FR II radio galaxies with SKA pathfinders: from MHz to GHz

Jeremy Harwood

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Collaborators:

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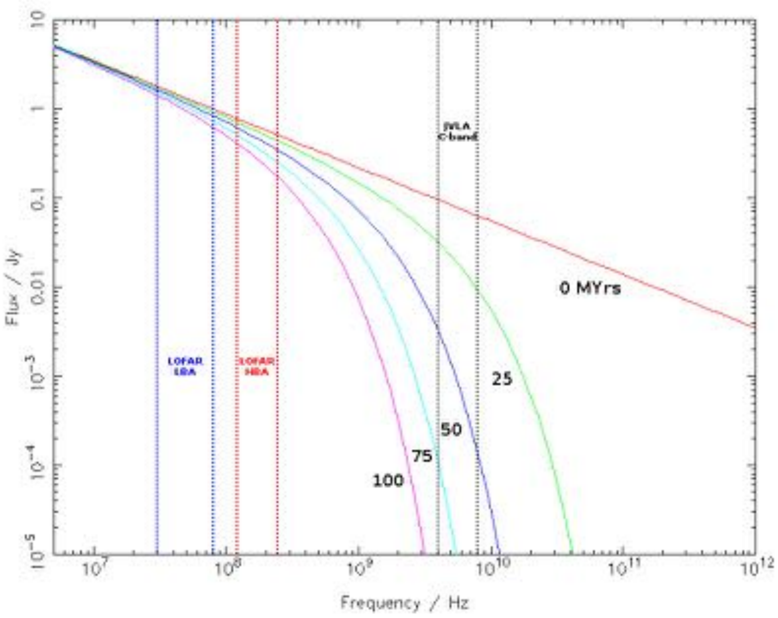
Outline

- What is spectral ageing and its key parameters?
- Why low frequencies? Why now?
- Spectral ageing, dynamics and particle acceleration in FR IIs
- Application of spectral ageing models to continuum surveys
- New questions and outstanding problems
- Future plans

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**

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)
- Pitch angle of electrons to the magnetic field (model type, JP vs KP)
- Magnetic field strength and distribution (Tribble model)
- Negligible cross-lobe and line of sight variations
- Low and high energy cut offs

Spectral ageing model parameters and assumptions

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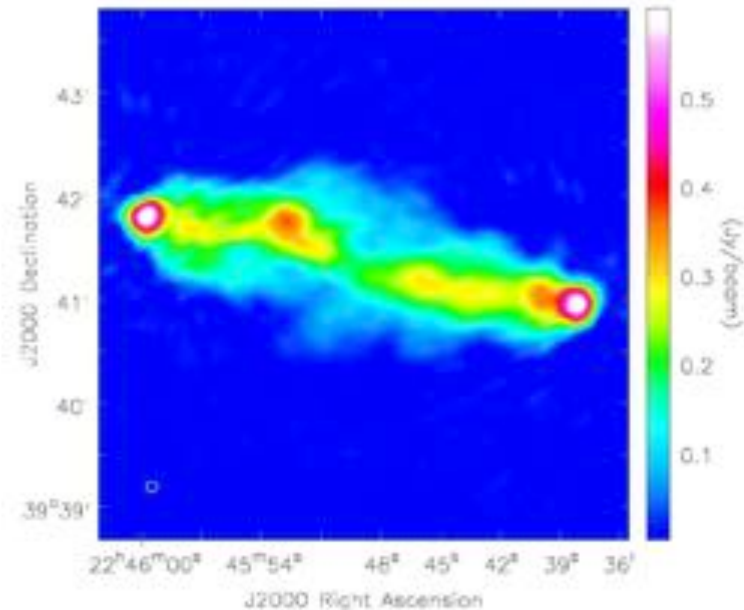
- **Initial electron energy distribution (injection index, expected α_{inj} = 0.5 to 0.6)**
  - **Flat or steep? (this talk)**
- **Pitch angle of electrons to the magnetic field (model type, JP vs KP)**
  - **Conflicting observational evidence (physical plausibility vs model fitting)**
- **Magnetic field strength and distribution (Tribble model)**
  - **Reasonable estimates of the mean field possible (this talk) 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**

Why low frequencies, why now?

