Initial Results from a Very Deep Chandra Observation of the Galaxy Group NGC 5813

S. W. Randall - CfA
P. Nulsen, W. Forman, T. Clarke, M. Donahue, S. Giacintucci, C. Jones, M. Sun, E. Churazov, L. David, R. Kraft, E. Blanton, A. Simionescu, & N. Werner
Deepest Chandra Group Observation to Date

NEW 650 ksec image, previous work in Randall+11
Why NGC 5813?

- NGC 5813 shows three pairs of collinear cavities and associated concentric surface brightness edges from three *distinct* outbursts of the central AGN.

- Is therefore *uniquely* well suited to the study of AGN feedback (the balance of heating and cooling in the IGM, evolution of buoyantly rising cavities or "bubbles", outburst history of the central AGN, etc.).

- Feedback is the most likely solution to the cluster “cooling flow problem”.
Early XMM-Newton and Chandra observations showed that there is not as much gas cooling to low temperatures as predicted in "cool core" clusters.

Gas must be heated, most likely through feedback with the central AGN (McNamara & Nulsen 2007).
The AGN Feedback Cycle

Gas cools → Flows onto AGN → Drives AGN outburst → Jets inflate cavities, driving shocks

Slows mass flow, and heating ← Slows cooling ← Cavities and shocks heat ICM ← Cavities rise buoyantly

Mechanical energy available to heat the ICM and balance radiative cooling is in cavities and shocks
Why Do We Care About Feedback?

- Solution to the “cooling flow problem”
- Affects the structure and evolution of clusters and groups
- Buoyant bubbles redistribute gas and metals
- Need to understand to use clusters as cosmological probes
- Regulates black hole growth rate
- Regulates star formation rate => galaxy evolution theory
Many Cavity Examples...

NGC 5044: David+09

M87: Forman+07

Abell 2052: Blanton+09,10,11

M84: Finoguenov+08

Galaxy Clusters, Madrid, 2012
...Only a Few Shocks

Kraft+08, Croston+09

McNamara+05

Blanton+11

Forman+07

Fabian+06

Galaxy Clusters, Madrid, 2012
Observations of Cavities

- Cavities are easy to detect, and are seen in many systems (clusters, groups, and galaxies), but typically less ordered than in NGC 5813

- Generally, the total energy of the cavities (estimated from PV work) is sufficient to offset cooling (Birzan+04, Dunn & Fabian 04, Rafferty+06)

- However, the details of how and where the cavities release their energy to heat the ICM are poorly understood
What About Shocks?

- Expect a total shock energy similar to cavities, especially soon after the outburst

- Basic shock physics is well understood

- Shocks will naturally heat the ICM isotropically, and more strongly near the AGN, as required for feedback
Three pairs of collinear, regular cavities, with associated edges (SW outer cavity and outer edge revealed by new obs.)

Radio spectral index steepens rapidly with cavity radius

Cooler group temperatures easier to measure with Chandra

Beta-model divided images
Shocks are clearly visible, even in the temperature map.

Cool gas filament, lifted by buoyant bubbles.
Azimuthally averaged profiles
(from original 150 ks observation, SR+11)

NW shock, 150 ks

NW shock, 650 ks

Galaxy Clusters, Madrid, 2012
$kT$ profile of outer SE shock from new deep observations
Shock Structure

- All surface brightness edges are well-modeled by a discontinuous power law density model:
  - Core shocks: $\rho_1/\rho_2 = 1.97$, $M = 1.71$
  - Middle shocks: $\rho_1/\rho_2 = 1.74$, $M = 1.52$
  - From new data (preliminary):
    - Outer shocks: $\rho_1/\rho_2 = 1.44$, $M = 1.30$
IGM Heating from Shocks

- Only some fraction of shock energy goes into heating (and this fraction is small for weak shocks)

- Lasting heating comes from change in entropy, so the heating done by the shock expressed as a fraction of the thermal energy in the gas $E_{\text{therm}}$ is:
  $$\Delta Q \sim T \Delta S \Rightarrow T \Delta S / E_{\text{therm}} \sim \Delta \ln [ P / \rho^\gamma ]$$  (see Nulsen+07) (known from shock physics)

- Therefore, $(1/ \Delta \ln [ P / \rho^\gamma ]) \text{ shocks per *local* cooling time}$ are needed to replenish $E_{\text{therm}}$ and fully balance radiative cooling (repetition rate is $\sim 2 \times 10^7$ yr, form shocks)
Shocks Alone Can Do the Job!

- Can calculate local cooling time directly from observations
  - \( t_{\text{cool,inner}} \sim 2 \times 10^8 \text{ yr} \) (10 shocks per \( t_{\text{cool}} \), 10 required)
  - \( t_{\text{cool,middle}} \sim 9 \times 10^8 \text{ yr} \) (45 shocks per \( t_{\text{cool}} \), 20 required)
  - From new data: (at \( \approx 26 \text{ kpc} \))
    - \( t_{\text{cool,outer}} \sim 2 \times 10^9 \text{ yr} \) (100 shocks per \( t_{\text{cool}} \), 77 required)
    - \( (t_{\text{cool,outer}} \text{ on the order of the group age}) \)
  - Agreement is remarkably good for rough estimates!

