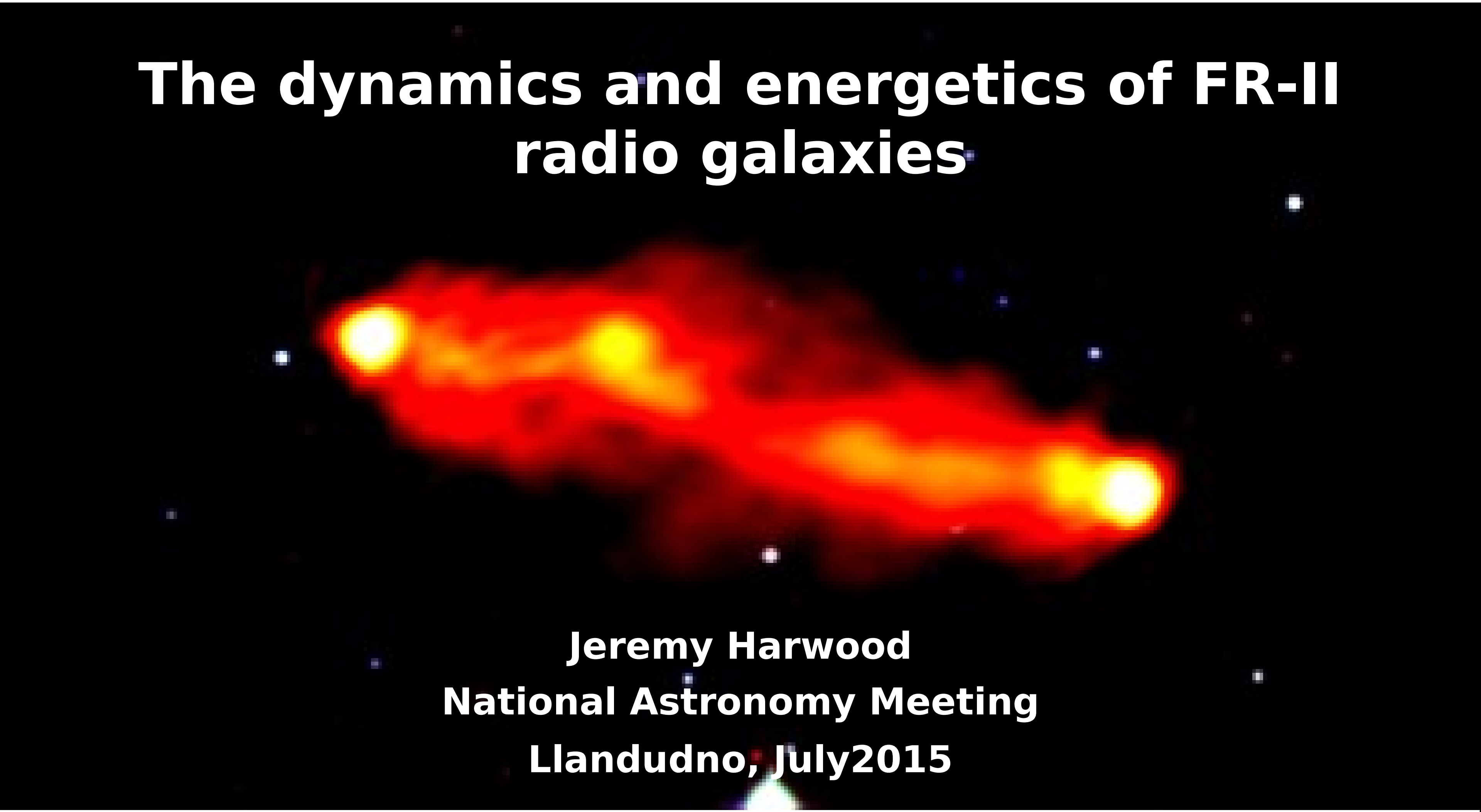
The dynamics and energetics of FR-II radio galaxies



Jeremy Harwood

National Astronomy Meeting

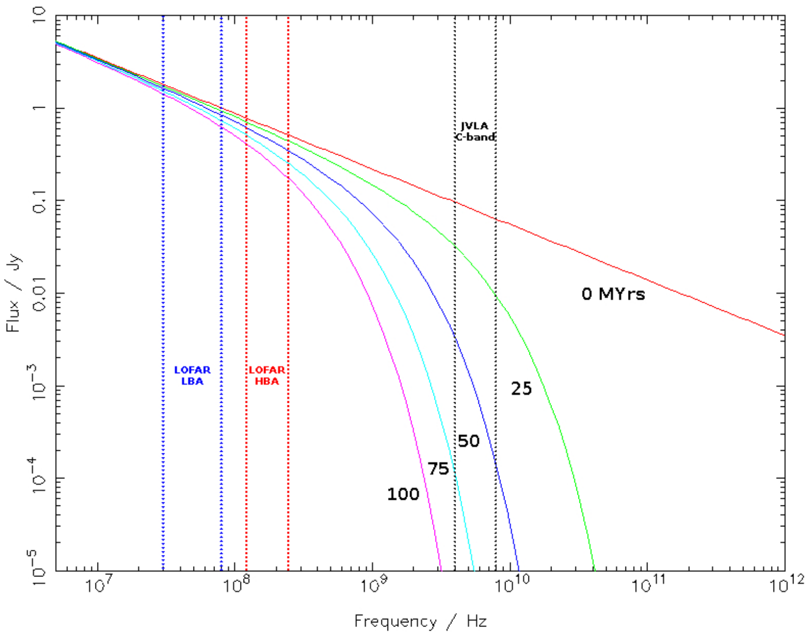
Llandudno, July2015

Collaborators:

Martin Hardcastle (Hertfordshire) Judith Croston (Southampton) Raffaella Morganti (ASTRON)
Huib Intema (NRAO)
Adam Stewart (Oxford) Marisa Brienza (RUG / ASTRON) & the LOFAR nearby AGN KSP team

