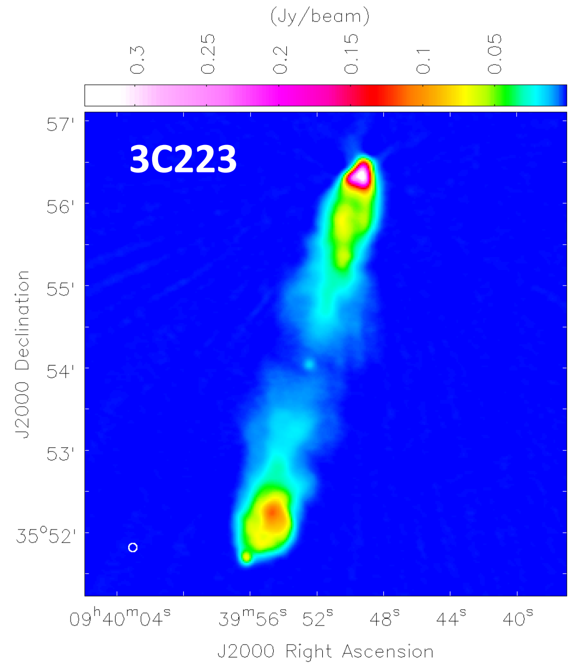


- Low frequency observations are able to probe previously unseen emission
- Able to constrain the low-energy electron population
- We are now able to achieve much higher resolutions at low frequencies
- Excellent for determining parameters in models of their emission

Target sources

Name	IAU name	Redshift	5 GHz core flux density (mJy)	178 MHz flux density (Jy)	Spectral index (178 to 750 MHz)	LAS (arcsec)
3C452	J2243+394	0.081	130	59.3	0.78	280
3C223	J0936+361	0.137	9.0	16.0	0.74	306



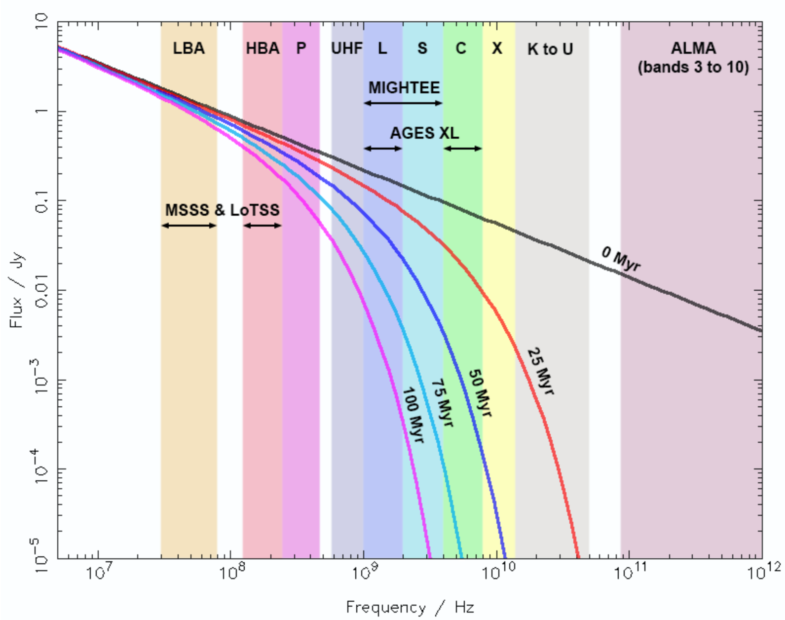


- **Phase I:**
  - Integrated flux
  - LOFAR and archival observations
  - Energetics
- **Phase II:**
  - Resolved studies
  - LOFAR, VLA, and GMRT
  - Spectral ageing and dynamics
- **Phase III:**
  - Sub arc second resolution
  - LOFAR international stations, e-MERLIN

- VLA P-band (368 MHz) images
- Combined configurations
- Bandwidth: 192 MHz
- RMS: 0.16 mJy beam^{-1}
- Beam: 6 arcsec

Jeremy Harwood – Bologna, June 2017

What is spectral ageing



Example JP model between 0 and 100 Myrs with various frequency bands noted

- The shape of the energy spectrum can give key insights into the underlying physics of a radio source
- Particles undergo shock acceleration (e.g. the hotspots in FR-IIs)
- Preferential cooling of higher energy electrons (spectral ageing)
- This leads to a more strongly curved spectrum in older regions of plasma
- If we can determine an accurate model we can determine the age, hence total power, of a source

