X-ray and radio observations of galaxy groups: the history of AGN heating

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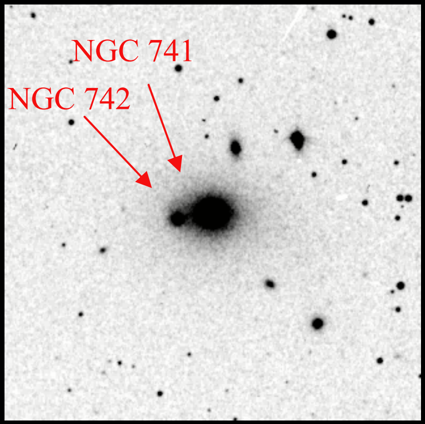
The big picture with the central regions of groups & clusters:

- Often occupied by massive elliptical galaxies

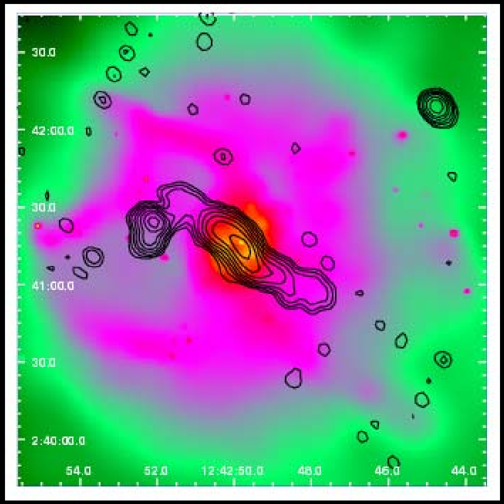
NGC 741 group



DSS image

- These often have powerful radio sources, which interact with surrounding gas

NGC 4636



Chandra image with 610MHz contours

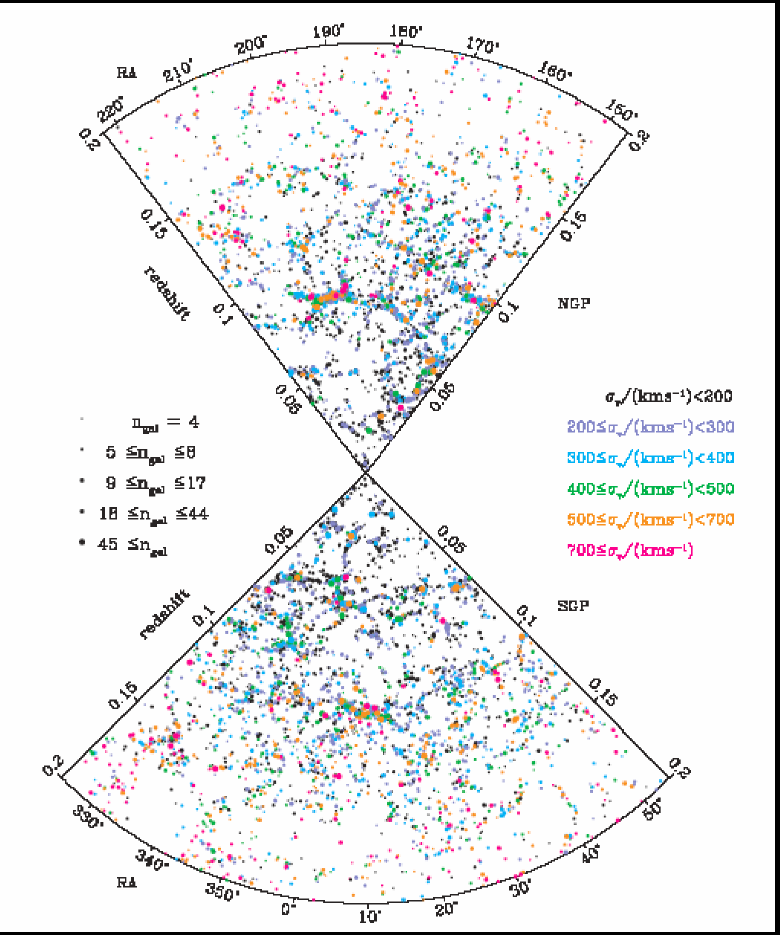
- Prime candidates for feedback/regulation of cooling flows

Why do galaxy groups matter?

- Location of many (most?) galaxies, hence baryons
  - Geller & Huchra 1983: CfA Redshift Survey; density contrast ≥ 20
  - Nolthenius & White 1987: comparison with numerical models
  - Tully 1987: analysis of redshifts
  - Eke et al. 2004 (2dFGRS)
- Prerequisite for understanding formation of structure:

  galaxy => group => cluster hierarchy

  (e.g., Blumenthal, Faber, Primack, Rees 1983, and large subsequent enterprise)
- Most galaxies evolve in the group environment



2dFGRS Percolation-Inferred Galaxy Groups (2PIGGs)

Questions:

- How do X-ray and radio structures correlate?
- What are the properties of central radio sources over a broad freq. range (and what do they imply for ages, repetition times…)?
- What are the effects of AGN at various phases of activity?
- What are the mechanisms of energy injection?

