A Multi-Wavelength Study of BCGs in Cooling Flow Clusters with the MMTF

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Massive galaxy clusters have $L_X$ high enough in the central region that the X-ray plasma should cool radiatively in less than a Hubble time.

$$\dot{M} = \frac{2L\mu m}{5kT}$$

Should dump 10-100 $M_\odot\,\text{yr}^{-1}$ of cool gas on the BCG

- Not seen!
- Invoke AGN feedback to prevent cooling…
  - “Housekeeping mode”
Warm Ionized Gas in BCGs

- A distinguishing property of cooling flow clusters is the presence of ionized gas in the BCG.
  - i.e. Perseus A (NGC1275)
- In local Universe, typically see thin, filamentary morphology.
- Hard to build large database due to the rarity of rich clusters
  - i.e. few at a given $z$

(Perseus A; Conselice 2001)
Warm Ionized Gas in BCGs

Several theoretical explanations for the presence and heating of the gas:

- Star formation
- Buoyant radio bubbles
- Gas drag in the cooling flow
- Cosmic ray heating
- Stripped gas from infalling galaxies

But hard to argue for a formation scheme with only 1-2 systems!

(Perseus A; Conselice 2001)
1. Background: The Maryland-Magellan Tunable Filter

The Maryland Magellan Tunable Filter

- PI: Sylvain Veilleux
  - 3 nights/yr guaranteed
- On Baade 6.5m telescope in Chile
  - DIQ ~ 0.4” - 0.7”
- Wavelength coverage ~ 5000 - 9200Å
- Bandwidth ~ 6 - 20Å
  - Low resolution
- FOV ~ 27’ x 27’
  - Largest FOV of any FP currently in operation
- Data reduction pipeline fully operational.
Abell 1795 – A Pilot Study

Cowie et al. (1983)       McDonald & Veilleux (2009)
A Multi-Wavelength Database

- Sample of 23 galaxy clusters with a wide variety of properties
  - 1-2 orders of magnitude range in dM/dt, L_x, M_x, T_x
  - 23/23 have Hα & NIR imaging from MMTF and 2MASS.
  - 19/23 have X-Ray & UV imaging
    - X-ray from Chandra (19/23)
    - UV from GALEX & XMM-OM (21/23)
  - 18/23 have VLA 1.4 GHz fluxes

<table>
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<th>(1) Name</th>
<th>(2) z</th>
<th>(3) E(B-V)</th>
<th>(4) T_x</th>
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2. Results: Multi-wavelength Sample

Hα Filaments in BCGs
2. Results: Multi-wavelength Sample

A Multi-Wavelength Database
While several clusters are consistent with heating from young stars, there is a lot of scatter in this relation!

- Other mechanisms may be more important:
  - Cosmic ray heating
  - Conduction from ICM
  - Mechanical energy from a shearing flow
- Too difficult to pursue this without higher quality data
  - FUV data from HST
  - Long-slit spectra along filaments
X-Ray Properties of ICM

- Appears to be a temperature threshold at which Hα filaments are able to form:
  - $kT < 5$ keV

- Strong correlation between cooling rate and the UV or Hα flux.
  - Too little Hα flux to be stars forming out of cooling gas, too much to be purely recombination
X-Ray Properties of ICM

- The Hα emission never extends further than the cooling radius of the ICM!
  - Combined with the correlation between cooling rate (dM/dt) Hα flux in filaments, suggests that the warm gas is linked to the cooling flow.
X-Ray Properties of Filaments

- We can also extract X-ray spectra coincident with the Hα filaments
  - Filaments have:
    - Low temperature
    - High density
    - Low entropy
    - Short cooling time

→ Direct link between warm gas and X-ray cooling flow!
Summary of Results

- The X-ray and Hα morphologies are similar in cases where we see optical filaments.
- There is a strong correlation between the mass of warm gas in filaments and the mass of gas cooling out of the X-ray.
- The warm filaments only extend as far as the X-ray cooling radius.
- The cooling time of the X-ray gas coincident with the warm gas is ~10x less than the surrounding ICM.

➤ The Hα emission is linked to the cooling ICM!
Interpretation of Results

- Hα filaments trace the X-ray cooling flow!
  - Inside of $R_{\text{cool}}$, ICM cools rapidly, collapsing into thin streams which fall onto the BCG at the cluster potential minimum
    - Morphology of warm and hot gas resemble that seen in recent high-resolution hydro sims of gas cooling by Ceverino et al.
    - Heating probably due to a combination of star formation in filaments, conduction from ICM and drag heating.
Work in Progress

- High resolution far-UV survey with HST
  - Are stars forming in the gas filaments?
  - How does the SFR compare to the X-ray cooling rate?
- Extension to galaxy groups
  - Is there a lower mass/temperature limit for the presence of Hα?
- Long-slit spectra of extended filaments and BCGs
  - What ionization processes can be excluded?
  - What are the kinematics of the filaments?
  - Further classification of AGN
- High resolution sub-mm imaging of clusters
  - What is the distribution of the cold molecular gas?
  - Is the amount of cold gas consistent with the cooling flow hypothesis?