ASTRON Netherlands Institute for Radio Astronomy

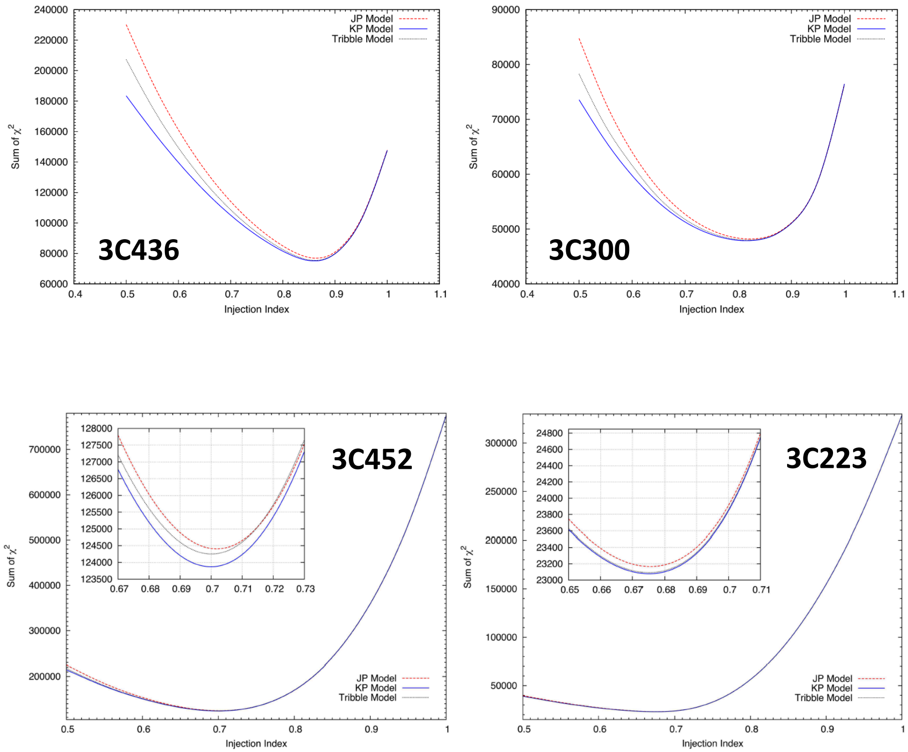
LOFAR

Spectral ageing model parameters and assumptions

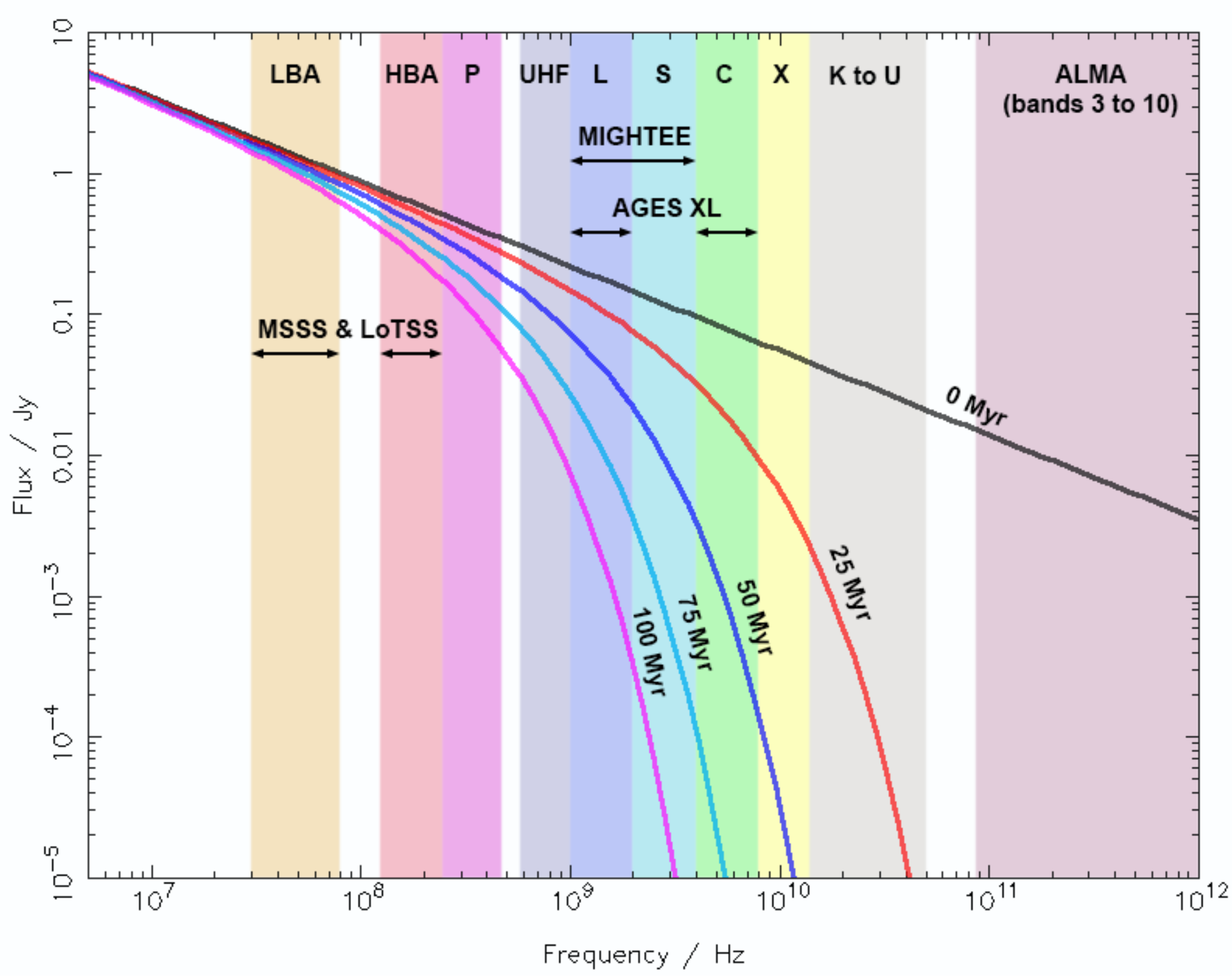
$$I_\nu(t) = 4\pi C_3 N_0 s B \int_0^{\pi/2} d\theta \sin^2\theta \int_0^{1/E_T} dE F(x) E^{-\delta} (1 - E_T E)^{\delta-2}$$