A project to combine X-ray and low-frequency radio data

Examining outbursts in systems smaller than rich clusters has several virtues:

- shallow group potentials $\Rightarrow$ large impact on intragroup medium
- low pressure environment $\Rightarrow$ more apparent ICM interaction
- significant influence on galaxy evolution

Describe *design*, *data*, and *first results* from this project

Sketch of groups observed with *Chandra* and *XMM*

Group	Chandra	XMM
HCG7	(17+19, S, Garmire)	(43, Belsole)
HCG15	-	(35, Lloyd-Davies)
HCG16	(12, S, Mamon)	(42, Schartel, CAL/PV)
HCG31	(39, S, Gallagher)	-
HCG37	(20, S, Ponman)	-
HCG40	(33+15, S, Ponman)	-
HCG42	(35, S, Ponman)	(22+9.5, Ponman)
HCG48	-	(18, Ponman)
HCG51	(40+13, S, Vrtilek)	(15, Turner)
HCG57	-	(46, Fukazawa)
HCG59	(39, S, Gallagher)	-
HCG62	(50+9, S+I, Vrtilek+Fukazawa)	(12+162+32, Turner+Fabian)
HCG68	-	(23, Ponman)
HCG92	(20+100, S, Trinchieri+Vrtilek)	(46, Trinchieri)
HCG97	(58, S, Vrtilek)	(33, Dupke)
NGC315	(56, S, Worrall)	(51, Croston)
NGC326	(100, S, Worrall)	-
NGC383	(45, S, Hardcastle)	(24, Croston)
NGC410	(2.6, S, Murray)	(28+28, Mushotzky)
NGC499	(27, S, Murray)	(12+48, O'Sullivan)
NGC507	(45+27, I+S, Murray)	(36, Kim)
NGC533	(38, S, Sarazin)	(40+8+6, Brinkman)
NGC720	(40+100, S, Garmire+Humphrey)	(47, Turner)
NGC741	(31, S, Vrtilek)	(21, Finoguenov)
NGC777	(10, I, Murray)	(28+28, Mushotzky)
NGC1132	(40+14, S, Garmire+Zabludoff)	(47, Matthews)
NGC1316	(30, S, Kim)	(180, Kim)
NGC1407	(49, S, White)	(67+8, Tully)
NGC1549	(37, S, Bregman)	(20+8+29, Irwin)
NGC1550	(2x10ks, I, Murray)	(31, Takahashi)
NGC1587	(20, I, Ponman)	-
NGC1600	(54, S, Sarazin)	(85, Sarazin)
NGC2300	(46, S, Rasmussen)	(55, Mushotzky)
NGC2563	(48, I, Mulchaey)	(66, Mushotzky)
NGC3079	(30, S, Strickland)	(25+44+11, Watson+Pietsch+Lloyd-Davies)
NGC3091	(32, S, Ponman)	(22, Ponman)
NGC3245	(10, S, Ptak)	-
NGC3411	(31, I, Vrtilek)	(41, Mulchaey)
NGC3557	(40, I, Ponman)	-
NGC3585	(36+60, S, Bregman+Kim)	(22, Ponman)
NGC3623	(2, S, Garmire)	(33, Irwin)
NGC3640	(9, S, Humphrey)	-

