Evaluation of Research Reports

- **Originality**: Are any new thoughts presented? Are the ideas and thoughts critically examined. Do the conclusions make sense?

- **Thoroughness**: How clear are the thoughts and data analysis procedure presented? Can one reproduce the results by reading the report?

- **Conciseness**: Is the report written in a logic way? Are there unnecessary redundancies in statements?
Clusters, groups, and beyond

• Formation processes
• Physical properties
• X-ray data analysis issues
• De-projection
• Other measurements
• Substructure and origins
• Metal abundances
• Diffuse IGM and Baryon matter in the universe
• X-ray background

Based partly on the lecture given by Keith Arnaud (NASA/GSFC)
Formation and Evolution of Galaxy Clusters

Dark matter simulation

Klypin, Kravtsov, Gottlöber
Dark matter and X-ray emission simulation
Formation of Clusters of galaxies

- Clusters of galaxies are formed from the extreme high end ("high sigma peaks") of the initial fluctuation spectrum. They exist at the intersections of the Cosmic Web.
- The way that structure evolves depends on the geometry and contents of the Universe (total density, dark matter density, dark energy density, ...).
- Because clusters are formed from the high sigma peaks their numbers and evolution in time depend sensitively on cosmological parameters.
X-rays from Clusters of Galaxies

- Clusters of galaxies are self-gravitating accumulations of dark matter which have trapped hot plasma (intracluster medium - ICM) and galaxies.
- The baryons thermalize to $> 10^7$ K, making clusters strong X-ray sources.
- Most of the baryons in a cluster are in the X-ray emitting plasma - only 10-20% are in the galaxies (ie the galaxies are the least important constituent).
z=1.26 cluster observed using Chandra and Keck
Physical Properties of the ICM

- Ignore the B field, the mean free path of electron (nearly the same as that of protons):
  \[ \lambda_e = (23 \text{ kpc}) \left( \frac{n_0}{10^{-3} \text{ cm}^{-3}} \right)^{-1} \left( \frac{T}{10^8 \text{ K}} \right)^2 \]
  About 1% of the radius of a cluster
  -> the ICM can be treated as a fluid.

- Timescale for Coulomb collisions to reach kinetic equilibrium:
  \[ t_{\text{eq}}(e,e) = (3.3 \times 10^5 \text{ yr}) \left( \frac{n_0}{10^{-3} \text{ cm}^{-3}} \right)^{-1} \left( \frac{T}{10^8 \text{ K}} \right)^{3/2} \]
  \[ t_{\text{eq}}(p,p) = (m_p/m_e)^{1/2} t_{\text{eq}}(e,e) = 43 t_{\text{eq}}(e,e) \]
  \[ t_{\text{eq}}(p,e) = (m_p/m_e) t_{\text{eq}}(e,e) = 1870 t_{\text{eq}}(e,e) \]
  All of these are shorter than the typical ages of clusters.
  -> a Maxwellian dist at a kinetic temperature T.

- The ICM density is low and radiation is diffuse
  -> coronal equilibrium or optically-thin thermal plasma
What we try to measure

• From the spectrum we can measure a mean temperature, a redshift, and abundances of the most common elements (heavier than He).

• With good S/N we can determine whether the spectrum is consistent with a single temperature or is a sum of emission from plasma at different temperatures.

• Using symmetry assumptions the X-ray surface brightness can be converted to a measure of the ICM density. If $T_g =$const. and $\rho_g = \rho_{g0}[1+(r/r_c)^2]^{-3\beta/2}$, for example:
  
  - $M_g = 3.15 \times 10^{12} M_{\text{sun}} \left( n_0 / 10^{-3} \text{ cm}^{-3} \right) \left( r_c / 0.25 \text{ Mpc} \right)^3 \Gamma[3(\beta-1)/2] / \Gamma[3\beta/2]$
  
  - $E I = \int n_p n_e dV = 3.09 \times 10^{66} \text{ cm}^{-3} \left( n_0 / 10^{-3} \text{ cm}^{-3} \right)^2 \left( r_c / 0.25 \text{ Mpc} \right)^3 \Gamma[3(\beta-1)/2] / \Gamma[3\beta]$
Abell 2125

$z=0.25$
Analysis Issues for diffuse X-ray emission

- **Response matrix for large regions**
  - Energy resolution varies across the detector, particularly for ACIS-I data because of the CTI effect.
  - It is possible to produce an average response for the region:
    1. Assuming the spectral properties are the same across the selected region.
    2. Constructing a good weight map by limiting its energy range to maximize the S/B ratio and possibly by subtracting the background.