- **Initial electron energy distribution (injection index, expected α_{inj} = 0.5 to 0.6)**
  - **Flat or steep? ($\delta = 2\alpha + 1$)**
- **Pitch angle of electrons to the magnetic field (model type, JP vs KP)**
  - **Conflicting observational evidence (physical plausibility vs model fitting)**
- **Magnetic field strength and distribution (Tribble model)**
  - **Reasonable estimates of the mean field possible but uncertain on smaller scales**
- **Negligible cross-lobe and line of sight variations**
  - **Cross-lobe non-negligible (but solvable), line of sight uncertain (what impact?)**
- **Low and high energy cut offs**
  - **Reasonable but uncertain**

The initial electron energy distribution



- The power law which describes the initial electron energy distribution (injection index) is steeper than previously assumed
- First noticed in 3C436/3C300 at GHz frequencies
- Seen using X^2 minimisation which better accounts for model curvature
- Higher injection index values observed in all subsequent sources
- At LOFAR frequencies losses should be negligible

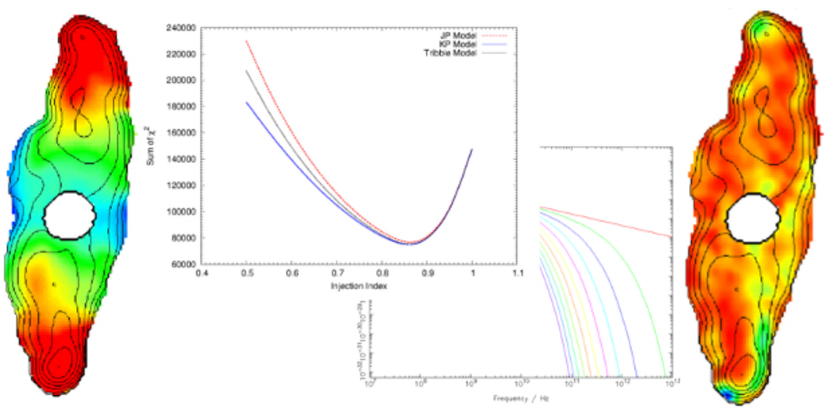


The broad impact of low frequency observing

Jeremy Harwood – Bologna, June 2017

BRATS: Broadband Radio Astronomy ToolS

Spectral analysis software for the new generation of broadband of radio telescope