Group	Chandra	XMM
NGC3665	(20, I, Ponman)	(41, Lloyd-Davies)
NGC3923	(20+85, S, Murray, Kim)	(45, Buote)
NGC4104	(2.5+36, I+S, Murray+Buote)	(13, Wolter)
NGC4125	(65, S, WhiteIII)	(45, Sarazin)
NGC4168	(5, S, Terashima)	(23, Turner)
NGC4261	(35+100, S, Birkinshaw+Zezas)	(33+103, Sambruna+Trinchieri)
NGC4325	(30, S, Ponman)	(22, Mushotzky)
NGC4636	(50S+150I, Mush.+Jones)	(65, Kaastra)
NGC4649	(40+75, S, Sarazin+Humphrey)	(54, Sarazin)
NGC4709	(30, S, Sun)	(43+8, Dupke)
NGC5044	(20+80, S, Goudfrooij+David)	(24+43+59, Mathews+Lewis)
NGC5129	(47, S, Buote)	(26, Mushotzky)
NGC5171	(25, Ponman)	(25, Ponman)
NGC5266	-	(9, Goudfrooij)
NGC5322	(15, S, Capetti)	(36, Ponman)
NGC5775	(65, S, Maloney)	(41, Dettmar)
NGC5846	(30+90, S+I, Trinchieri+Forman)	(30, Sarazin)
NGC6482	(20, S, Ponman)	(60, Mushotzky)
NGC6338	(48, I, Ponman)	-
NGC6861	(25, I, Murray)	-
NGC6868	(25, I, Murray)	-
NGC7582	(19, S, Murray)	(23+105, Turner+Schurch)
NGC7619	(37+27, S+I, Kim+Forman)	(41, Kim)
IC1459	(60, S, Fabbiano)	(32, Fukazawa)
IC1860	-	(39, Mulchaey)
IC1867	-	(28, Mushotzky)
IC4296	(49, S, Pellegrini)	-
AWM4	(80, S, Vrtilek)	(21, Vrtilek)
MKW2	-	(46, Vrtilek)
MKW4	(30, S, Fukazawa)	(16, Vrtilek)
MKW4S	(36, S, Buote)	-
MKW8	(25, I, Reiprich)	(25, Reiprich)
MKW9	-	(45, Arnaud)
ESO3060170	(2x15, I, Murray)	(18, Forman)
ESO5520200	(26, S, Forman)	(39, Boehringer)
Abell262	(112+29, S, Blanton+Sarazin)	(36+47, Bleeker+Fabian)
Abell2717	(67, I, Markevitch)	(54, Arnaud)
RGH80	(11+39, I+S, Fukazawa+Buote)	(33, Aschenbach)
MS0116.3-0115	(39, S, Buote)	-
RXJ1159.8+5531	(76+19, S+I, Buote+Vikhlinin)	(48, Mathews)
Pavo Group	-	(32, Davis)

83 groups:
15 *Chandra* alone; 10 *XMM* alone; 58 both.

Radio data principally from the GMRT (Giant Metrewave Radio Telescope)

- 30 parabolic reflectors of 45m diameter, with baselines >25 km ⇒ few arcsec resolution even at long wavelengths
- latitude +19º , near Pune, India
- Usable from 50 - 1500 MHz
  (we use 235, 325, and 610 MHz bands)
- Equals or exceeds best sensitivities at these frequencies

- Supplement with archival VLA data at 1.4, 5, 8 GHz

Program targets and status

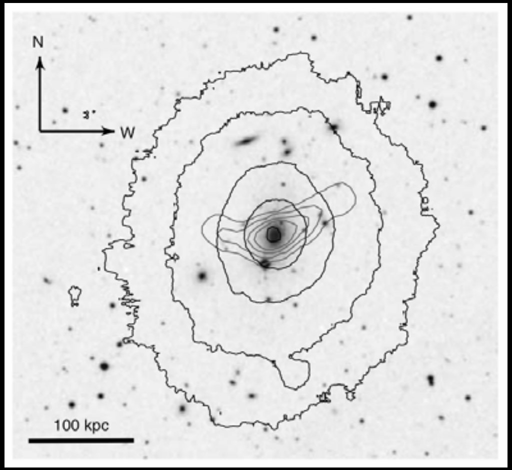
SOURCE	z	S(1.4 GHz) (mJy)	------GMRT observations------ 235MHz	325 MHz	610 MHz	X-ray data Chandra	XMM
UGC 408 (NGC 193)	0.0147	309		4.0 h	3.0 h	C	
NGC 315	0.0165	637			(3.5 h)	C	X
NGC 383 (3C 31)	0.0170	1100			(3.5 h)	C	
NGC 507	0.0165	100			3.7 h	C	X
NGC 741	0.0185	1000	5.0 h	4.0 h	2.3 h	C	X
HCG 15	0.0208	10			4.0 h		X
NGC 1407	0.0059	90			3.3 h	C	
NGC 1587	0.0123	120			3.3 h	C	
MKW 2	0.0380	384	1.7 h		1.7 h		X
NGC 3411	0.0153	38	(5.0 h)		?	C	X
NGC 4636	0.0031	300	(4.0 h)		2.0 h	C	X
HCG 62	0.0137	5	(7.0 h)		4.0 h	C	X
NGC 5044	0.0090	35	2.3(+7.0)h	0.8 h	2.3 h	C	X
NGC 5846	0.0057	20			2.0 h	C	X
AWM 4	0.0318	650	3.0 h	2.0 h	2.5 h	(C)	X
NGC 6269 (AWM 5)	0.0344	51	(5.0 h)		(3.0 h)	C	
NGC 7626	0.0114	130			3.0 h		X