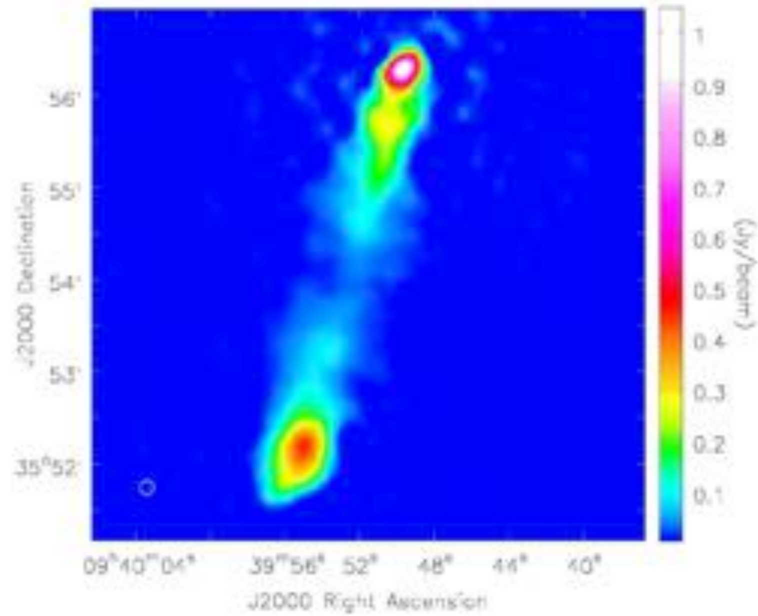
- **Low frequency observations are able to probe previously unseen emission**
- **Constrain the low-energy electron population**
- **We are now able to resolve low frequency emission at much higher resolutions**
- **Excellent for determining spectral ageing and synchrotron/IC model parameters**
- **Important to determine what mechanisms are at play if we are to apply such models to large surveys (e.g. LOFAR Tier 1 & 2, MeerKAT, SKA)**
- **Life expectancy, duty-cycle, total power output, and ultimately the impact on their environment, feedback and galaxy evolution**

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



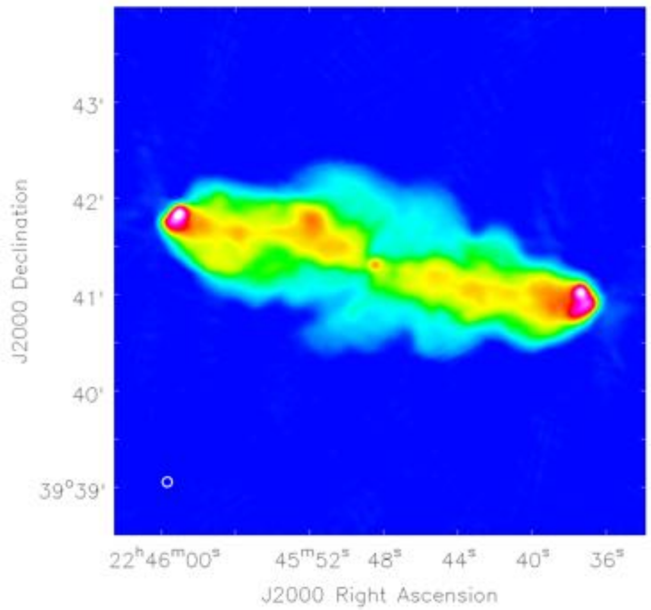
40 MHz bandwidth at 138 MHz



42 MHz bandwidth at 147 MHz

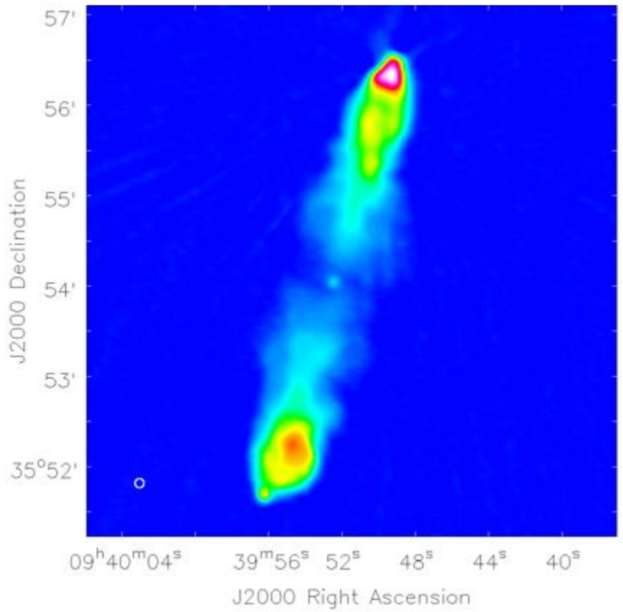
VLA P-Band (368 MHz) Images

3C452



- Combined A, B and C-config.
- Bandwidth: 192 MHz
- RMS: 0.16 mJy beam^{-1}
- Beam: 6 arcsec