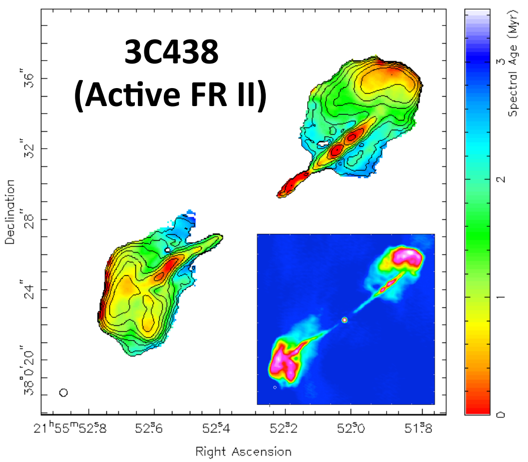


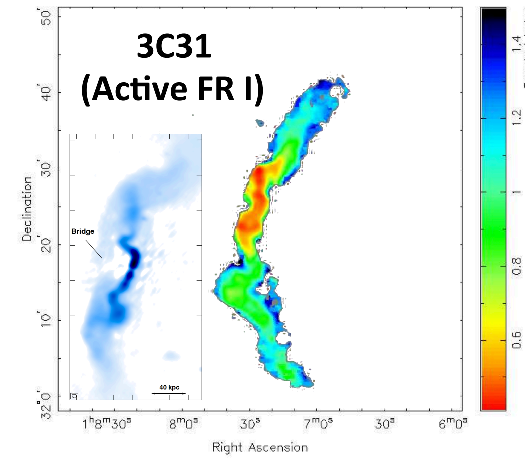
Described in Harwood et al. 2013, 2015

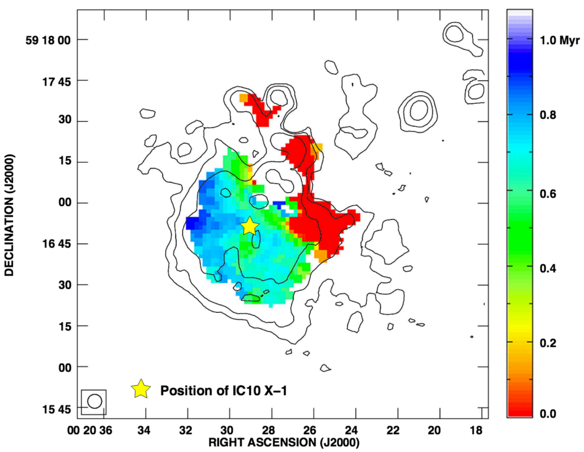
http://www.askanastronomer.co.uk/brats

- **Software package for the analysis of radio observations**
- **A wide range of functions including:**
  - **Spectral age model fitting (resolved and integrated)**
  - **Model parameter determination**
  - **Fitting statistics and uncertainty calculation**
  - **Legacy ageing analysis methods (e.g. colour-colour plots)**
  - **Image manipulation (e.g. bulk image resizing, subtraction)**
  - **Source reconstruction from ageing models**
- **Requires no additional programming by the user**
- **Extensive cookbook, tutorial and example data available via the website**
- **Easily adaptable to new models and applications**