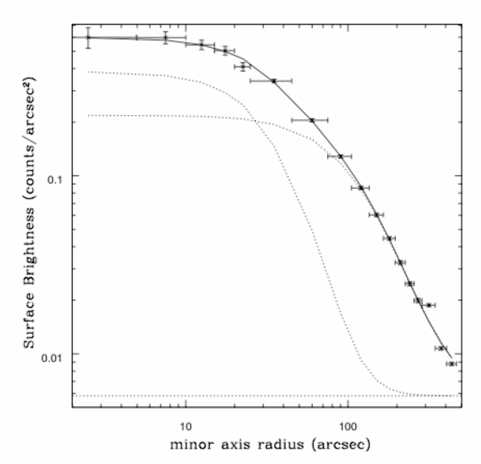
(indicates GMRT observations approved for 2008 January)
(C) => Chandra observation approved for cycle 9

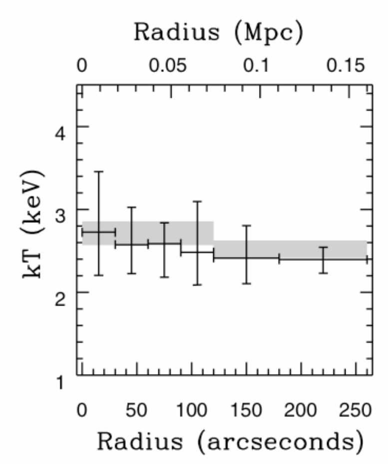
- 17 groups
- All have good *Chandra* or *XMM* data (9 have both)
- Temperatures 1-3 keV
- All have at least NVSS data initially
- Presence of X-ray or radio structure indicative of AGN interaction with hot gas

First example... AWM 4

- Poor cluster (~30 members) centered on giant elliptical NGC 6051
- X-ray bright (~2×10^{43} erg s^{-1}), T~3 keV
- Apparently relaxed (but temperature and abundance maps show extensive disturbance)
- FR I radio source



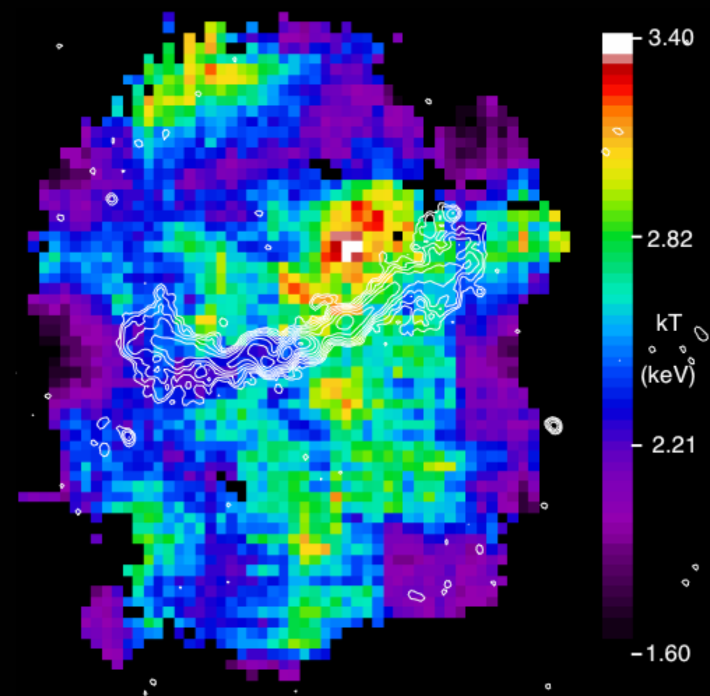


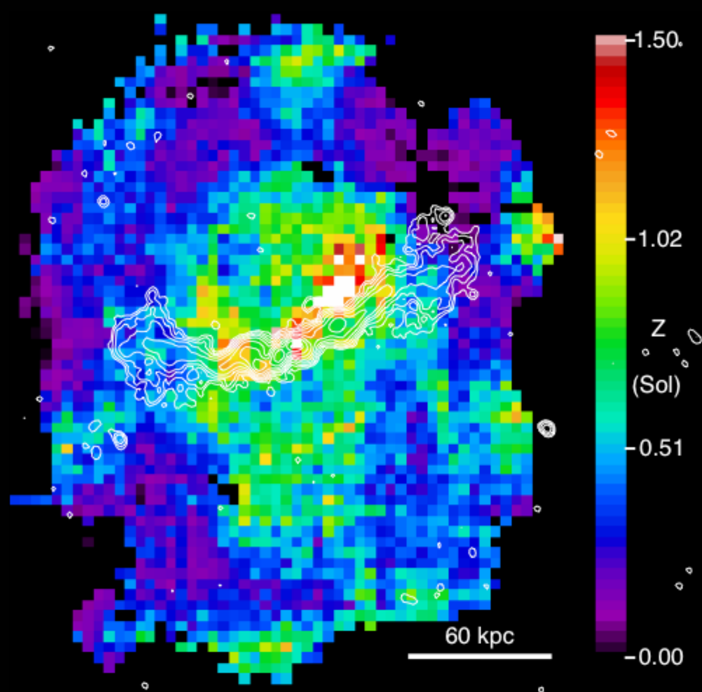


O'Sullivan, Vrtilek, Kempner, David, & Houck (2005)