Spectral ageing and its parameters

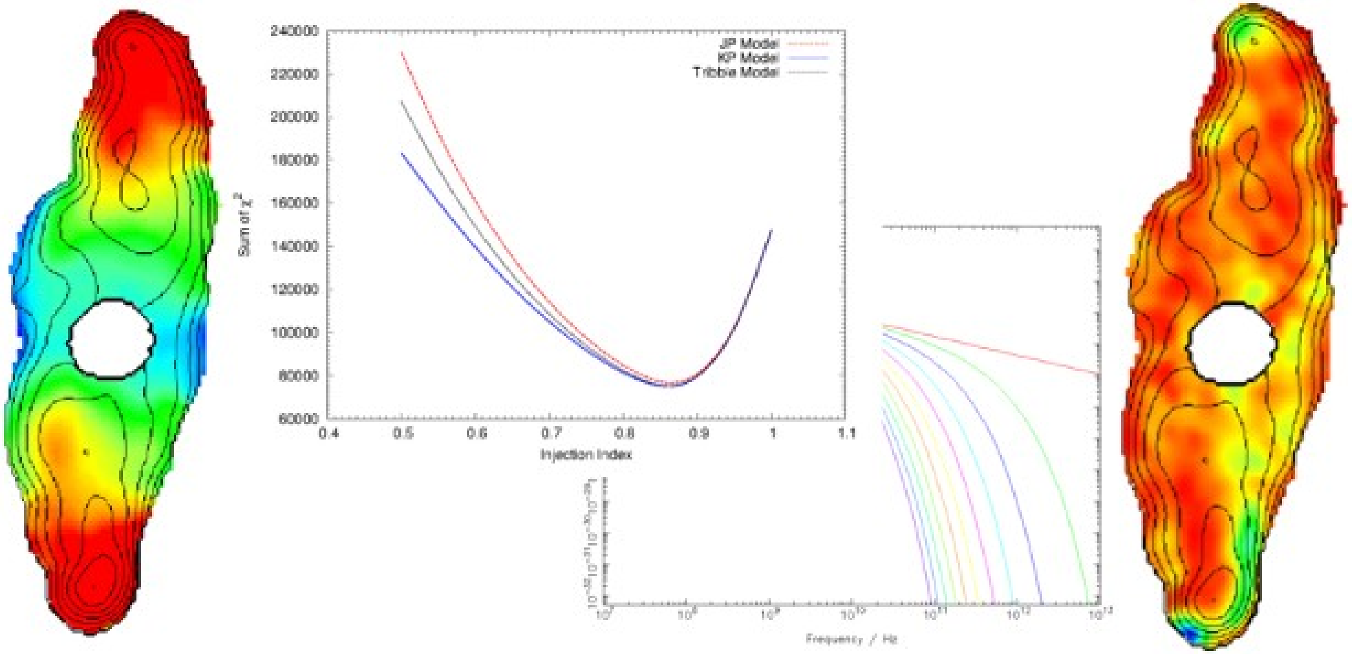
$$I_\nu(t) = 4\pi C_3 N_0 s B \int_0^{\pi/2} d\theta \sin^2\theta \int_0^{1/E_T} dE F(x) E^{-\delta}(1-E_T E)^{\delta-2}$$



- **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**
- **δ (or the observable α_inj) describes the initial electron energy distribution**

BRATS: Broadband Radio Astronomy ToolS

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



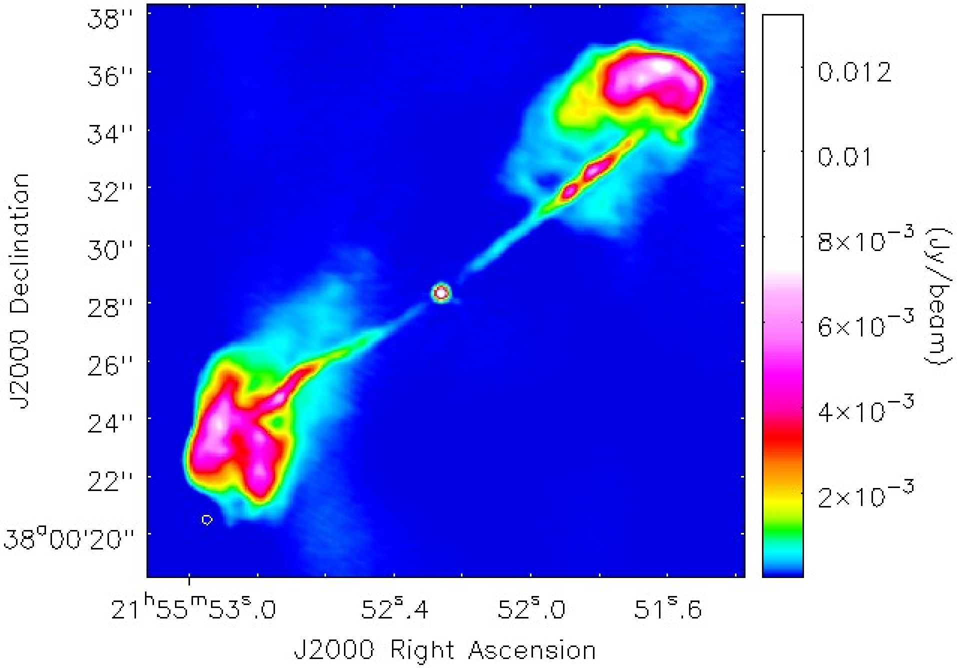
Described in Harwood et al. 2013
http://www.askanastronomer.co.uk/brats

What can BRATS do?