- **Background subtraction**
  - Nearby galaxies or clusters of galaxies are large objects - they may well cover a substantial fraction or even the entire field of view of a CCD chip.
  - The background level may also change from one part or another within the chip field, let alone different chips.
The background consists of multiple components:

- X-ray background, local or cosmic, all subject to the telescope vignetting, which is energy dependent.
- Similarly for events induced by low-energy cosmic-rays that were focused by the X-ray telescope mirrors.
- Events induced by cosmic-rays that didn’t pass the X-ray mirrors -> a flat distribution.
The cosmic X-ray background varies with position on the sky at energies < 2 keV (see ROSAT all-sky survey maps).
Both the local X-ray background and the cosmic-ray induced components vary with time - big flares are easy to see, but smaller and/or long-term variations are difficult to recognize.
What might be the solution?
My recommended solution

• Construct a “blank-sky” background observation from a stacked source-excised data set (provided for a specific instrument configuration and time period) and re-orient it to mimic your observation. This background observation is used as the 0th order estimate of the background. However, the “blank-sky” background may be different from the true background in your field.

• Extract the on-source spectra from both your observation and the “blank-sky” background observation.

• Further extract the off-source spectra from both your observation and the blank-sky background observation in a reference region, which may be in a different chip.

• These two (or more) sets of spectra can be fit simultaneously, in principle accounting for all the instrumental variations across the detector. The net spectrum in the reference region is used to constrain the net background difference, which is assumed to be intrinsically uniform across the detector.
Abell 2125
Count image of an ACIS-I obs.
A2125 ACIS-I spectrum
2D -> 3D

• Clusters are optically-thin 3-D objects. We would like to determine properties in 3-D but we observe them projected onto 2-D.

• For regular shapes it is possible to derive 3-D information from the 2-D observation. (There is a helpful XSPEC model called projct)
Gravitational Mass distribution

Sound crossing time much shorter than heating or cooling time → hydrostatic:
• \( \frac{dP}{dr} = -\frac{GM(r)\rho_g}{r^2} \), assuming spherical symmetric
• \( P = \frac{\rho_g k T_g}{\mu m_p} \)
• \( M(r) = -\frac{k T_g(r)r}{(\mu m_p G)}[\frac{d\ln \rho_g}{d\ln r} + \frac{d\ln T_g}{d\ln r}] \)
• If we can measure the temperature and density at different positions in the cluster, we can derive the gravitational potential and hence the amount and distribution of the dark matter.
What we try to measure II

• But Chandra is showing us that there are many irregularities (at least in the cluster core). How do we derive 3-D information in this case?

• There are two other ways to get the gravitational potential:
  - The galaxies act as test particles moving in the potential so their redshift distribution provides a measure of total mass.
  - The gravitational potential acts as a lens on light from background galaxies
Top Questions in Clusters of Galaxies

• Are clusters fair samples of the Universe?
• Can we derive accurate and unbiased masses from simple observables such as luminosity and temperature?
• Does the gravitational potential have the same shape as the baryons (stars and gas)?
• What is happening in the centers of clusters - how does the radio galaxy and the cluster gas interact?
• What is the origin of the metals in the ICM and when were they injected? What is the origin of the entropy of the ICM?
Why do we care?

- We used to have a simple model for the cores of clusters:
  - Clusters were spherically symmetric balls of plasma that evolved in isolation.
  - In their centers they would lose energy by radiating X-rays - leading to a steady cooling inflow of plasma.
  - So the X-ray spectra should show evidence for a range of temperatures from the ambient for the cluster down to zero.
Coma cluster

XMM image

temperature map
Chandra image of 1E0657-56
Abell 1835
XMM RGS

Peterson et al.
Chandra image of Perseus cluster
Optical image of Perseus A (NGC 1275)
Effect of a rising bubble of hot plasma

White is hot and black is cold - the coolest gas is produced from uplifted, adiabatically expanded gas.

Churazov et al.
Metal Abundances

Abundance (fraction of Solar)

Temperature (keV)

Horner et al.
Si and S abundances

[Baumgartner et al.]

[Graph showing abundance ratio vs. cluster temperature in keV, with data points for Si/Fe and S/Fe]
NGC 4636

black line: observed data
red line: best-fit model

Xu et al.
First trees in the X-ray Absorption
Line Forest?

First measurements of the local warm/hot intergalactic medium by Chandra and XMM-Newton!

Nicastro et al., 2002; Rasmussen et al., 2002

Chandra (2002)