AWM 4

- Relaxed system, SB profile well described by two β-models
- Isothermal kT profile





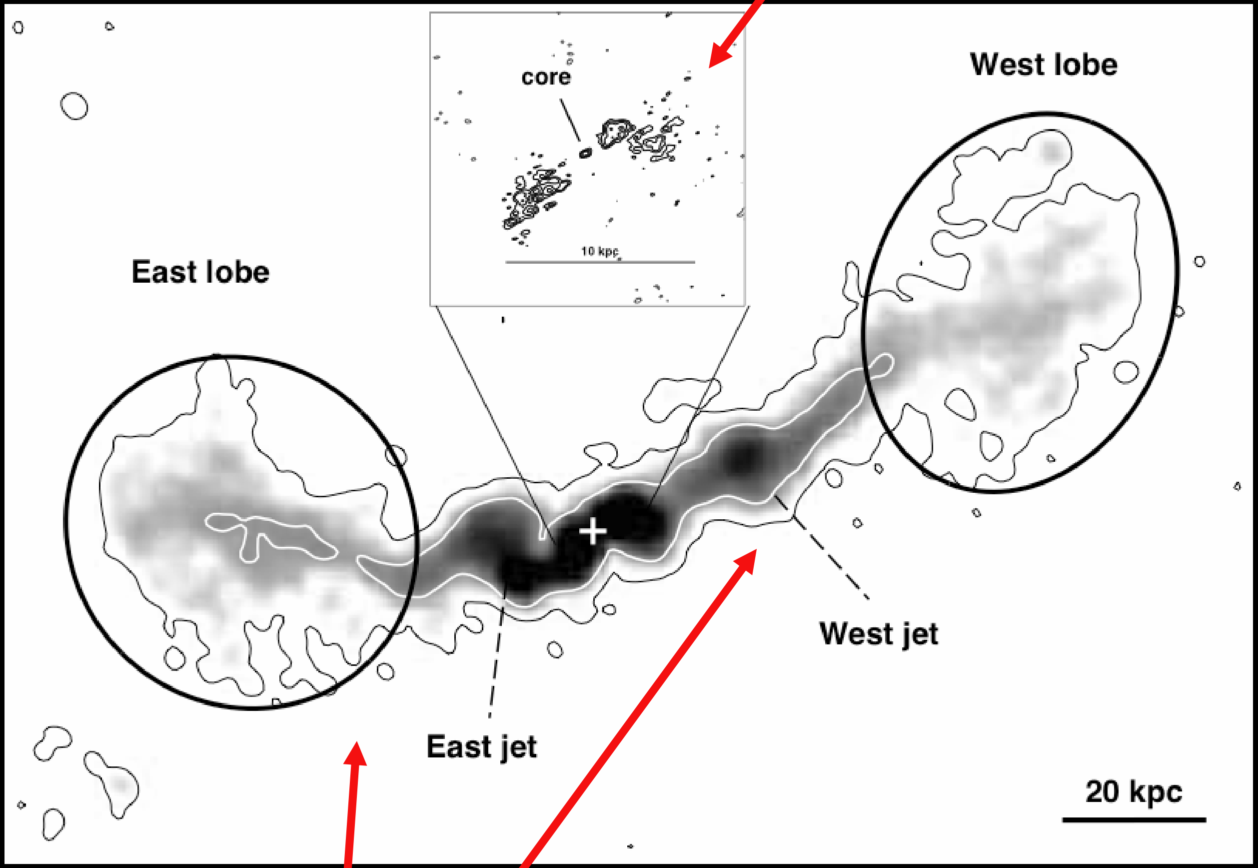
kT and abundance clearly affected by AGN activity - cavity to E, shock and high abundance to NW

X-ray: O'Sullivan, Vrtilek, Kempner, David, & Houck (2005)
Radio: 610 MHz GMRT

Radio overview

- $P(1.4\ GHz) = 1.4 \times 10^{24}\ W\ Hz^{-1}$
- $L_x = 0.8 \times 10^{44}\ erg\ s^{-1}$
- FR type I
- “extreme wide-angle-tail”
- no cooling core
- brightness ratio between east and west jets => jets within ~10° of plane of sky (Lind & Blandford 1985)

