'New' Physics - See Longair 4.5

- The Cooling time $t_{\text{cool}} = \frac{3NkT}{\langle dE/dt \rangle} \sim 8.5 \times 10^{10} \text{yrs}(n/10^{-3})^{-1}T_8^{1/2}$ For bremmstrahlung (Longair eq 4.24,4.25)
  - but for line emission dominated plasmas it scales as $T_8^{-1/2}$
- That is as the gas gets cooler it cools faster

$\Lambda = \text{cooling function}$

- $T_{\text{cool}} = 5/2nT/n\Lambda \sim t_{\text{Hubble}}T_8\Lambda^{-1.23}n_2^{-1}$
- In central regions of many clusters the density ($n$) is large, so the gas can cool in $t<10^9$ yrs
  - $5/2$ (the enthalpy) is used instead of $3/2$ to take into account the compression as it cools (and remains in pressure equilibrium)

**Observed Temperature Profiles**

- If the gas is in equilibrium with the potential (of the NFW form) it should be hotter in the center
- But in many clusters it is cooler - evidence for gas cooling

Left panel (from Burns et al 2010) shows the theoretical temperature profile if a NFW potential (in grey) compared to an set of actual cluster temperature profiles
Cooling Cores

![Graph showing XMM-Newton RGS spectrum of the central region of a prominent cool-core cluster, A1835.]

\[ t_{\text{cool}} = 69 \left( \frac{n_e}{10^{-3} \text{ cm}^{-3}} \right)^{-1} \left( \frac{T}{10^8 \text{ K}} \right)^{1/2} \text{ Gyr} \]

Notice that the central surface brightness of cool core clusters (left panel) is much higher than non-cooling core clusters.

Cooling Time for a Sample of Clusters

- So what happens to the gas? ...
Star Formation

- Bursts of Star Formation in Cluster Centers
  - At $z<1$ elliptical galaxies show very little evidence for star formation
    - elliptical galaxies dominate the stellar population of clusters
  - However in the center of cool core clusters there can be lots of star formation! See Deep Chandra, HST-COS, and Megacam Observations Of The PhoeNix Cluster: Extreme Star Formation And AGNFeedback On Hundred Kiloparsecc Scales Michael McDonald et al

High Redshifts

- The 'cooling flow' clusters tend to show higher star formation rates at higher redshifts.
  - Up to $1000\,M_{\odot}/yr$ (!)
  - However the amount of material involved in star formation is much less than the amount of gas theoretically predicted to cool
Theoretical and Observed Spectrum of 'Cooling' Regions

- The theoretical models of cluster cooling predict strong lines from gas at $kT<10^7$K—these are not seen
- So the gas does not cool isobarically—what else is going on??

How much Gas is at Each Temperature

- Theoretical cooling model predicts the flat line
- Data are in strong disagreement
- Something is wrong with the assumptions (gravity, cooling)
- Best idea is 'something else' is happening—input of energy from active galaxy in center
- Not all the gas theoretically predicted to cool forms stars
Feedback

• There is evidence from
  – cluster evolution,
  – relation of temperature and luminosity,
  – cutoff in galaxy star formation etc
• that additional physics beside gravity is needed to model
  structure formation- this is called 'feedback'
• The injection of energy (momentum, entropy) from the
  structures that have formed into the system
  – We do not know how this process occurs but the only two forms of structures
    that potentially have enough energy are
    • star formation- 7 Mev/proton (nuclear processes
    • AGN ~90-360 Mev/proton (star formation)

General Idea of Feedback

M. Gitti 2016
Feedback - How AGN Influence the Cluster Gas

Direct evidence from cluster x-ray images combined with radio data that central AGN has strongly influenced the gas

Effects of Feedback in Image and Temperature
AGN Feedback

- 'Color' Image of the Perseus Cluster

Fig. 25 False color image of the central region of the Perseus cluster produced from images in three energy bands 0.3–1.2, 1.2–2, and 2–7 keV. An image smoothed on a scale of 10 arcsec (with 80% normalization) has been subtracted from the image to highlight regions of strong density contrast. The image shows a series of nearly concentric “ripples” which are interpreted as sound waves or weak shock waves set off by the activity of the central AGN (Fabian et al. 2006)
X-ray and Radio Image

- Abell 2052 (Blanton et al 2015) the radio plasma (red) 'fills' the 'holes' in the x-ray image (blue)

Cavaties and Low Freq Radio Emission

- The giant cavities seen in many cooling flow clusters are often 'filled' by low frequency radio emitting plasma

A262 Clarke et al 2009

Hydra A Wise et al 2007
Effects of Feedback in Image and Temperature

the hot gas can apparently be strongly affected by AGN activity- direct evidence of the ability of SMBHs to influence environment on large scales

Other Signs of Unexpected Activity

- Strong emission from Hα (gas at T~10^4 k) in centers of many cool core clusters

Sanders et al 20098

McDonald and Veilleux 2009
Formation

- Galaxy clusters form through gravitational collapse, driven by dark matter (~80% of their total mass)
- In the hierarchical scenario more massive objects form at later times: clusters of galaxies are produced by the gravitational merger of smaller systems, such as groups and sub-clusters

