Gas in Galaxy Clusters

Tracy Clarke (NRAO)
June 5, 2002
Albuquerque, AAS

Outline

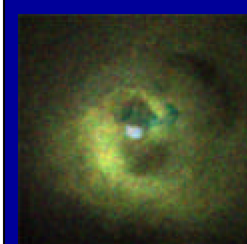
- Radio sources in dense cluster cores
- Mergers & their connection to diffuse radio emission
- Intracluster magnetic fields

Properties of Clusters

- **constituents:** member galaxies
  thermal gas (~10^8 k)
  relativistic particles
  magnetic fields
  dark matter
- **types of clusters:**
  - dense, peaked core, & relaxed morphology
  - flat core & X-ray substructure

Cluster center radio sources

Perseus cluster – z = 0.0183



- brightest cluster X-ray source
- HRI images revealed central holes
- Chandra image of 0.5-1, 1-2, & 2-7 keV data
- colours show holes not due to absorption

Fabian et al. (2000)

Cluster center radio sources

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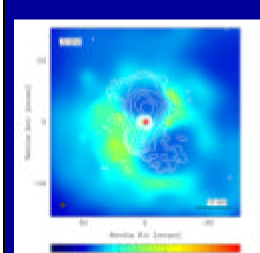
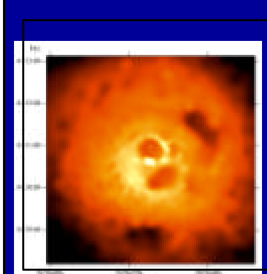


- brightest cluster X-ray source
- HRI images revealed central holes
- Chandra image of 0.5-1, 1-2, & 2-7 keV data
- colours show holes not due to absorption
- VLA 1.4 GHz contours of 3C84 show the radio lobes occupy the X-ray holes
- bright X-ray ridges due to cool (2.7 keV) gas ► not due to shocks
- appears as though radio lobes have pushed aside the thermal gas but there may be some thermal gas remaining

Fabian et al. (2000)

Cluster center radio sources

Perseus cluster continued

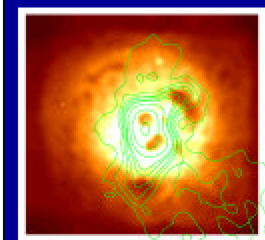


- smoothed Chandra ACIS-S image
- outer X-ray holes to the NW and S of the cluster core (previously seen by Einstein)
- sharp edges on NW hole

Fabian et al. (2002)

Cluster center radio sources

Perseus cluster continued



- smoothed Chandra ACIS-S image
- outer X-ray holes to the NW and S of the cluster core (previously seen by Einstein)
- sharp edges on NW hole
- VLA 74 MHz contours of 3C84 show radio spurs toward outer X-ray holes
- spectral index map shows steepening toward outer X-ray depressions
- outer holes may be due to buoyant detached radio lobes

Fabian et al. (2002)

Cluster center radio sources

Perseus cluster – **Physics lessons** (details in Fabian et al. 2002)

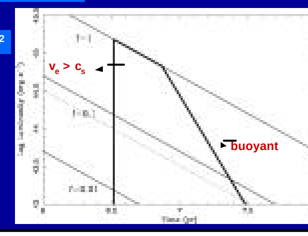
Inner Lobes – dynamics of N lobe

- expanding radio lobe does PdV work on surrounding gas to create holes
- for the observed radius of 7.5 kpc need: $L_{45} t_7 = 0.5\ P_{th} f$
- lack of shock requires: $L_{45} < 14\ P_{th}\ t_7^2\ f$
- pre-buoyant stage implies: $L_{45} > 1.2\ f^{5/2}\ t_7^2$

$L_{jet} = 10^{44} – 10^{45}$ ergs/s

$L_{rad} = 10^{40} – 10^{41}$ ergs/s

$t_{hole} \sim 10^7$ yr



Cluster center radio sources

Perseus cluster – **More Physics** (details in Fabian et al. 2002)

Inner Lobes –

Equipartition: ν_1=10MHz, ν_2=1.4GHz

$E_e = a\ B^{3/2}$ ergs

$E_{tot} = a\ k\ B^{3/2} + b\ f\ B^2$ ergs

↓

$B_{eq} = 1.9\times10^5\ (k/f)^{2/7}$ mG

$P_p + P_B = 1.3 \times 10^{-2}\ (k/f)^{4/7}$ keV/cm^3

Equilibrium:

rims: $P_{th} = 0.5$ keV/cm^3

$P_{th} / (P_p + P_B) = 40\ (k/f)^{-4/7}$

↓

- to be in equilibrium at equipartition need:

$k/f \sim 600$

Cluster center radio sources

Perseus cluster – **More Physics** (details in Fabian et al. 2002)

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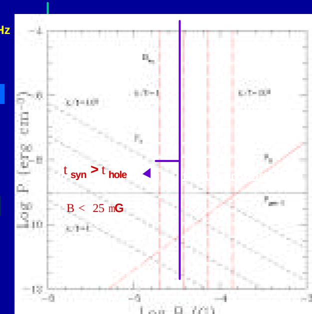
Equipartition is ruled out