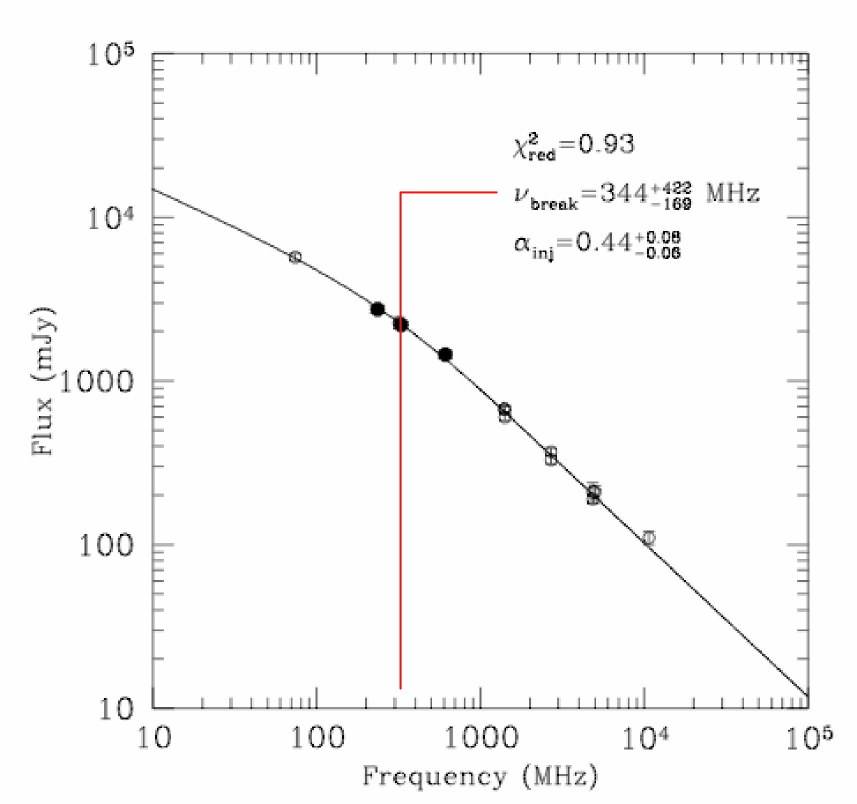
5 GHz VLA: locates core



610 MHz GMRT (resolution: 5 arcsec)

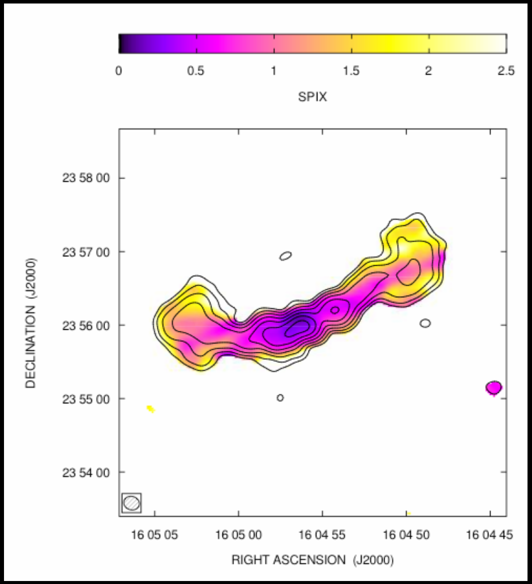
Age of the radio source (1)

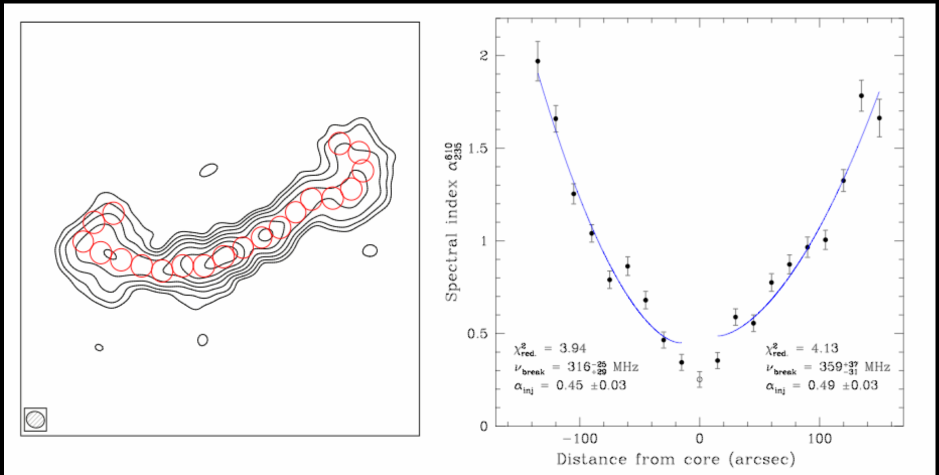
Spectrum of total radio power (filled circles: new GMRT; open circles: literature)



In the context of a continuous-injection model, with new relativistic particles characterized by a power law, the radiative age depends on the break frequency and the magnetic field.