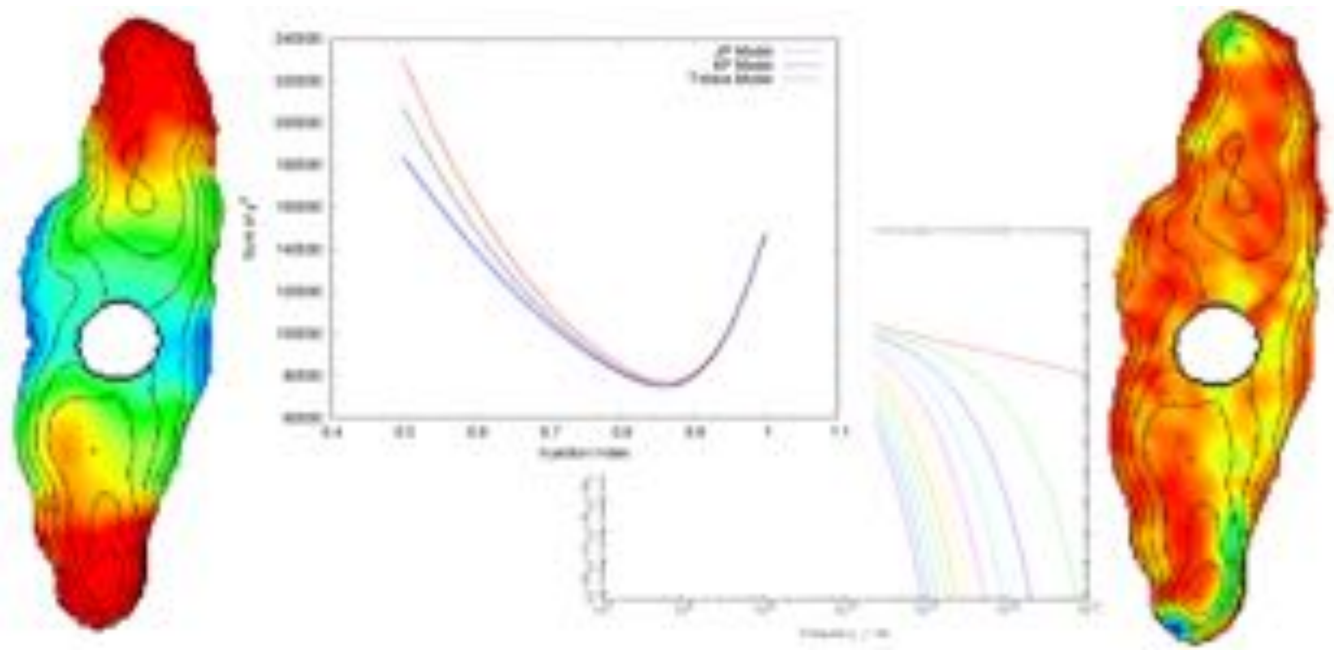
3C223



- Combined A and B-config.
- Bandwidth: 192 MHz
- RMS: 0.17 mJy beam^{-1}
- Beam: 6 arcsec

