Lecture 11: More Cluster cosmology

**Clusters**

- Cooling Time
  - Sanderson et al. 2006

- Groups
  - O'Sullivan et al., in preparation

---

**Multiwavelength view of a cluster**

- Optical image + X-ray (XMM)
- Radio (GMRT) + X-ray (Chandra)

**Why Feedback is Necessary:**

- Cooling Flows are expected in the dense cores of clusters and groups
- But, Gas in cluster cores does not appear to cool by more than a factor ~3

- XMM RGS: Peterson & Fabian 2006
- O'Sullivan et al., in preparation
- AWM4

---

**External Links**

- Somak Raychaudhury
  - [http://www.iucaa.in/~somak/teaching.html](http://www.iucaa.in/~somak/teaching.html)
What are the possible sources of heating?

Mergers
- Large amounts of energy available (few $\times 10^{63}$ erg)
- But only few groups or clusters affected at any time
- Merger shocks would not break self-similarity
- Simulations show that in cluster mergers, cool cores are not destroyed (Poole et al 2007)
- Might be more important in groups

Chandra X-ray intensity contours on optical (left) and X-ray temperature (right). Govoni et al 2004

Heating of the ICM - supernovae

Supernovae potentially provide up to ~1 keV per particle of energy - this might be enough to account for the similarity breaking

However, there is little active star formation in cluster cores today

Also conduction from the hot exterior doesn’t work

Deep Chandra observation of the Antennae - Fabbiano et al 2004

AGN Outbursts in Giant Ellipticals

In an AGN outburst, jets inflate radio lobes
- displace surrounding gas
- drive shocks in a hot atmosphere
- lobes make X-ray “cavities”
- shocks cause breaks in surface brightness

McNamara & Nulsen (2007)

AGN feedback is necessary to match the luminosity function of galaxies in semi-analytic models (Downsizing at the bright end)

Outbursts are seen in the hot (X-ray emitting) atmospheres of galaxy clusters, galaxy groups, isolated ellipticals

M84 (Finoguenov & Jones 2001)

NCG 4502 (Kharchev et al 2006)

NGC 4836 (Jones et al 2002)

MaNGa: No AGN feedback

With AGN feedback

Croton et al 2004
AGN activity in clusters: X-ray + Radio
the brightest ones

Perseus

MS0735.6+7421

E ~ 10^{59} \text{ erg}

E ~ 10^{62} \text{ erg}

1' = 20 kpc

Fabian et al. 05

McNamara et al. 05

optical, radio, X-ray

Why low frequency radio

- Synchrotron emission is brighter at lower frequencies (negative slope)
- The slope gets steeper as the radiating electrons lose energy and get old
- Extrapolation from > 1 GHz can get the estimate of total energy wrong by several orders of magnitude if there is a significant population of low energy electrons (low Lorenz factor $\gamma$)

Energetics

Energy output from AGN per unit mass of IGM

\[ \frac{\eta M_{\text{BH}} c^2}{M_{\text{gas}}} = \frac{\eta f_1 f_2 c^2 M_{\text{baryons}}}{f_{\text{gas}} M_{\text{baryons}}} = \frac{10^{-1} \times 10^{-3} \times 10^{-1} c^2}{10^{-5} c^2} = 10^{-4} c^2 \]

Hydra A

2 x 10^{43} \text{ erg/s}

McNamara et al. 2000

HCG 62

6 x 10^{40} \text{ erg/s}

Our work

HCG 62

- X-ray brightest and one of the most intrinsically luminous of the 100 Hickson compact groups $L_x = 10^{44} \text{ erg s}^{-1}$
- Central galaxies: two very similar early-type galaxies ($\Delta m \approx 0.5$);
- $D = 59 \text{ Mpc}$, giving 1' = 17 kpc
- $M_{\text{gas}} = 10^{12} M_{\odot}$ within ~20'
Rich Clusters of Galaxies: The Sunyaev-Zel’dovich (S-Z) Effect

- Photons from the Cosmic Microwave Background (CMB) are affected by passing through the gas in a cluster.
- The optical depth is related to the probability that a photon will interact with the gas. It is given by $\tau = n_e \sigma_T L$ where $n_e$ is electron density, $\sigma_T$ is the Thompson cross-section, and $L$ is the path length.
- Electrons dominate the cross-section because the electron-photon cross-section is >> the nuclei-photon cross-section.
- Compton scattering photon-electron interactions are when the electrons gain energy because they start essentially at rest.
- However, a cluster contains many fast moving electrons and their interaction is with lower energy photons. This leads to inverse-Compton scattering in which the photons gain energy.
- At $v << c$, the scattering is almost elastic and so we have essentially classical Thompson scattering.
- The frequency shift for a CMB photon scattered by an electron is given by:

$$\frac{\Delta \nu}{\nu} = \frac{\Delta E}{E} = \frac{kT_e}{m_e c^2}$$

Sunyaev-Zel’dovich Effect

In 1970 Sunyaev & Zel’dovich realized that the CMB spectrum would be affected by passage through a hot gas via Inverse Compton scattering.

Exaggerated spectral distortion due to the SZ effect. Scattered through an atmosphere with Compton parameter $y = 0.1$ and $\tau \beta = 0.05$

(Birkinshaw)
Rich Clusters of Galaxies: The Sunyaev-Zeldovich (S-Z) Effect

- Radio telescopes are used to look for 'dips' in the background in order to identify clusters independently of any concerns of galaxy over-density.
- The background decrement is measured for known clusters of galaxies in the Rayleigh-Jeans portion of the CMB spectrum:
  \[
  \frac{\Delta I}{I_c} = 2 \tau \frac{\Delta \nu}{\nu}
  \]
- By combining these data with x-ray measurements of clusters we can measure the Hubble constant, \( H_0 \) (at least in principle).
- However, quantifying the decrement is not easy since the effect is only of the order of \( \sim 10^{-4} \) even for the richest, most massive clusters.

There is a good correlation between the S-Z effect and the distribution of x-ray emission over a cluster of galaxies. An example is shown in this figure. Here the S-Z effect data are shown as contours which overlay the image of x-ray emission in false colours for the Galaxy cluster CL0016+16.

Generally however, it is very difficult to detect.

The lower image shows the background fluctuations in another cluster, Abell 401.

The full width half maximum resolution is just over six minutes of arc and the peak temperature difference that is detected is only 300 \( \mu K \). The noise level is approximately 20 \( \mu K \).