Cluster center radio sources

Perseus cluster – **Yet More Physics** (details in Fabian et al. 2002)

Inner Lobes – radiative losses

keep equilibrium assumption:

$P_p + P_B = P_{th}$

- observe distribution of emission requires synchrotron cooling time to be greater than age of X-ray hole

$t_{syn} = 40\ B^{3/2}\ n_9^{-1/2} > r/c_s = 10^7$ yr

↓

B < 25 mG

Rules out equipartition solution

Cluster center radio sources

Perseus cluster – **Yet More Physics** (details in Fabian et al. 2002)

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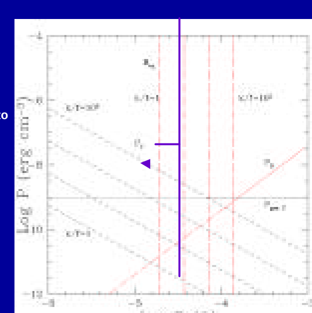
Rules out equipartition solution

- combining radiative and dynamical constraints yields region of k and f



Cluster center radio sources

Perseus cluster – Yet More Physics (details in Fabian et al. 2002)

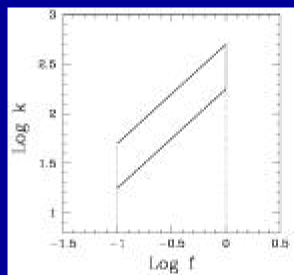
Inner Lobes – results

combining the dynamical and radiative constraints:

- k – ratio of the total particle energy to energy of particles radiating at n > 10 MHz
- f – filling factor of relativistic particles

If f = 1 then: 180 < k < 500

typical values from the literature are k = 100, f = 1



Cluster center radio sources

Perseus cluster – Physics cont. (details in Fabian et al. 2002)

Outer Lobes –

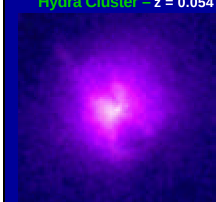
- based on buoyancy arguments and assuming a high filling factor:

t_{hole} ~ 6x10^7 yr

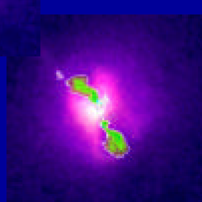
- synchrotron spectral ageing arguments from low frequency emission agree well with buoyancy arguments for B ~ 10 m G
- this field is ~ pressure equilibrium with surroundings
- sharp edges suggest magnetic fields in bubbles are suppressing instabilities

Cluster Center radio sources

Hydra Cluster – z = 0.054

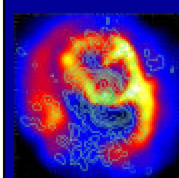


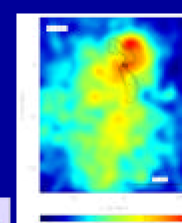
McNamara et al. (2000)

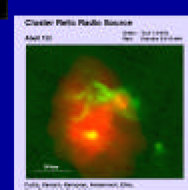


- X-ray data show clear depressions in the X-ray surface brightness coincident with the radio lobes of Hydra A.
- no evidence of shock-heated gas surrounding the lobes suggesting subsonic expansion of the lobes
- need pV ~ 1.2 x 10^{59} ergs to make holes which at c_s give t_{hole}~2 x 10^7 yr

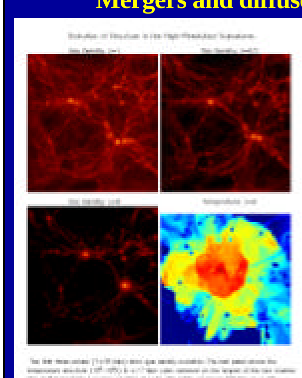
Cluster center radio sources







Mergers and diffuse radio emission

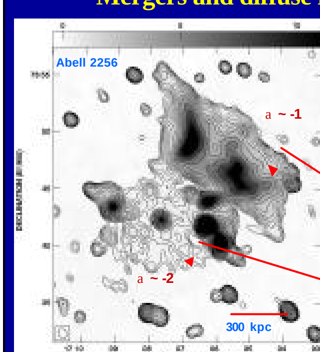


- clusters form at the intersection of filaments

Burns et al. (2002) AMR simulation of ΛCDM closed universe

- major cluster merger can inject few x 10^{63} ergs into the ICM
- energy will go into heating and compression of thermal gas, particle acceleration and magnetic field amplification

Mergers and diffuse radio emission



Clarke & Ensslin (2001)

Observations toward some clusters reveal large regions (>500 kpc) of diffuse synchrotron emission which has no optical counterpart. Connected to clusters showing evidence of merger activity.