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

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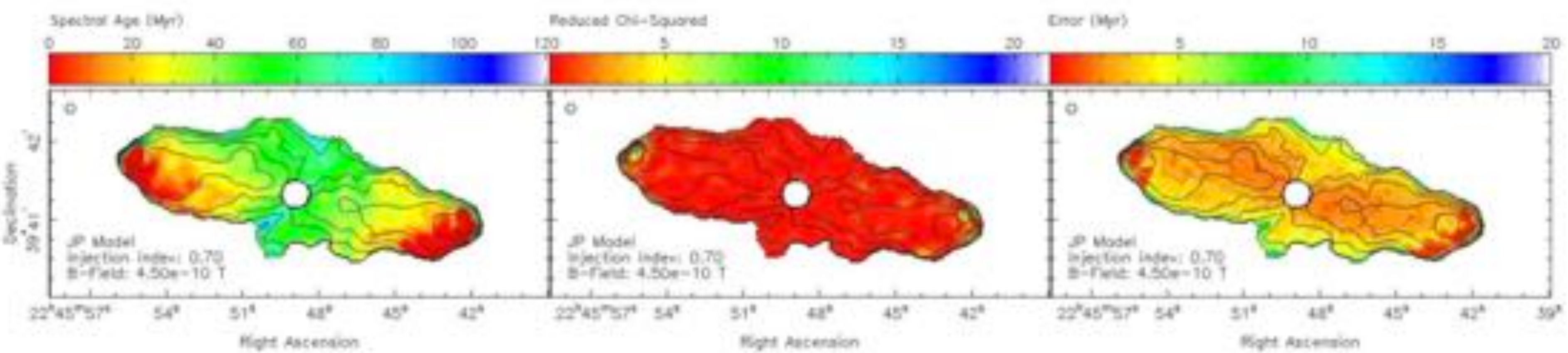
ASTRON Netherlands Institute for Radio Astronomy

LOFAR

Spectral Ageing Maps

LOFAR HBA, VLA P-band, GMRT (610 MHz) and VLA L-band (1.4 GHz)

3C452

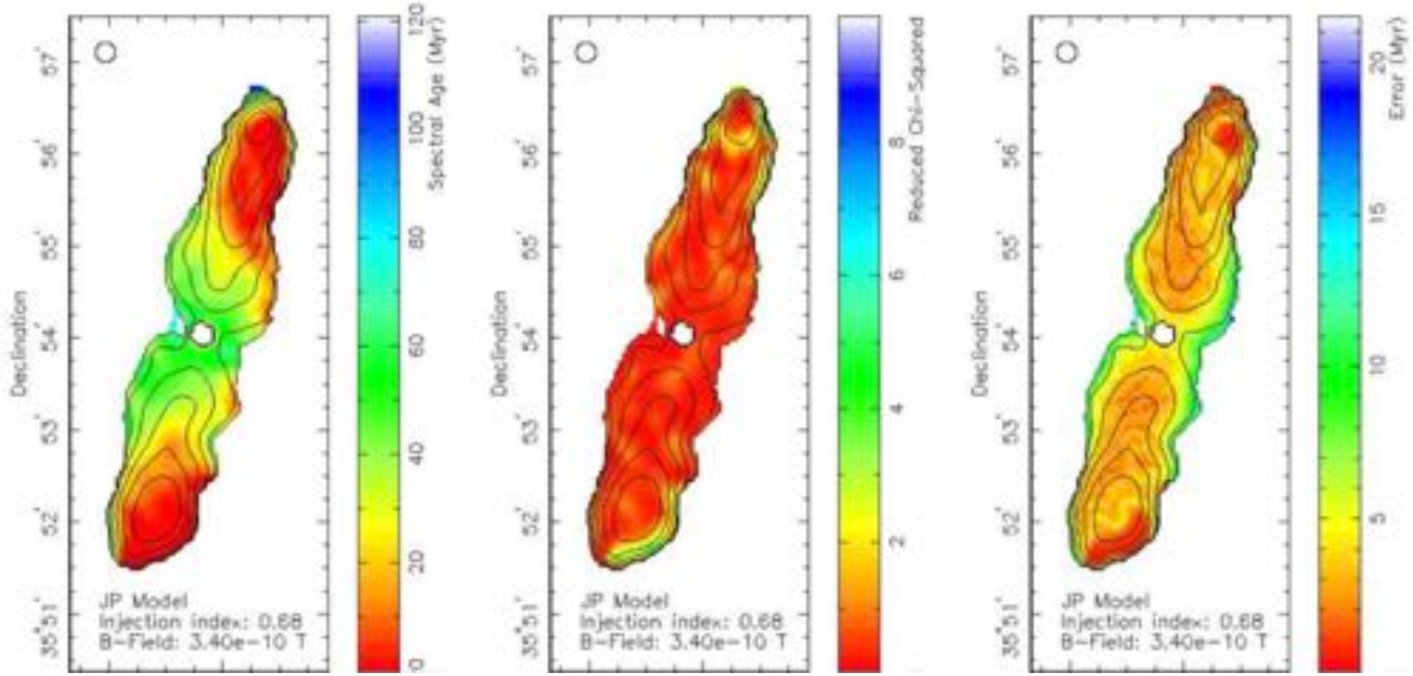


7 arcsec - Injection index: 0.70 (vs 0.85 vs 0.78) - Max Age: ~85 Myr (vs 27 Myr)