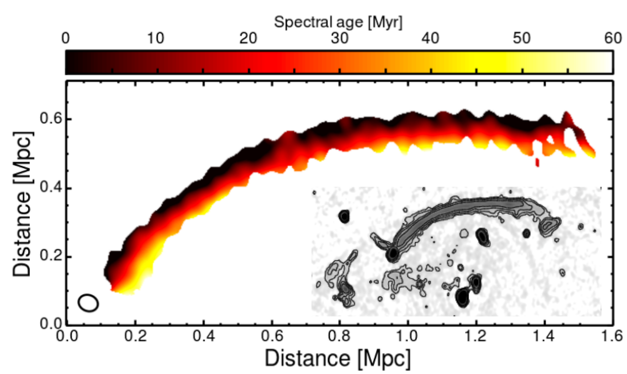
http://www.askanastronomer.co.uk/brats



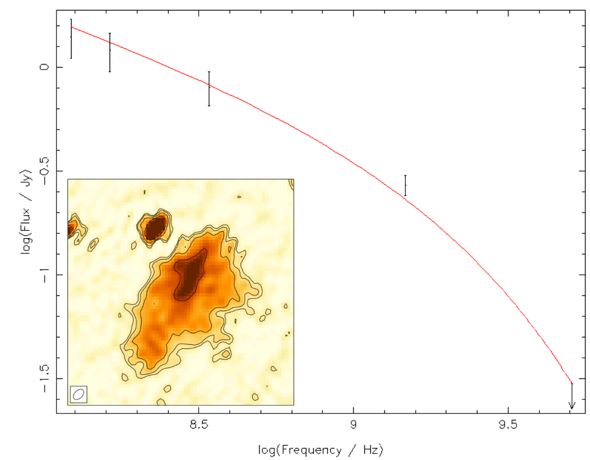




Non-thermal super bubble



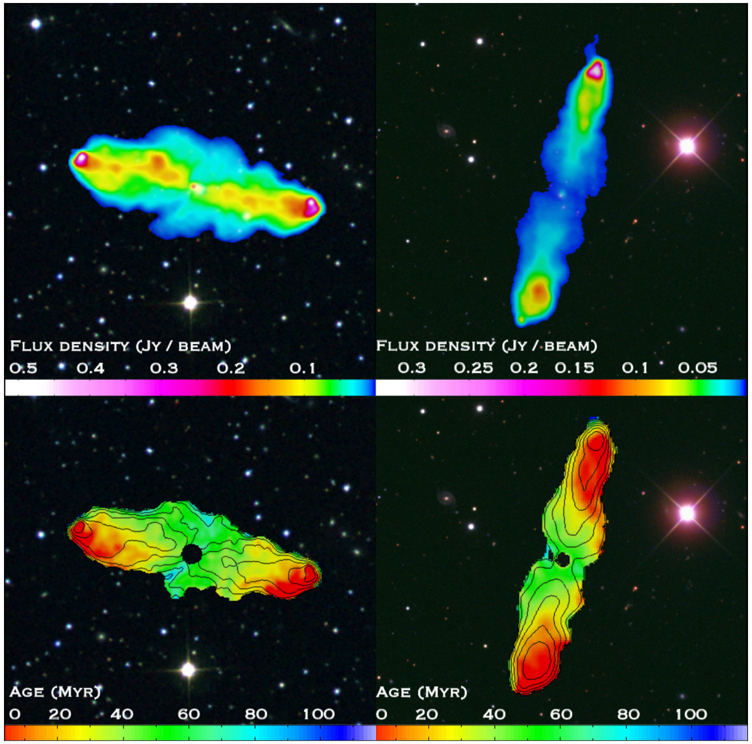
`Sausage' Cluster relic



BLOB1 (Remnant RG)