Observational classifications of diffuse emission:

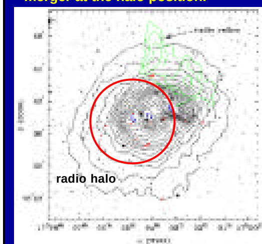
Relics: peripherally located, elongated, generally have sharp edges, often highly polarized (P > 20%), spectral index (a ~ -1.1)

Halos: centrally located, symmetric, no obvious edge, no measurable polarization, steep spectral index (a < -1.5)

Mergers and diffuse radio emission

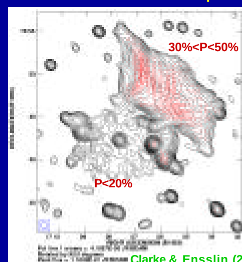
Chandra observations of A2256

X-ray substructure reveals evidence of both a current merger at the location of the relics and possibly a remnant of an older merger at the halo position.



Sun et al. (2001)

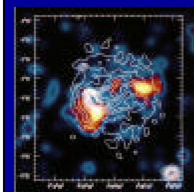
Polarization studies of A2256 show a high degree of linear polarization in the radio relics. The fields follow bright synchrotron filaments and are ordered on scales of > 300 kpc.



Clarke & Ensslin (2001)

Mergers and diffuse radio emission

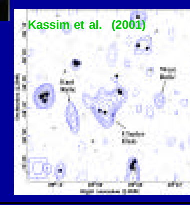
Abell 754



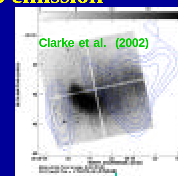
Zabludoff & Zaritsky (1995)

- smoothed galaxy distribution shows bimodal structure along same axis as X-ray substructure indicating a merger event

- VLA 74 MHz observations reveal extended emission is the cluster core and steep spectrum emission toward cluster periphery
- emission confirmed by follow-up observations



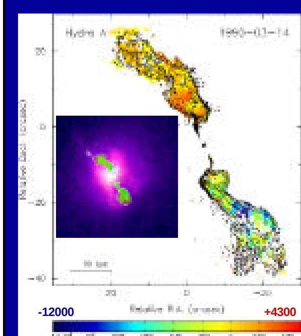
Kassim et al. (2001)



Clarke et al. (2002)

- locations of steep spectrum (a ~ -1.5) emission at edge of X-ray bar suggests that merger shock has accelerated relativistic particles
- B_{min}(halo) ~ .94 mG, U_{min} ~ 1.8x10[58] erg
- B_{min}(relic) ~ .86 mG U_{min} ~ 1.1x10[58] erg

Intracluster Magnetic Fields



Taylor & Perley (1993)

- high-resolution VLA polarimetry of Hydra A reveals extremely high RMs
- RM distribution shows fluctuations on scales of 3 kpc with a tangled field strength of ~ 30 mG
- large scale order across the lobes requires scales of 100 kpc for a uniform field component ~ 6 mG

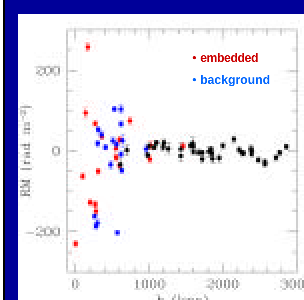
- Faraday rotation measure studies of radio sources embedded in dense (cooling flow) cluster cores reveal:

|B|~10 – 50 mG, l ~ 2 – 10 kpc

- In less dense clusters RMs show:

|B|~0.5 – 10 mG, l ~ 10 – 30 kpc

Intracluster Magnetic Fields



Clarke et al. (2002)

- statistical study of RMs in a sample of 16 galaxy clusters

RM excess to b > 500 kpc

B_{slab} ~ 0.5 – 3 mG

- analysis of 3 extended sources:

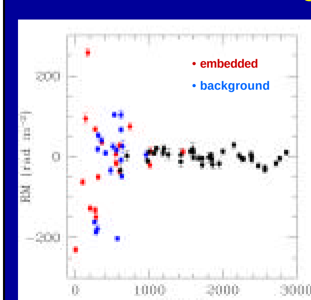
Scale ~ 10 kpc

B_{cell} ~ 5 – 10 mG

- more realistic field topology contains filaments
- areal filling factor on 5 kpc scale of magnetic fields > 95%
- splitting the Faraday probes into embedded and background sources shows clear RM excess in both samples

Faraday excess is due to presence of magnetic fields in the foreground intracluster medium

Intracluster Magnetic Fields



Clarke et al. (2002)

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Summary

- spatial resolution of low frequency interferometric observations is well matched to the new generation of X-ray data
- radio observations at n < 2 GHz are critical to understanding the merger history and dynamics of the intracluster medium
- detailed joint analysis of the thermal and non-thermal components of the ICM is needed in more systems

Future Instruments

- new low frequency capabilities of the VLA and the GMRT are just the beginning
- the improvement in sensitivity of the EVLA may detect > 100 radio relics, while the low frequency capabilities of LOFAR may increase this to > 1000 (Ensslin & Bruggen 2001). The high resolution and sensitivity of these instruments will provide critical details on the low energy particle population in cluster center radio galaxies. The EVLA will permit statistical Faraday studies of IC magnetic fields in individual galaxy clusters.