Spectral Ageing Maps

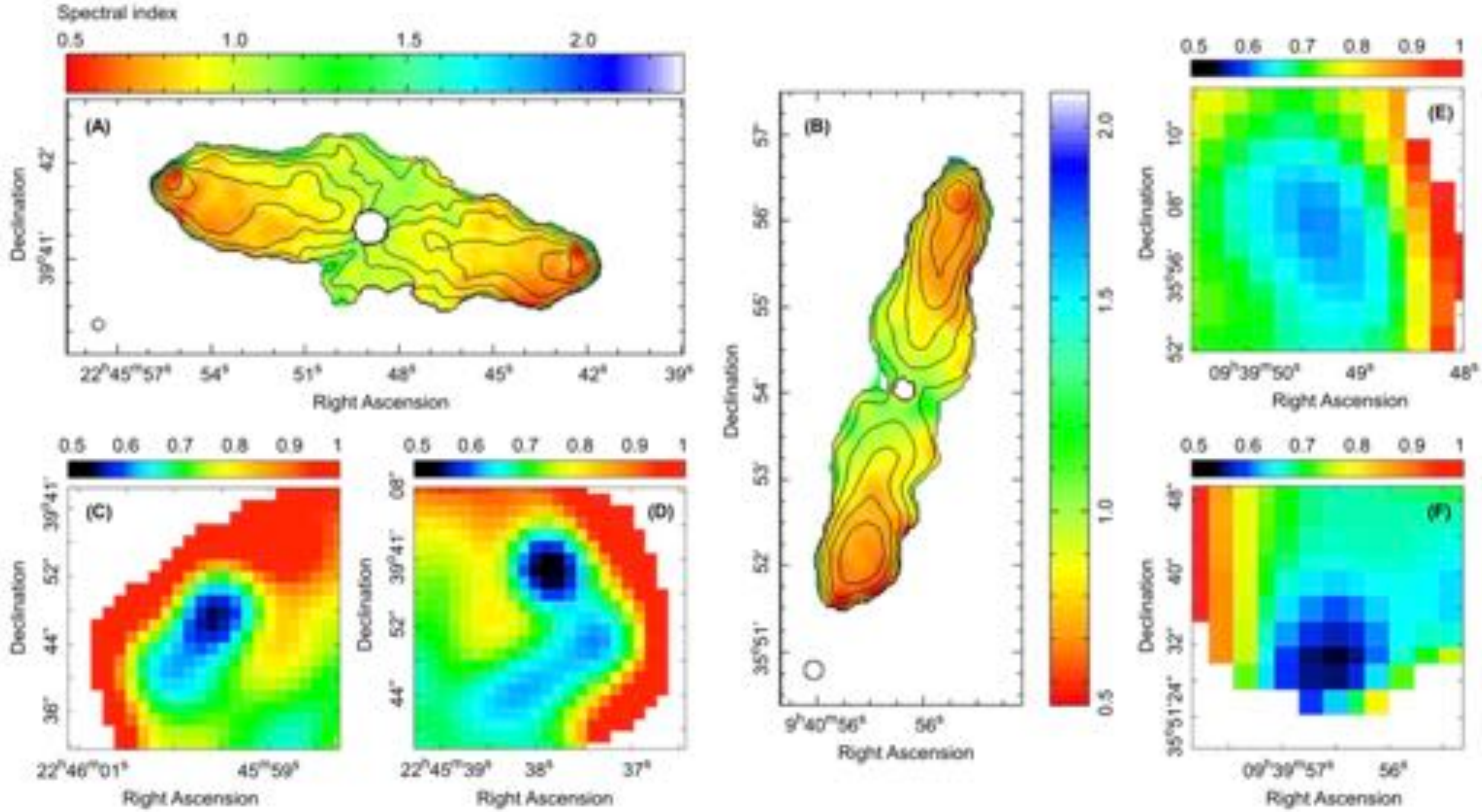
LOFAR HBA, VLA P-band, GMRT (610 MHz) and VLA L-band (1.4 GHz)