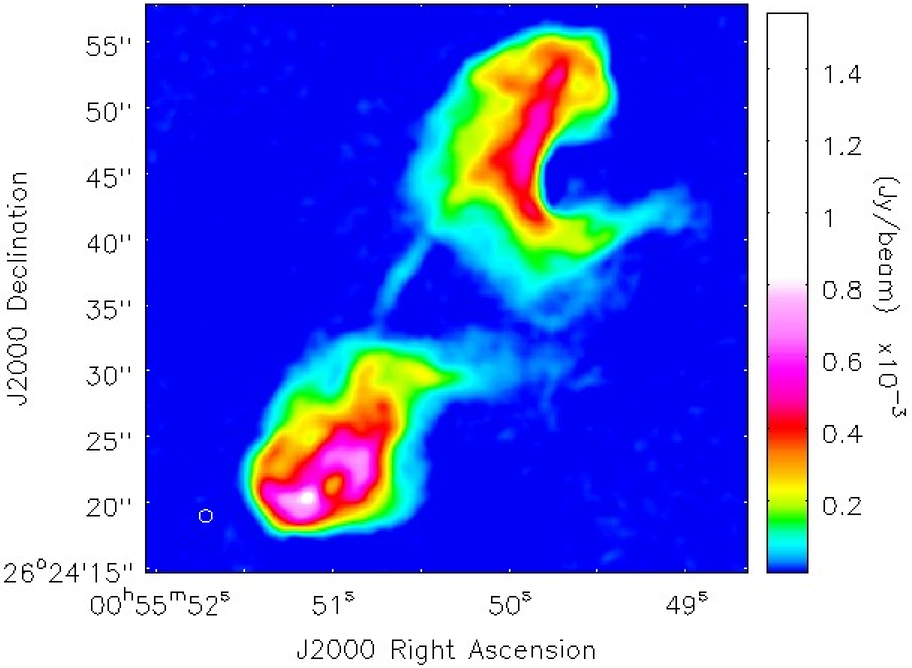
- Fitting of spectral ageing models to sources on small spatial scales
- Injection index determination (spectral index is often not the best way!)
- Spectral index / polynomial fitting, combining maps in the image plane, resizing images, difference maps... plus much more
- If you plan on doing a spectral ageing analysis, come and talk to me
- Available to download from the website, including cookbook, tutorial etc.
- http://www.askanastronomer.co.uk/brats

Spectral ageing in the lobes of cluster-centre FR-II radio galaxies

(Harwood et al. 2015, submitted)