http://www.askanastronomer.co.uk/brats

Spectral Ageing Maps

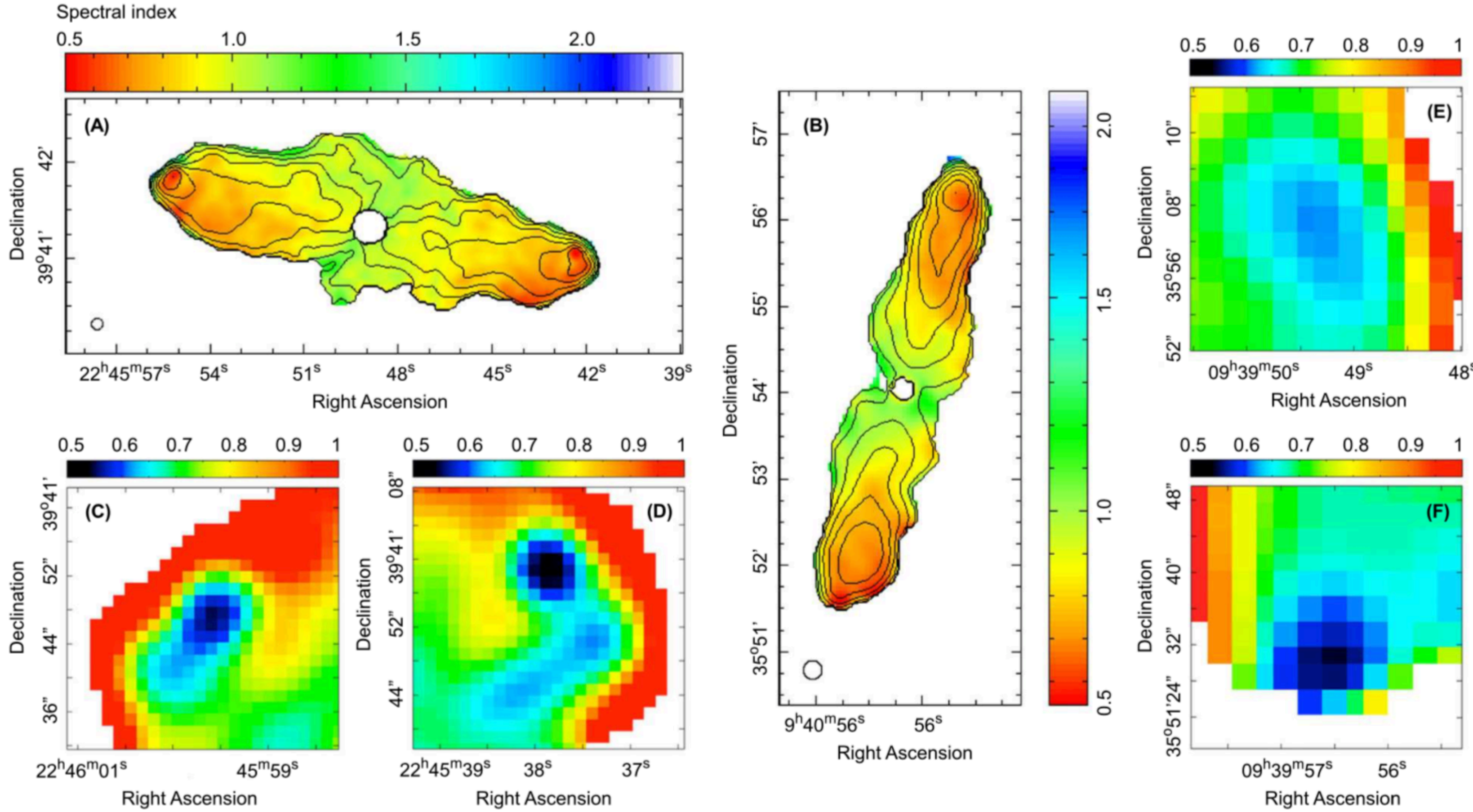


Top: 368 MHz radio images of 3C452 (left) and 3C223 (right) overlaid on optical backgrounds. Bottom: The spectral age of each source as a function of position.

- LOFAR HBA, VLA P-band, GMRT (610 MHz) and VLA L-band (1.4 GHz)
- 3C452
  - 7 arcsec resolution
  - Injection index: 0.70
  - Max Age: ~85 Myr
- 3C223
  - 13 arcsec
  - Injection index: 0.68
  - Max Age: ~80 Myr
- Feint extension to northern lobe of 3C223
- Injection index remains steep for both sources