- This heating takes place near the core, close to the central AGN where the Mach numbers are large, as is required for AGN feedback (in contrast to the internal energy in bubbles)
What to Take Away

- Although the energetics of X-ray cavities are sufficient to offset radiative cooling, the details of the heating process are not well understood.

- Shocks also heat the gas, isotropically and in the core, in an understood way.

- Detecting outburst shocks (especially with measured temperature jumps) is difficult.
NGC 5813 *uniquely* shows collinear cavities and shocks with temperature jumps from *three* outbursts, and is ideal for studying AGN feedback, shock heating, outburst history, and buoyant bubble evolution.

- With the new deep data, we can see that, in this case, shocks *alone* offset cooling within the central 26+ kpc (improvement from 15+ kpc from initial observations).

- Entirely plausible that shocks do the job at small radii in other systems, but are more difficult to find.

- This not only solves the cooling flow problem, but also has important implications for galaxy evolution theory (e.g., Kormendy+09).
Thank You
Outburst History of the AGN

- Total shock energy from pressure change within shock front: $\nabla P \sim E_{\text{shock}}/V$
- Cavity internal energy $E_{\text{cav}} \sim 3PV$
- Outburst age from shock travel time
- Gives outburst total kinetic luminosity:
  - $W_{\text{inner}} \sim 0.6 \times 10^{42} \text{ erg/s}$
  - $W_{\text{middle}} \sim 6.5 \times 10^{42} \text{ erg/s}$
- With new deeper observation:
  - $W_{\text{outer}} \sim 7.5 \times 10^{42} \text{ erg/s}$
Hα image from SOAR

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Galaxy Clusters, Madrid, 2012
Observations of Outburst Shocks

- There are a handful of AGN outburst shocks detected, many fewer than X-ray cavities

- Outburst shocks tend to be weak, with $M\sim 1.1-1.8$

- Need to measure temperature rise across edge to confirm as a shock (and not a “cold front” from gas sloshing)

- Detecting temperature rise is generally very difficult (weak shocks, thin shock fronts, obscured by complicated central structure, ICM projection, and rarified region)
Deprojected temperature, density, and pressure for A2052. Positions of the shocks are indicated.

Blanton+11

A2052: 660 ksec
kt jump only across inner shock, after deprojection

Perseus: 900 ksec
Originally isothermal shock claimed. kt rise detected behind shock with deprojection (Graham+08)
Model shock with hydro-code as a point explosion in an isothermal, power law density gas sphere

Predicted projected temperature jump of \(~ 0.1 \text{ keV}\) is consistent with observations (and Mach number exactly matches above estimate)
What About Heating?

- Within 170” (26.3 kpc) $U_{\text{gas}} = 1.7 \times 10^{58} \text{ erg}$, $t_{\text{cool}} = 1.0 \text{ Gyr}$

- Outburst repetition rate (from bubble rise times and shocks) is $\sim 10^7 \text{ yr}$

- Gives 100 shocks per cooling time, with $E_{\text{shock}} = 2 \times 10^{57} \text{ erg per shock}$ (from observations and hydro simulations), gives more than 10 x’s total energy needed to offset cooling
To measure shock properties, fit the integrated emission measure profile with a discontinuous power law density model.
- Three pairs of collinear, regular cavities
- Sharp surface brightness edges associated with inner and middle pairs
- Radio spectral index steepens rapidly with cavity radius
Outburst Energy

- The total shock energy is roughly $E_{\text{shock}} \sim PV (f_p - 1)$
  [Also estimated shock energy from hydro simulations]

- Cavity internal energy is $\sim 3 PV$

- Total outburst energy $\sim$ shock energy + cavity internal energy

- Outburst repetition rate is $\sim 10^7$ yr (from cavities and shocks), so we can calculate the mean outburst power
Results

- Total previous outburst energy more than 10 x’s that of the current outburst ($1.5 \times 10^{56}$ erg vs. $4 \times 10^{57}$ erg)

- Mean power of the current outburst is also less ($1.5 \times 10^{42}$ erg/s vs. $1 \times 10^{43}$ erg/s)

- Conclusion: Mean outburst power can vary significantly over long ($\sim 10^7$ yr) timescales, even in an otherwise relaxed system
High resolution temperature map of the core

- Rims around central cavities are hot and over-pressured, also consistent with shocks
Moral: Outburst Shocks with kT Jumps are VERY Difficult to Detect

- Shocks are weak, and shock fronts are thin
- Obscured by complicated central structure
- Projection effects (from the ICM and post-shock adiabatic expansion) mask kT jumps
Hint of an outer edge associated with the outer cavities (?)

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Ideal for the Study of Feedback

- Three pairs of collinear, regular cavities
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Residual map (original 150 ks only)
Jumps in the projected temperature (left) and pseudo-pressure (right) maps identify edges as shock fronts.

- Cool trail corresponds to Hα emission, presumably buoyantly uplifted gas.
Red: 0.3 - 1.2 keV; Green: 1.2 - 2.0 keV; Blue: 2.0 - 7.0 keV.