3C223

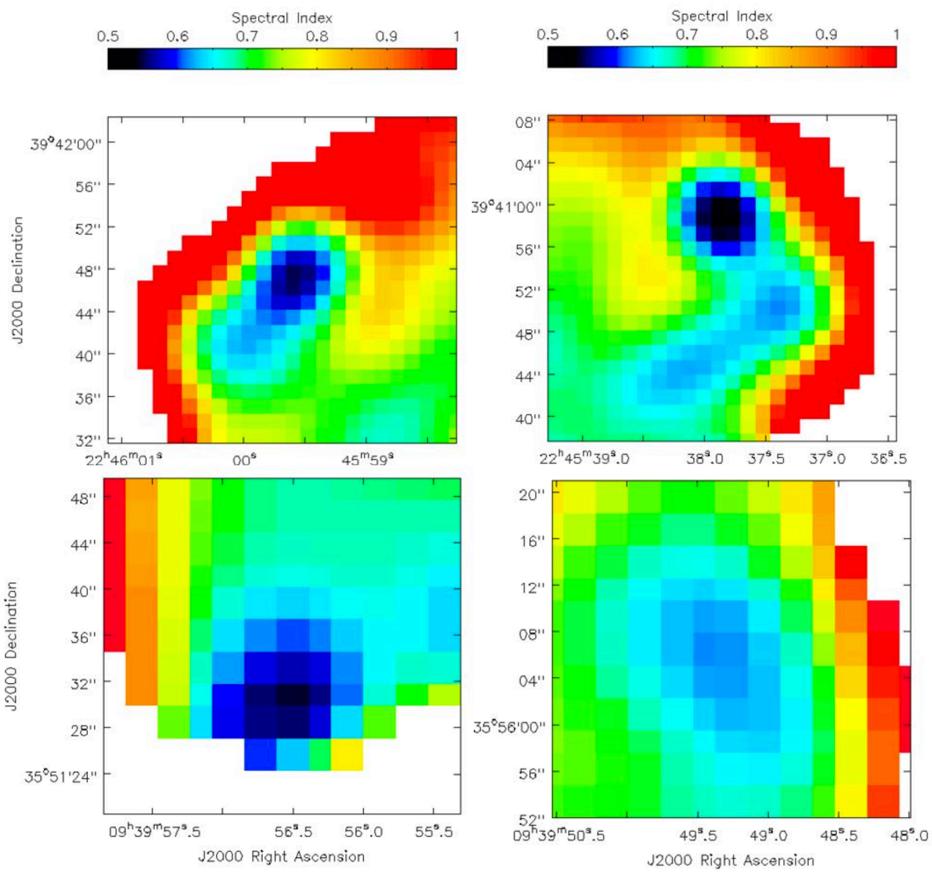


13 arcsec - Injection index: 0.68 (vs 0.71) - Max Age: ~80 Myr (vs 72 Myr)

Spectral Index Maps



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?
- X-ray hotspots seen in 3C452
- Optical counterparts known to exist in some sources, so if common cannot cannot always resolve the problem
- Likely due to absorption similar to that seen in Cygnus A by McKean et al. (2016)