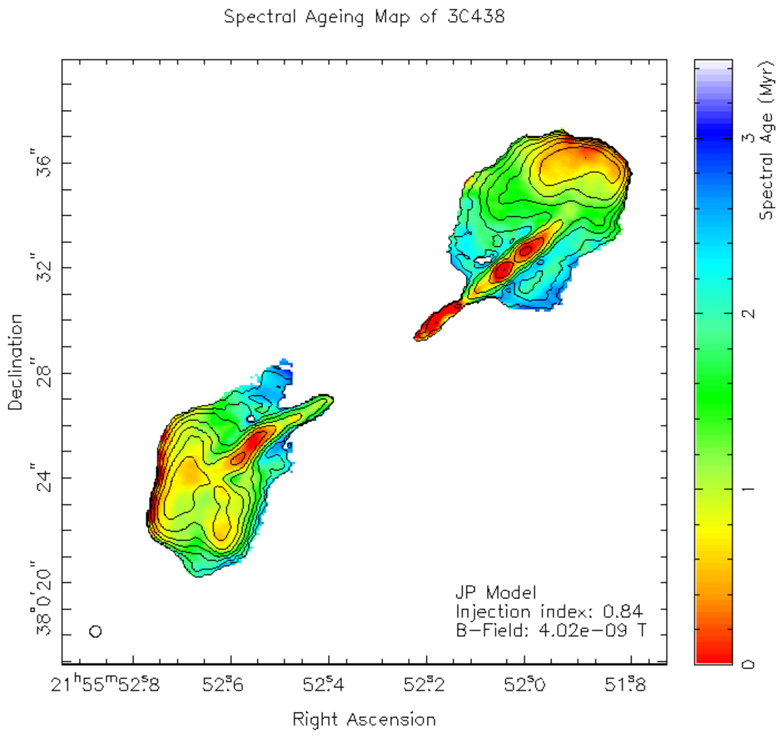


3C438 – 0.3” beam
4 GHz bandwidth at 6 GHz

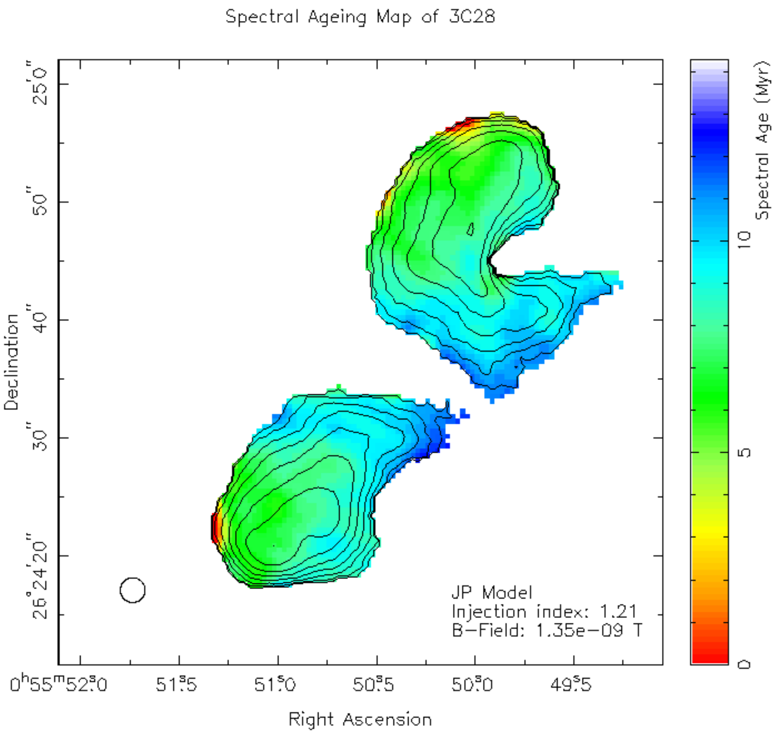


3C28 – 1” beam
4 GHz bandwidth at 6 GHz

Spectral age maps


Spectral Ageing Map of 3C438

3C438 – 0.3” beam
4 GHz bandwidth at 6 GHz


Spectral Ageing Map of 3C28

3C28 – 1” beam
4 GHz bandwidth at 6 GHz

Spectral ageing models

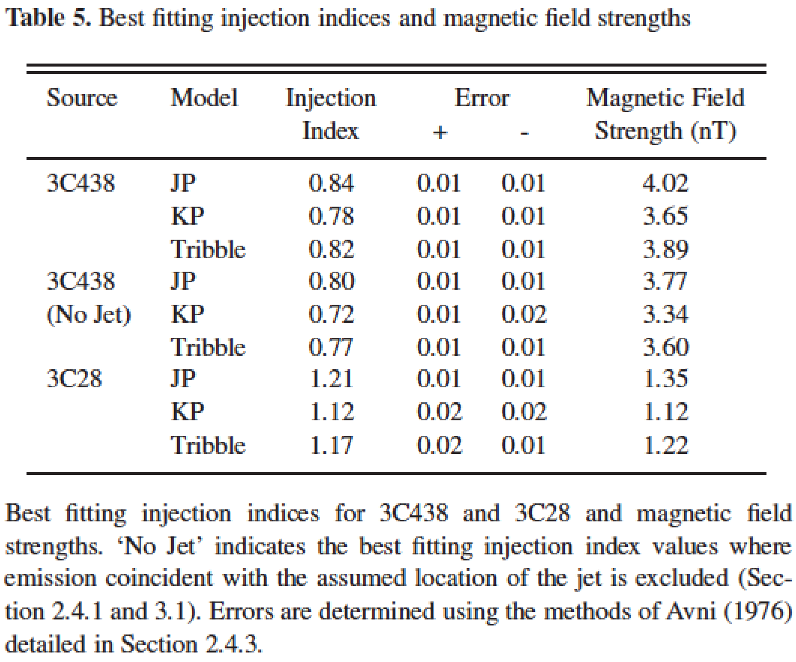


Table 5. Best fitting injection indices and magnetic field strengths

Source	Model	Injection Index	Error +	Error -	Magnetic Field Strength (nT)
3C438	JP	0.84	0.01	0.01	4.02
	KP	0.78	0.01	0.01	3.65
	Tribble	0.82	0.01	0.01	3.89
3C438	JP	0.80	0.01	0.01	3.77
(No Jet)	KP	0.72	0.01	0.02	3.34
	Tribble	0.77	0.01	0.01	3.60
3C28	JP	1.21	0.01	0.01	1.35
	KP	1.12	0.02	0.02	1.12
	Tribble	1.17	0.02	0.01	1.22

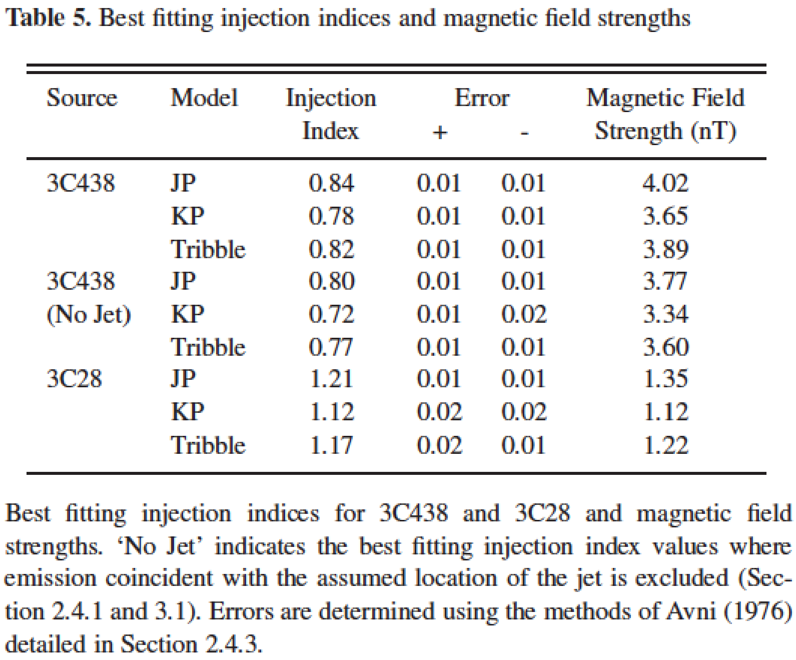
Best fitting injection indices for 3C438 and 3C28 and magnetic field strengths. 'No Jet' indicates the best fitting injection index values where emission coincident with the assumed location of the jet is excluded (Section 2.4.1 and 3.1). Errors are determined using the methods of Avni (1976) detailed in Section 2.4.3.

- **Injection index remains higher than previously assumed, consistent with Harwood et al. (2013)**