Age of the radio source (2)





Derive age from dependence of spectral index on position along jet (Jaffe and Perola 1974): electron population ages as moves outward with constant expansion velocity

	α_{inj}	ν_{br} MHz	B_{eq} μG	P_{min} dyne cm^{-2}	U_{min} 10^{57} erg	u_{min} erg cm^{-3}	t_{rad} 10^8 yr	v_{growth} (c)
total source (*a*)	$0.44^{+0.08}_{-0.06}$	344^{+422}_{-169}	5.4	8.0×10^{-13}	3.4	2.7×10^{-12}	1.5	0.003
West jet+lobe (*b*)	$0.48^{+0.03}_{-0.03}$	359^{+37}_{-31}	5.5	9.3×10^{-13}	1.7	2.8×10^{-12}	1.4	0.002
East jet+lobe (*b*)	$0.45^{+0.03}_{-0.03}$	316^{+29}_{-26}	5.4	9.0×10^{-13}	1.7	2.7×10^{-12}	1.5	0.002

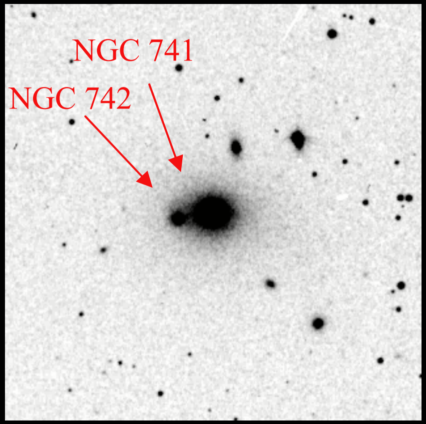
Questions…

- How can we explain the large abundance fluctuations associated with the NW shocked region?
- More detailed look at shocked region
- Reality/characteristics of possible SE cavity
- Explanation for "wiggles" in the jets