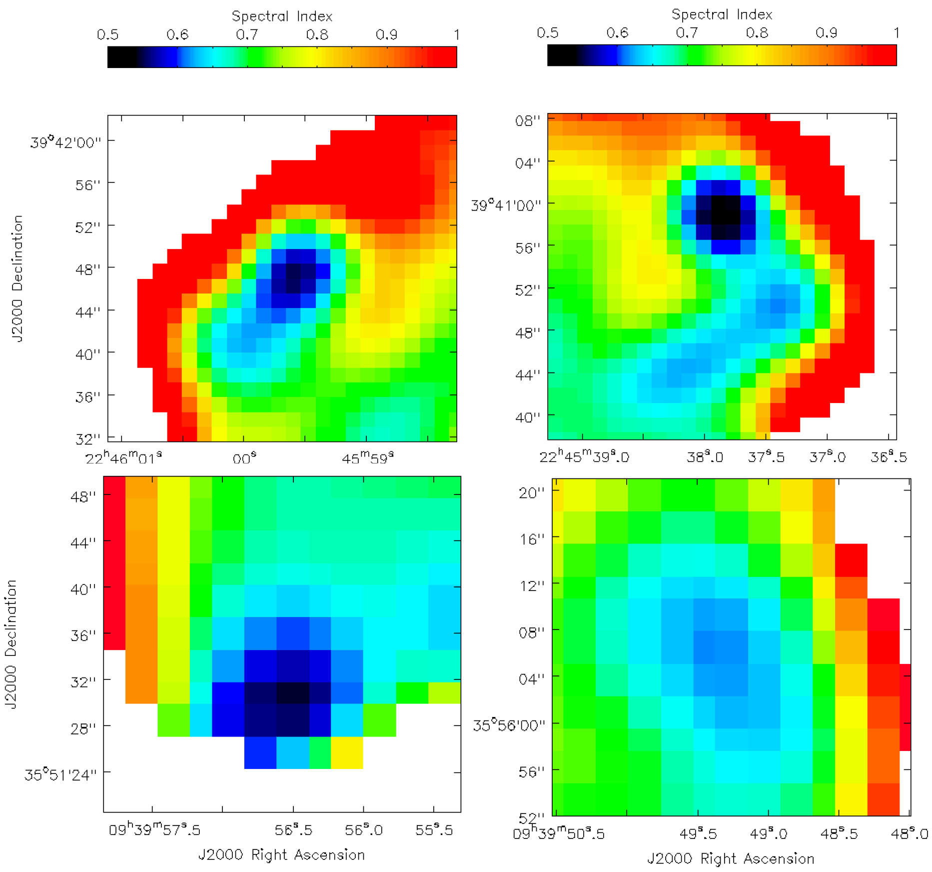
Harwood, 2017, MNRAS, 469, 639

Spectral Index Maps



Harwood, 2017, MNRAS, 469, 639

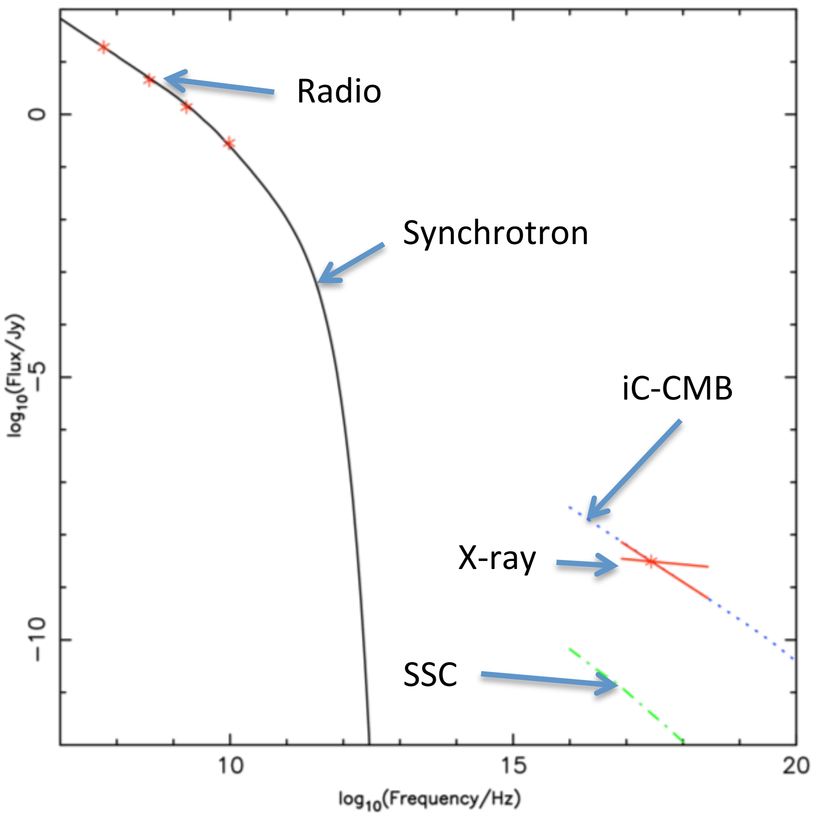
Acceleration Regions



- Sharp jump from expected value inside the hotspot (<0.6) to just outside (~0.7)
- Both regions well described by a power law (negligible curvature)
- Summation of high energy cut offs?
- Optical counterparts known to exist in some sources, so if common cannot cannot always resolve the problem
- Absorption similar to that seen in Cygnus A by McKean et al. (2016)
- Non-homogeneous and/or additional acceleration mechanisms

Harwood, 2017, MNRAS, 469, 639

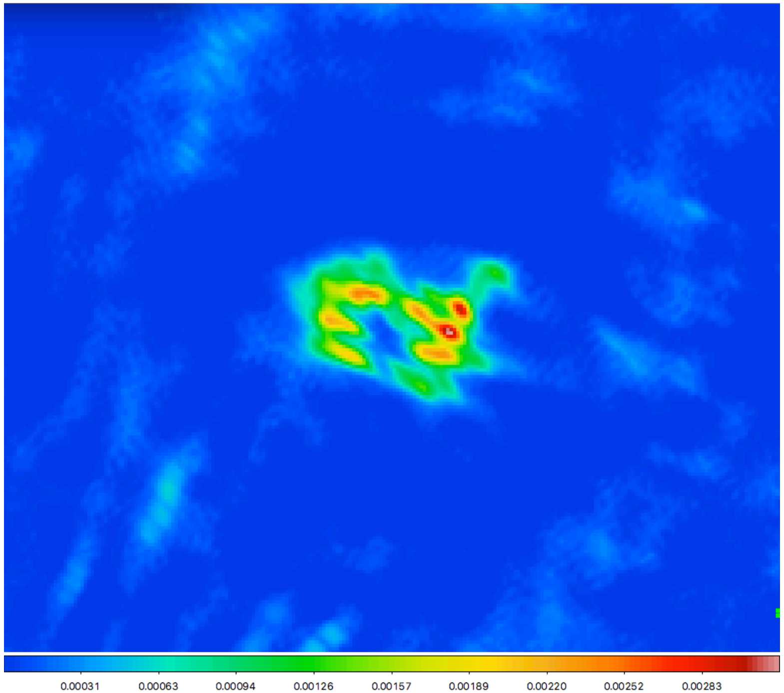
Consequences of a steeper injection index



- As FR IIs are steep spectrum, most of of its energy is at low frequencies
- Changes in the low-frequency spectrum can have a significant impact on its energetics
- Increase in the total energy content of the lobes by up to an order of magnitude
- Increase in magnetic field strength by ~60%
- From these results alone, we are unable to conclusively determine the cause of the disparity