- **Tribble model provides the most convincing description of these sources**

- **Significant cross-lobe age variations, using 'slices' not a good idea**

Dynamics and energetics



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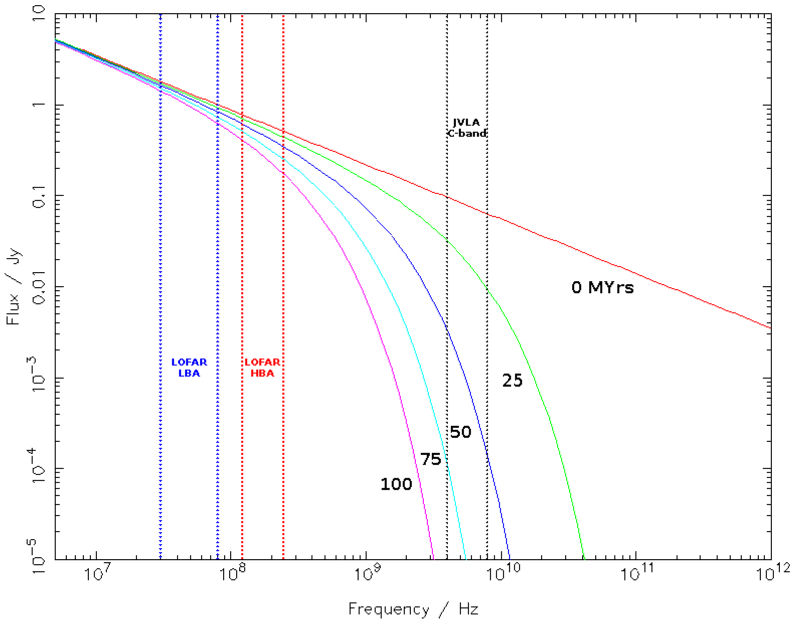
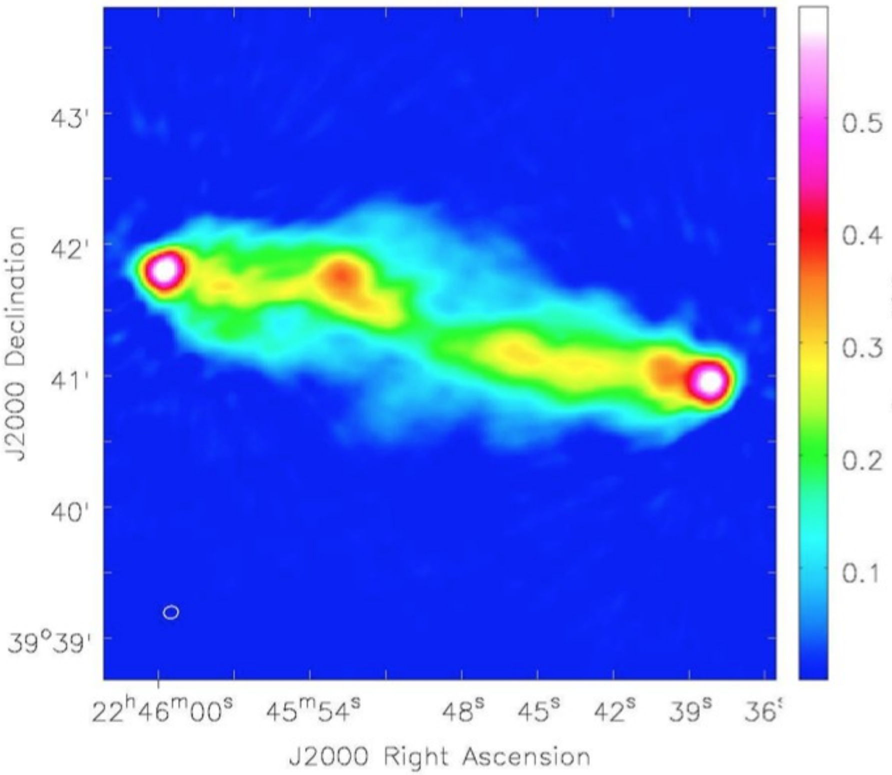
- **Dynamical age much larger than the spectral age**
- **Mach numbers suggest lobes are expanding supersonically**
- **Radiating particles and magnetic field at equipartition cannot support the lobes (i.e. underpressured)**
- **3C28 is most likely a relic source**
- **Off time of between 6 and 9 MYrs**

FR-II radio galaxies at low frequencies I: energetics and morphology (in prep)

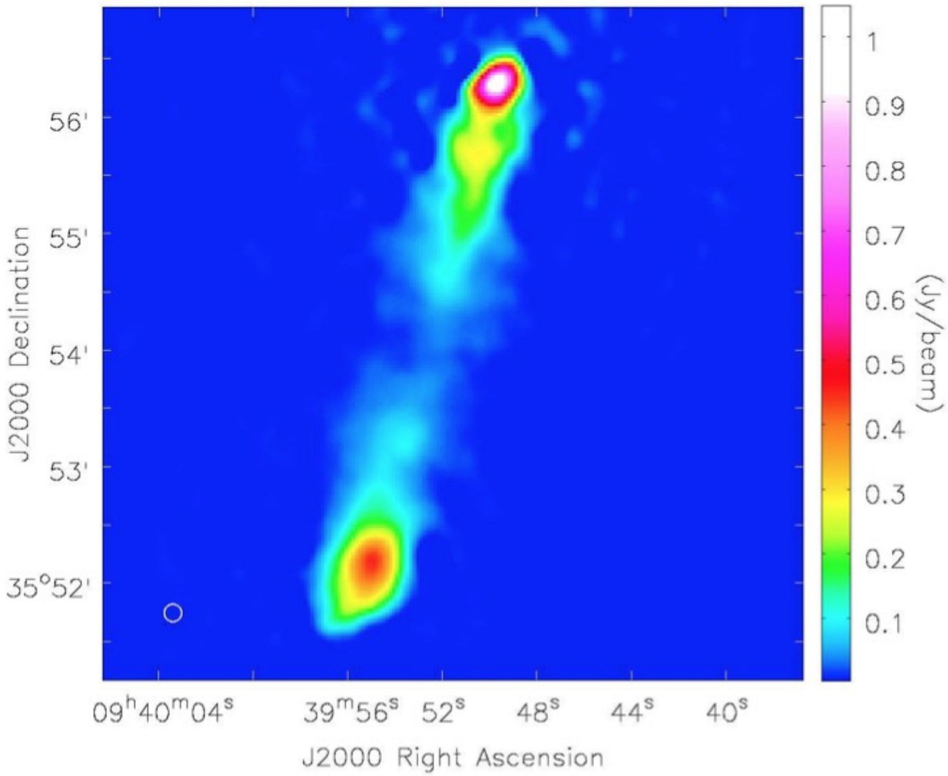
- **Excellent for determining the injection index due to low curvature**
- **Constrain the low-energy electron population (synchrotron / IC fitting)**
- **Low frequency observations are able to probe previously unseen emission**



	3C223	**3C452**
Redshift	0.137	0.081
LAS	306 arcsec	280 arcsec
Physics size	740 kpc	428 kpc