Fortunately….
In spring 2008: 80 ks *Chandra* observation is expected

Second example... NGC 741

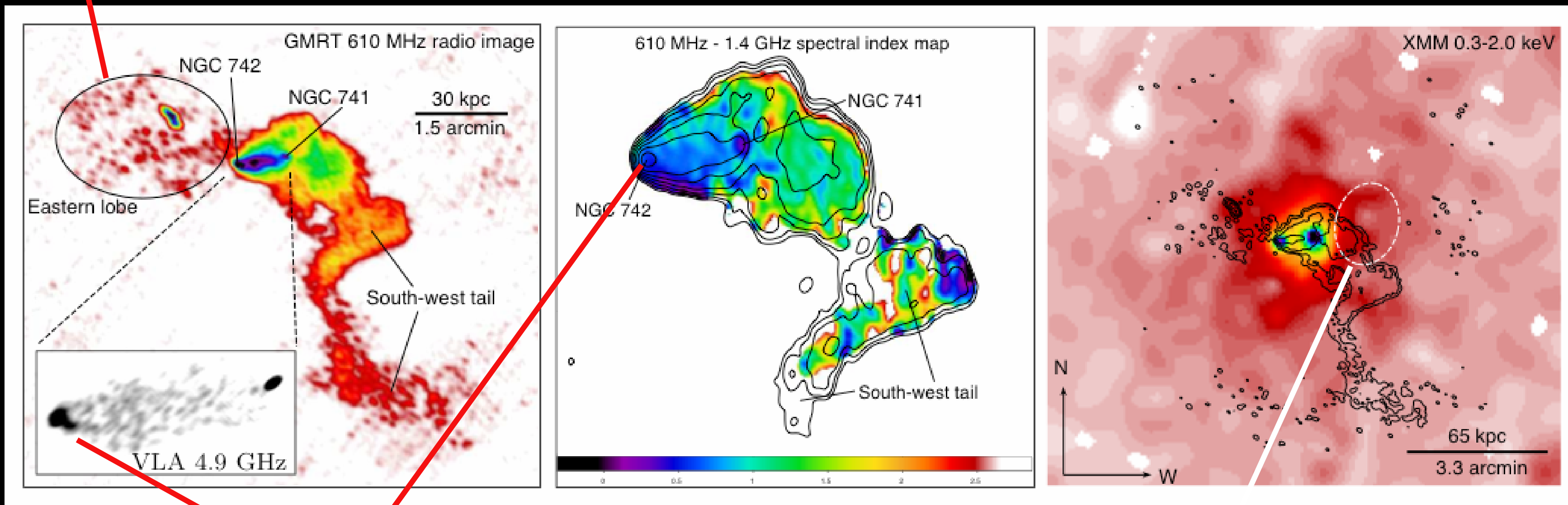
NGC 741 group



- Core of approx. 41-member group (Zabludoff & Mulchaey 1998), with $\sigma_r \sim 430$ km s^{-1}, centered on close (interacting!) pair of early-type galaxies
- $z = 0.019$
  D = 81 Mpc (1' = 24 kpc)
- Narrow-angle tail radio source; bright, complex morphology
- Fine X-ray and radio filamentary structure between central ellipticals

NGC 741: large-scale view

E lobe due to NGC *741*?
Spectral index coming!



NGC 721 is the likely source of
radio tail, and moving rapidly to E

Cavity: Jetha et al. 2007 (A&A, sub.)
Formed by NGC 741?

- NGC 741/742 long known to be strong radio source: 4C 05.10
- Is NGC 741 the principal source? No

- LOS relative velocity of NGC 741 and NGC 742 is ~400 km s^{-1}
- W. bubble imparts enough energy to counter radiative cooling

NGC 741: closeup

What are the effects of NGC 741/742 encounter?

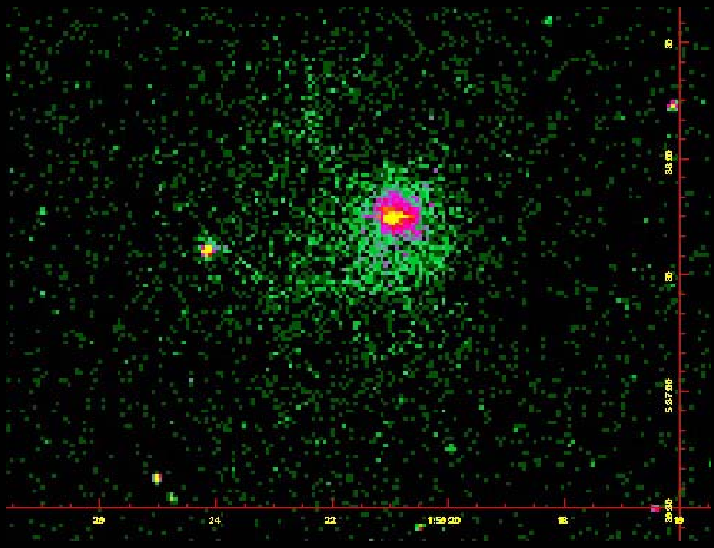
What is the nature of the filaments?

- Edges of “sheets”
- X-ray version of “taffy galaxies”?

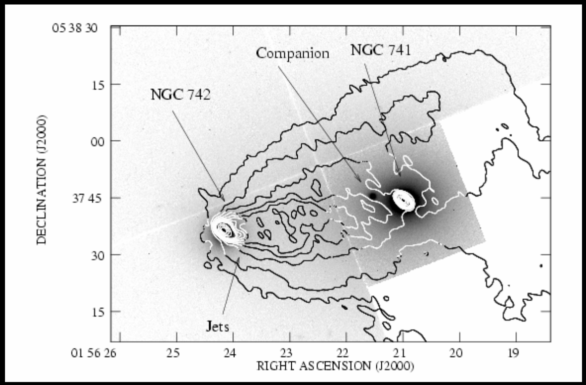
What is the outburst history of both ellipticals?

How have the complex dynamics affected the abundance distributions?

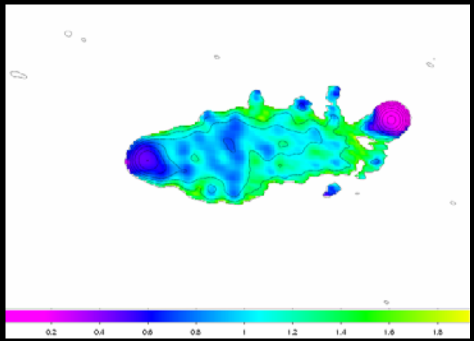
Chandra



1.4 GHz contours on opt. image



1.4 - 5 GHz spectral index



Summary

- *Chandra* and *XMM* provide examples that extend the developing model of the regulation of cooling through repetitive AGN outbursts from rich clusters through the low-mass group regime
- Groups show generally similar phenomenology to clusters, with many X-ray features the direct result of AGN activity
- Central AGN do more than just inject energy into the intergalactic medium: they also promote gas mixing and the distribution of heavy-element enriched material to peripheral regions
- The combination of X-ray and radio group and cluster data offers useful insight into AGN/hot gas interactions timescales, energetics, and