Sunayev-Zeldovich Effect

https://ned.ipac.caltech.edu/level5/Sept05/Carlstrom/Carlstrom2.html#2.1

Thermal SZE is a small (<1 mK) distortion in the CMB caused by inverse Compton scattering of the CMB photons

\[
\frac{\Delta T}{T_{\text{CMB}}} = g(z) \int \frac{\nu T_\nu}{m_e c^2} d\nu
\]

Total cluster flux density is independent of redshift!

\[
\Delta S_\nu = \int \Delta I_\nu \, d\Omega \propto \left[ \frac{\nu T_\nu}{E_A^2} \right] \propto \frac{f_{\text{gas}} M_{\text{gas}} T_\nu}{E_A^2}
\]
Sec 4.6 & 9.5 in Longair

The Sunyaev-Zel’dovich Effect: probe of Galaxy clusters

Small distortion $\tau_\alpha \sim 0.01$ for $10^{15} M_\odot$

from Leon Van Speybroeck

Redshift independent: $\frac{\Delta T_{\text{SZ}}}{T_{\text{CMB}}} \propto \int n_e T_e \, dl$

SPT
150 GHz
50 deg$^2$

Clusters of Galaxies
“Shadows” in the microwave background from clusters of galaxies
Sunyaev-Zel’dovich Effect

Single Clusters
- Measure of integrated pressure (total thermal energy)
- Distances, $H_0, H(z)$
- Cluster gas mass fractions, cluster structure, evolution studies
- Peculiar velocities at high $z$

SZ Cluster Surveys
- Exploit SZ redshift independence
- Measure growth of structure and large scale velocity fields to constrain Dark Energy

S-Z Simple Physics
- The optical depth for the S-Z effect is small
- The density of electrons is of order $n_e \sim 10^{-3}$ cm$^{-3}$, the path length through a cluster medium ~ several Mpc. With a Thomson cross section $\sigma = 6.65 \times 10^{-25}$ cm$^2$,
  optical depth $\tau = n_e \sigma l \sim 0.005$. $\sim 1\%$ probability that a CMB photon crossing a rich cluster is scattered by an electron.
- Since the electron energy is much larger that the energy of the photon, to first order $\Delta v/v \sim kT_e/m_e c^2 \approx 1\%$. The resulting fractional temperature change of the CMB is of the order of $10^{-3}$, $\sim 300\mu K$
- For a review see Carnegie Observatories Astrophysics Series, Vol. 3: Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution, 2004 Using the Sunyaev-Zel’dovich Effect to Probe the Gas in Clusters MARK BIRKINSHAW

The spectrum of the thermal SZE has a characteristic shape
all interacting CMB photons get approximately a 1% boost in energy, the result is a transfer of photons in the CMB spectrum from lower to higher frequencies, resulting in a decrease of brightness at low frequencies.
A Strange Fact

- The amplitude of the S-Z effect is independent of $D_\Delta$ the angular distance

Sunyaev-Zeldovich Distances

- The Sunyaev-Zeldovich effect is the Compton scattering of microwave background photons off the hot electrons in the IGM in the cluster
- At present ~400 clusters have measured S-Z effect “decrements” and x-ray temperatures (Primarily from Planck and the South Pole Telescope and the Atacama Cosmology telescope)

Angular distance $D_\Delta; \Delta T_0$ is the S-Z decrement, $S_{X0}$ the x-ray surface brightness, $T_{e0}$ the x-ray temperature,$\theta$ an angular size and $\Lambda$ the cooling function

Line integral of pressure

Geometry uncertainty

All quantities are directly measurable with an x-ray image, temperature map and S-Z image
Sunyaev-Zeldovich effect

- Compton scattering changes both the angular and energy distribution of the microwave background.
- At low frequencies the result is a diminution (decrement) in the surface brightness of the MWB whose amplitude and shape depends on the Compton optical depth, the 3-D distribution of the hot electrons and their temperature.

\[ \nu \Rightarrow L_{\nu} = L_{\nu}^0 \left( 1 + \frac{\tau}{1 + \beta} \right) \]

- The main technical limits are the long exposures required in both the x-ray band and the milli-meter (~1 day each for the highest z clusters).
- The S-Z decrement is independent of redshift, while the x-ray surface brightness drops as \((1+z)^4\).
  Setting a practical limit to \(z \approx 1.3\) for the x-ray measurements.
- In a massive cluster the typical optical depth is \(\tau \approx 0.1\).

- The scattering geometry, in the frame of rest of the electron before the interaction, one photon, at angle \(\theta\) relative to the \(x\), \(\beta\), is deflected by angle \(\beta_\theta\), and emerges.

X-ray image with S-Z contours for \(z=0.54\) cluster

S-Z contours images for a sample of clusters from \(z\approx 0.3-0.9\)
Dark Matter-Summary

- The existence of dark matter in clusters and groups of galaxies is indicated by very high mass-to-light ratio.

The observed optical luminosity of the galaxies corresponds to a mass that is much lower than the total cluster mass
- So a large quantity of matter not visible as stars
- X-ray emitting gas constitutes a portion-~1/6th of this "missing mass".

2) Direct evidence (Bullet cluster)
That dark matter and baryons can be in different places
3) Lensing