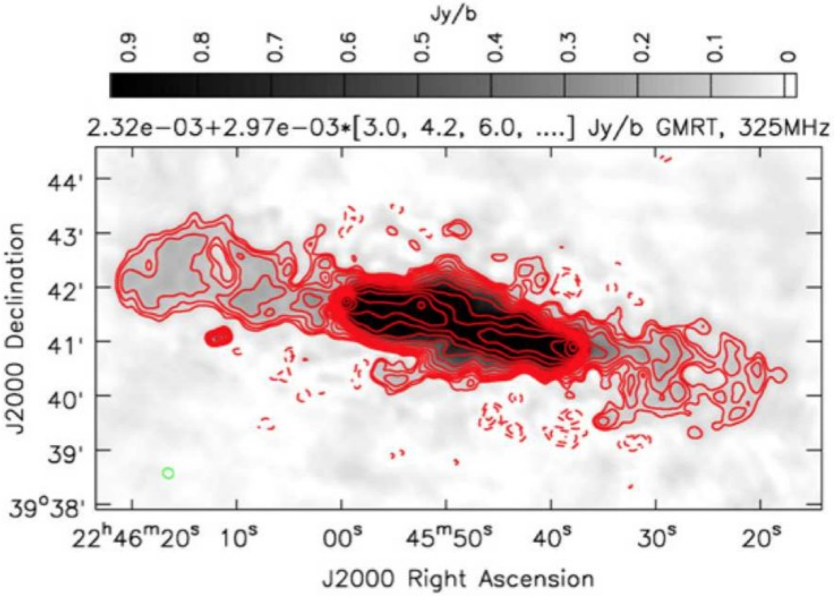


3C452 – 6” beam
48 MHz bandwidth at 138 MHz

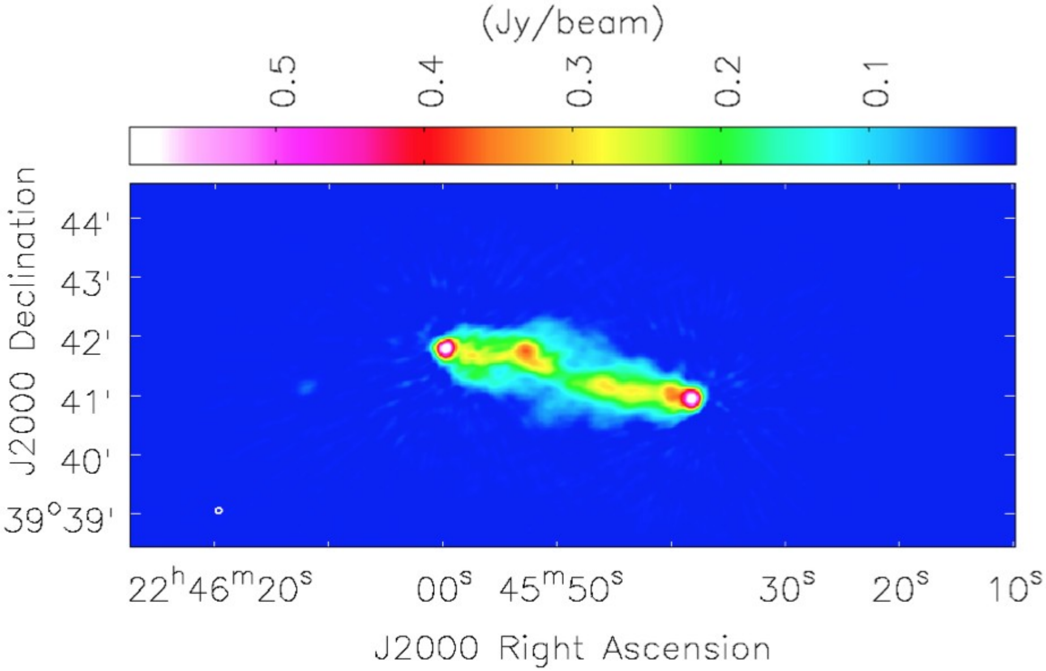


3C223 – 9” beam
42 MHz bandwidth at 147 MHz

325 MHz GMRT presented by Sirothia et al. (2013)

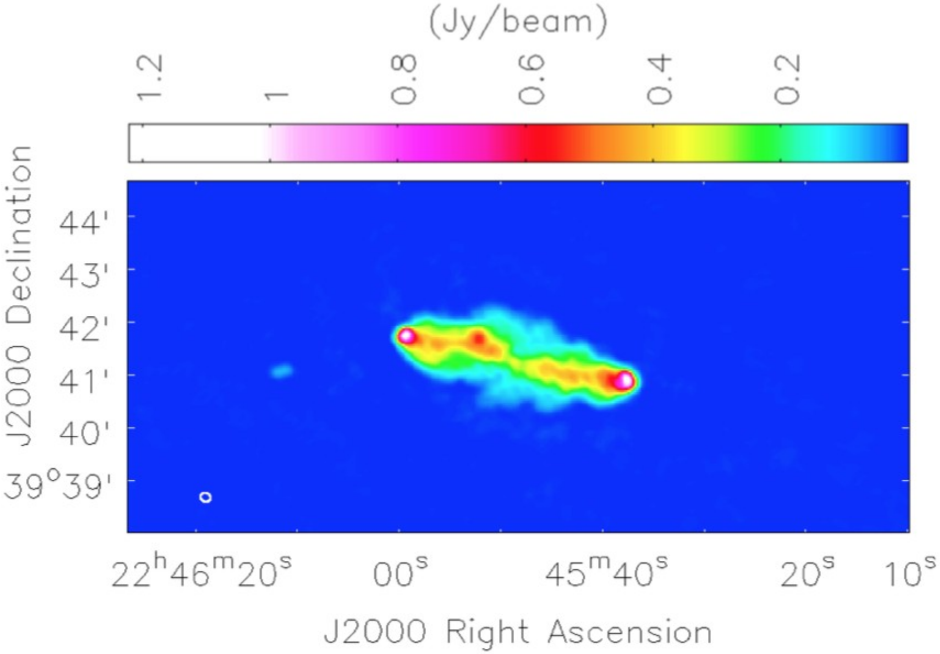


LOFAR Image with comparable field of view

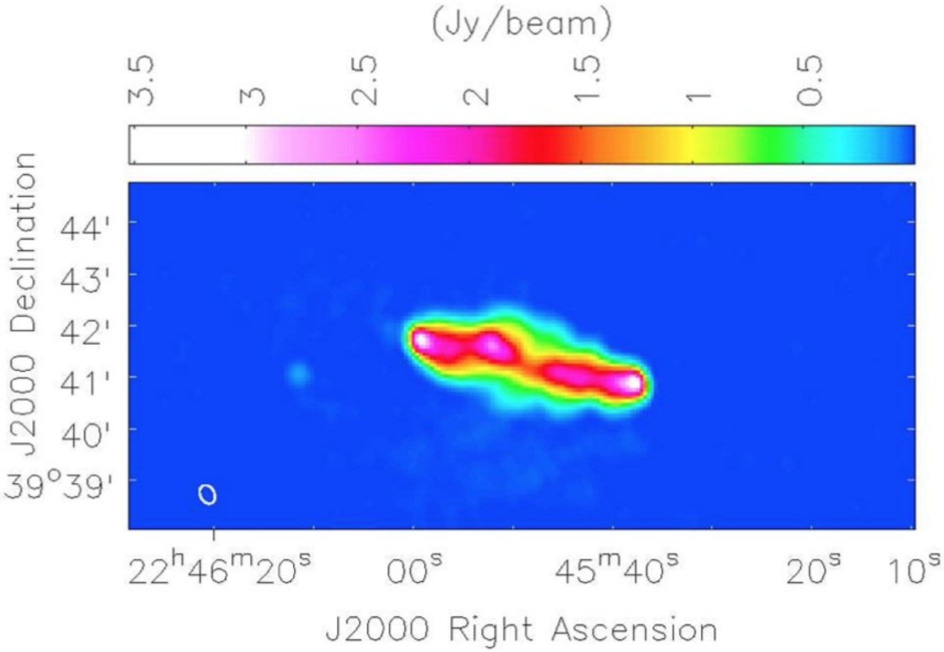


- Assuming an extremely conservative α = 0.5 gives a 3 sigma detection at 17 mJy / beam at 116 MHz (107 mJy / beam for α = 2.3 of Sirothia et al.).
- Outer lobes should be clearly visible with LOFAR, no sign of the relic lobes at HBA frequencies