Harwood et al. 2016, MNRAS, 458, 4443

e-MERLIN and the LOFAR International Baselines



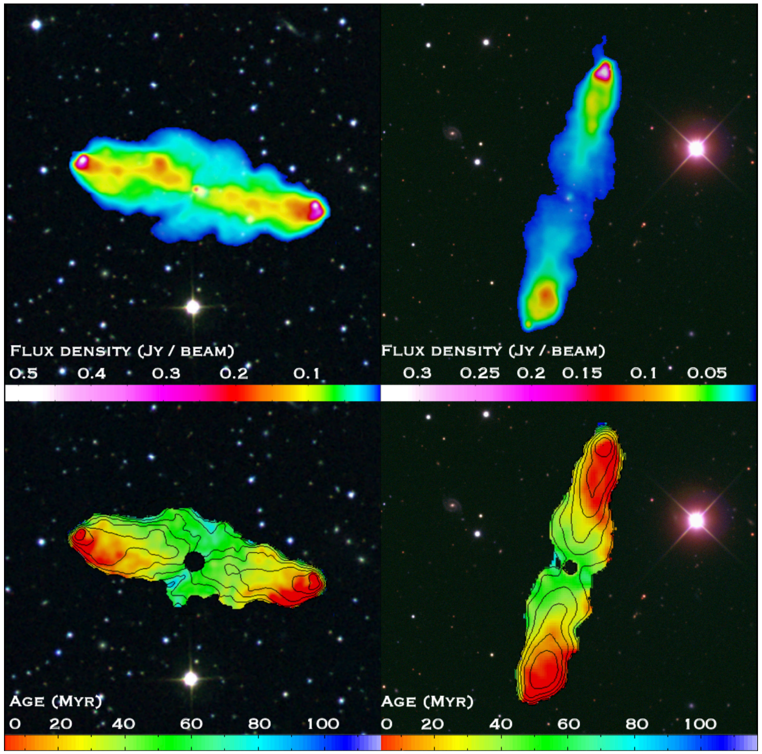
Preliminary 5.75 GHz e-MERLIN observation of the eastern hotspot in 3C351 at 2.8" x 1.1"resolution

- **Sub-arcsecond resolution imaging is required to investigate this further**
- **Sample of 5 FR IIs, observed with both e-MERLIN and LOFAR international baselines**
- **Frequency coverage at 150 MHz and 6 GHz**
- **Determine the spectrum of hotspots as a function of position**
- **Investigate the energy distribution of hotspots (e.g. single vs. broken power law distribution)**

ASTRON Netherlands Institute for Radio Astronomy

LOFAR

The radio galaxy population



Top: 368 MHz radio images of 3C452 (left) and 3C223 (right) overlaid on optical backgrounds. Bottom: The spectral age of each source as a function of position.

- Are these results applicable to the population as a whole?
- What is the age distribution of nearby radio galaxies?
- What is the distribution of total energy content and magnetic field strength?
- How does this vary as a function of redshift?
- Upcoming and future surveys (e.g. LoTTS, MeerKAT MIGHTY, AGES-XL)
- What models and techniques are best used for the analysis of large datasets and surveys?

VLA GHz survey of extragalactic sources in the XMM-LSS field (AGES - XL)

- **Targeted survey centred on 30 of the brightest sources in the XMM-LSS field**
- **97 hours split between L- and C-band at ~1 arcsec resolution**
- **Large amount of ancillary data available (e.g. LOFAR, XMM, VIDEO, DES)**
- **Primary science drivers:**
  - **What are a robust set of parameters for models of spectral ageing for the radio galaxy population?**
  - **If the hotspot discontinuity common in the population?**
  - **Are the revised RG energetics robust for larger samples?**
- **In conjunction with other surveys (e.g. MeerKAT, LOFAR) this will help to solve:**
  - **What is the characteristic age and lifespan of nearby radio galaxies?**
  - **How does this age vary as a function of redshift?**

Conclusions

- Injection index remains steeper than historically assumed (0.7 vs 0.5)
- Sharp jump between the hot spot and the plasma immediately surrounding it at low frequencies
- The high resolution spectral structure of hot spots needs to be explored. LOFAR international baselines and e-MERLIN will achieve this over the next 12 months
- Total energy content an order of magnitude greater than previously thought
- Absolute magnetic field strength 60 per cent greater
- Ratio of magnetic field strength to equipartition remains consistent ($\approx 0.7\ B_{eq}$)
- Standard integrated models of spectral ageing do not provide a robust measure of a source's age
- These problems need to be resolved if we are to investigate large samples (e.g. LOFAR, MeerKAT, SKA surveys) and determine characteristic ages (hence total power) of the population