Spectral ageing in the era of big data: integrated vs resolved models

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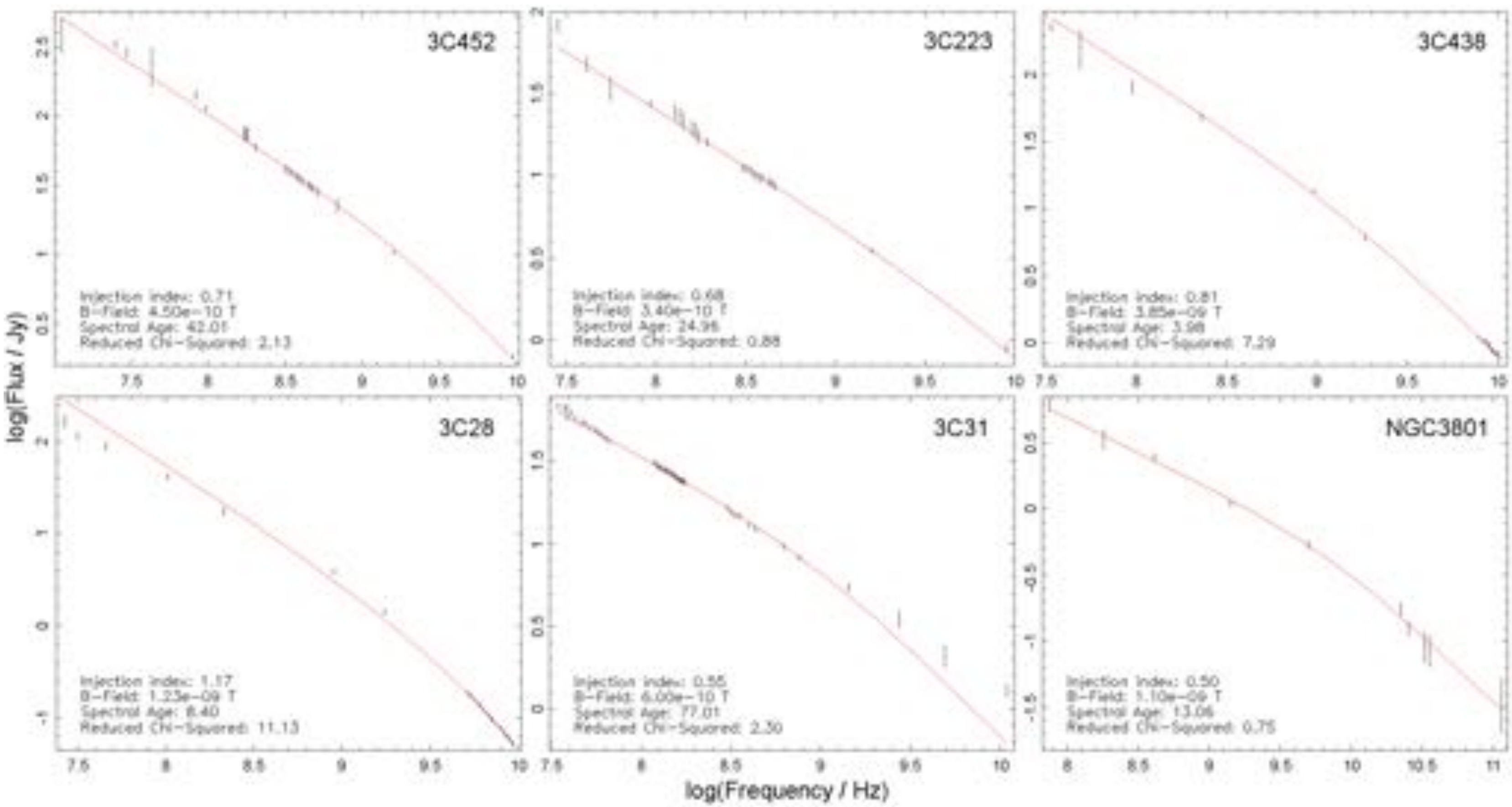
Name	IAU Name	Redshift	178 MHz Flux (Jy)	Type	Ref.
3C452	J2243+394	0.081	130	II	1, 2
3C223	J0936+361	0.137	9.0	II	1, 2
3C438	J2153+377	0.290	48.7	II	3
3C28	J0053+261	0.195	17.8	II (R)	3
3C31	J0104+321	0.017	18.3	I	4
NGC3801	J1137+180	0.011	3.4	I	5

- **CI (off) models commonly used for unresolved radio galaxies**
- **Sample comprises of galaxies where small scale fitting has been performed**
- **3 FR IIs, 1 FR II remnant, 2 FR Is**
- **Can these be applied to surveys? (MSSS, tier 1, MIGHTEE etc.)**
- **Can they be used as a source selection method for remnant galaxies?**