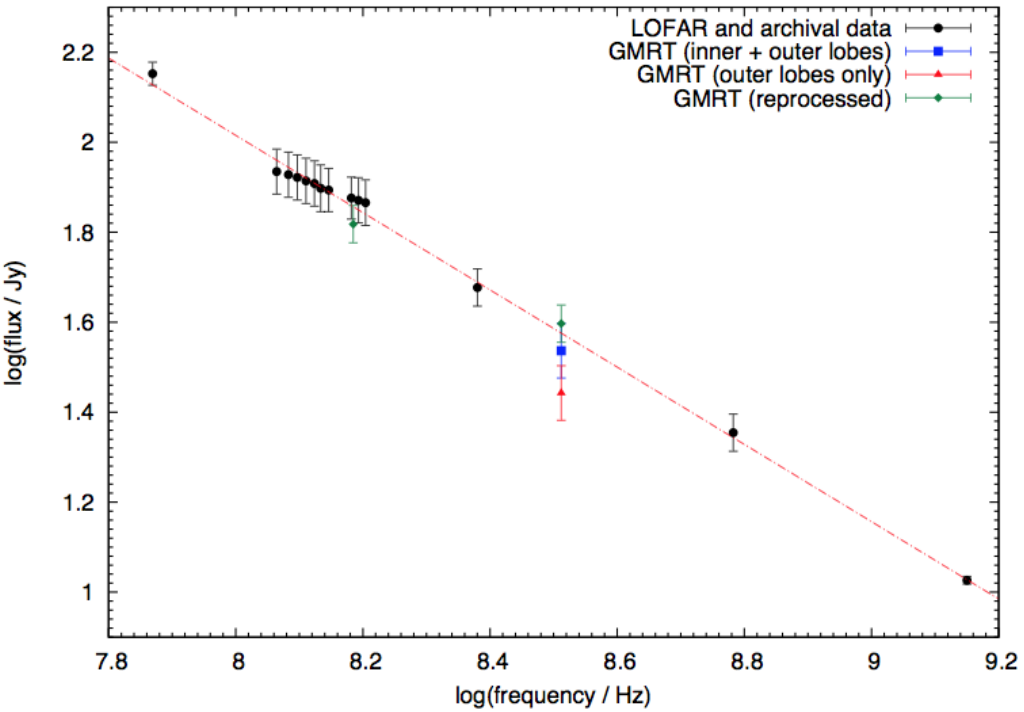
Reprocessed 325 MHz GMRT Image



150 MHz GMRT Image

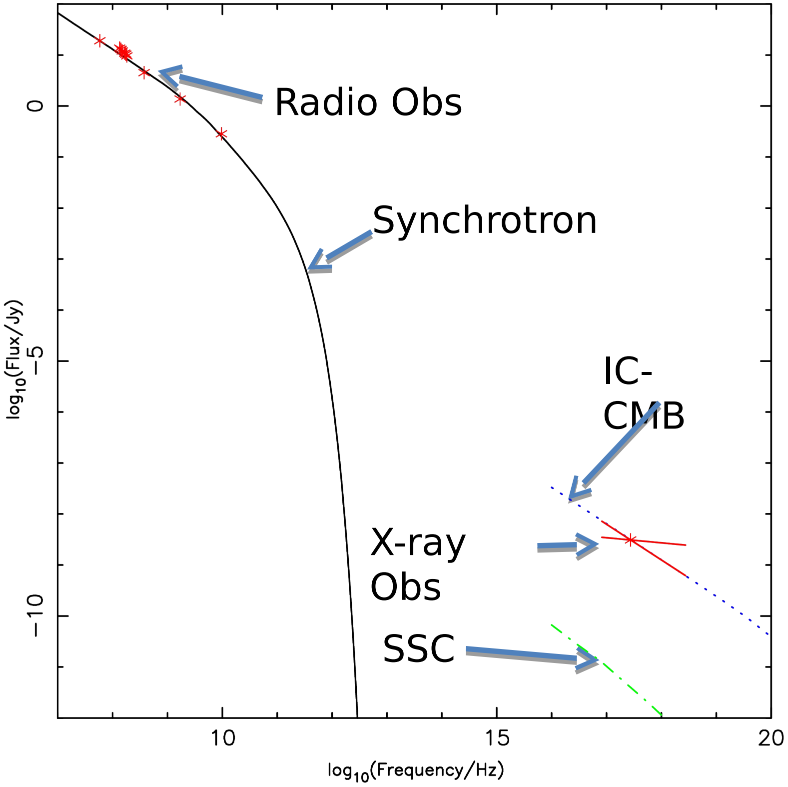


- **We have reprocessed the data at 325 MHz plus archival GMRT data at 150 MHz**
- **The relic emission is not observed at either frequency**



- **Reprocessed GMRT data falls on the expected power law**
- **Inner + outer lobes combined puts the flux of Sirothia et al. Back in agreement**
- **Most likely cause is artefacts introduced during the self-calibration and/or the imaging**

Synchrotron / IC modelling



- **Spectral / injection index of 0.7 - 0.85**
- **Synchrotron / IC modelling can determine the total energy content of the lobes (e.g. Croston et al. 2004, 2005)**
- **Models constrained by radio (synchrotron) and X-ray (inverse-Compton) emission**
- **Improved knowledge of the low-frequency spectrum**

What does this mean for FR-IIs?

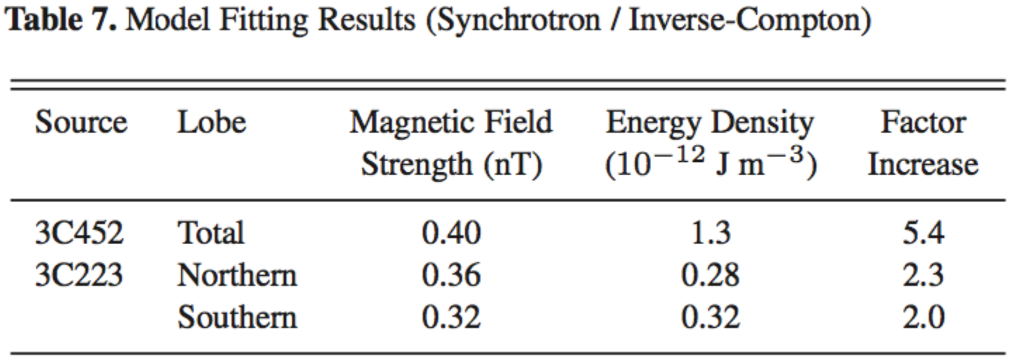


Table 7. Model Fitting Results (Synchrotron / Inverse-Compton)

Source	Lobe	Magnetic Field Strength (nT)	Energy Density (10^{-12} J m^{-3})	Factor Increase
3C452	Total	0.40	1.3	5.4
3C223	Northern	0.36	0.28	2.3
	Southern	0.32	0.32	2.0

- **Total energy content is increased by a factor of 2 for 3C223 and 5 for 3C452 compared to Croston et al. (2004, 2005)**
- **Magnetic field strengths increase, but the ratio of B_{iC} to B_{eq} stays roughly constant**
- **This may go at least part way to resolving the disparity between of spectral and dynamical ages**

What does this mean for FR-IIs?

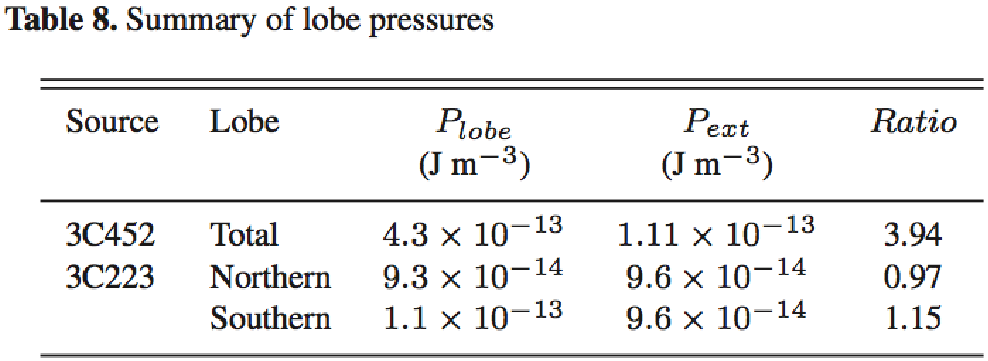


Table 8. Summary of lobe pressures

Source	Lobe	P_{lobe} (J m^{-3})	P_{ext} (J m^{-3})	*Ratio*
3C452	Total	4.3×10^{-13}	1.11×10^{-13}	3.94
3C223	Northern	9.3×10^{-14}	9.6×10^{-14}	0.97
	Southern	1.1×10^{-13}	9.6×10^{-14}	1.15

- **The lobes of 3C223 are brought back into pressure balance (vs. Croston 2004)**
- **The lobes of 3C452 are over pressured, double the estimate from X-ray measurement (Shelton et al. 2011)**
- **The same assumption of flattening has been applied to larger samples**

Summary

- **Injection index values are higher than previously assumed (~0.6 vs 0.8)**
- **The Tribble model provides currently provides the most convincing description when both goodness-of-fit and physical plausibility are considered**
- **3C428 is observed to be expanding, but the energetics cannot account for the necessary pressure to support the lobes (similar to other rich cluster sources e.g. Cygnus A)**
- **3C28 is likely a relic galaxy with an off time of ~6 to 9 Myrs**
- **The total energy content of 3C223 and 3C452 is higher that previously found by a factor of 2 – 5**
- **3C223 is brought back in to pressure balance, 3C452 is significantly overpressured**
- **Departure from equipartition may (in some cases) be able to partially resolve the spectral vs. dynamical age disparity**
- **BRATS software package http://www.askanastronomer.co.uk/brats**