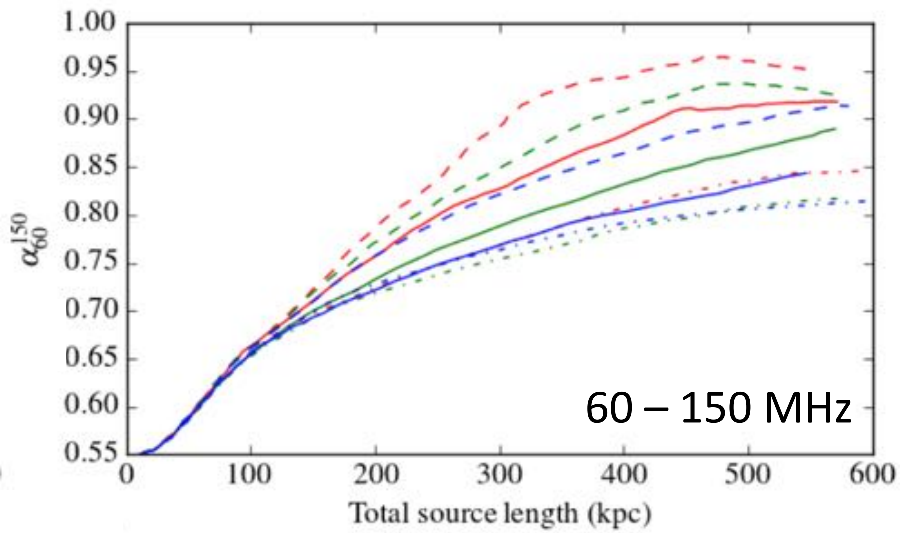
CI Fitting Result



Name	Frequency Coverage	χ^2_{Red}	Rejected	Confidence (%)	T_{Int} (Myr)	+	-	T_{Res} (Myr)	+	-	T_{Diff} (Myr)	+	-
3C452	Full	2.13	Yes	> 99	42.01	1.31	1.50	89.05	8.56	7.14	-47.04	8.66	7.30
3C452	Res	0.23	No	< 68	52.05	4.04	3.93	89.05	8.56	7.14	-37.00	9.47	8.15
3C223	Full	0.88	No	< 68	24.96	2.51	3.55	77.95	13.42	11.73	-52.99	13.65	12.26
3C223	Res	0.43	No	< 68	25.99	6.78	6.71	77.95	13.42	11.73	-51.96	15.04	13.51
3C438	Full	7.29	Yes	> 99	3.98	0.02	0.04	3.00	0.05	0.08	0.98	0.05	0.09
3C438	Res	8.34	Yes	> 99	81.04	7.11	5.87	3.00	0.05	0.08	78.04	7.11	5.87
3C28	Full	8.40	Yes	> 99	8.40	0.04	0.03	12.42	0.44	0.44	-4.02	0.44	0.44
3C28	Res	2.01	Yes	> 99	29.40	0.94	2.32	12.42	0.44	0.44	16.98	1.04	2.36
3C31	Full	2.30	Yes	> 99	77.01	3.49	2.68	169.99	32.72	30.15	-92.98	32.91	30.27
3C31	Res	0.12	No	< 68	84.99	6.40	7.43	169.99	32.72	30.15	-85.00	33.34	31.05
NGC3801	Full	0.69	No	< 68	12.06	1.50	1.12	2.00	0.40	0.40	10.06	1.55	1.19
NGC3801	Res	0.75	No	< 68	13.06	1.42	0.89	2.00	0.40	0.40	11.06	1.48	0.98

- **Half of the model fits rejected (parameters known a priori)**
- **Goodness-of-fit is frequency dependent**
- **Disparity of a up to a factor of 6 in age for those well fitted sources**
- **Allowing the injection index to be a free parameter means unreliable ages but allows them to be used a method of remnant radio galaxy selection**

Integrated flux



Integrated spectral index as a function source length (from simulations)

Hardcastle et al. (in prep)

- **Low frequency spectrum known to be ~0.8 from 178 MHz to 1.4 GHz (e.g. 3CRR sample)**
- **No obvious turnover at lower frequencies (down to ~10 MHz)**
- **Ageing should be negligible at very low frequencies**
- **Simulation suggest the integrated spectrum increases with lobe length hence (loosely) age**
- **Changing environment, magnetic field strength, jet power etc.**
- **Are we just seeing a sum of the sources history?**

New and outstanding questions

- Why does the (lobe) spectrum remain steep down to such low frequencies?
  - Simulations (including spectral ageing!) coming soon
- What is the spectral structure of hotspots?
  - LOFAR international baselines and eMERLIN
- What (if any) absorption processes are affecting the spectrum of hotspots?
  - LOFAR / eMERLIN / VLA / modelling
- How can we account for this when modelling the age?
  - Revised models, new models?
- How can this new understanding be applied in the context of upcoming surveys?
  - BRATS surveys module

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 most likely due to absorption
- 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
- 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
- Full simulations (including spectral ageing!) of 3C452 and 3C223 coming soon
- http://www.askanastronomer.co.uk/brats