

Using the Sunyaev-Zeldovich Effect to Determine H_0 and the Baryon Fraction

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Astronomy 278: Anisotropy and Large Scale Structure in the Universe

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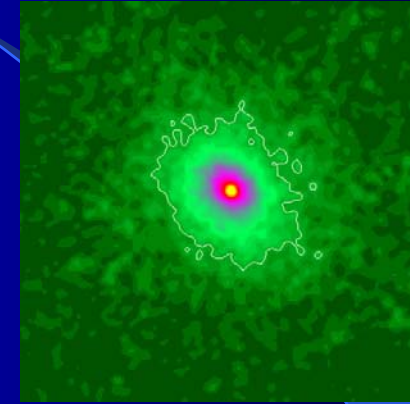
Overview

- Qualitative explanation of the Sunyaev-Zel'dovich Effect (SZE)
- Brief quantitative explanation of the SZE
- Instruments employed and observations
- Current Results

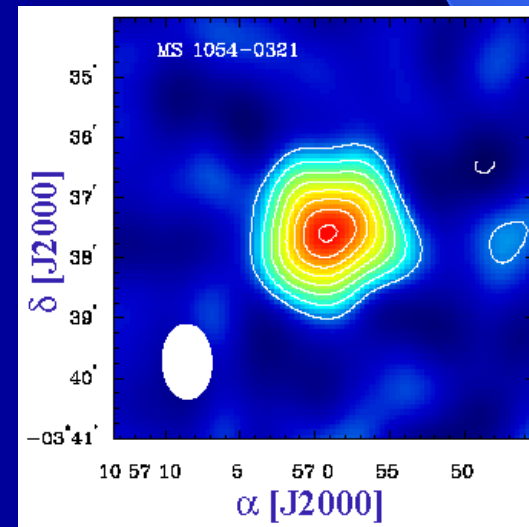
The Sunyaev-Zel'dovich Effect

- First predicted by the Russian scientists Sunyaev and Zel'dovich in 1969.
- Galaxy Clusters have hot gas
 - $T_{\text{gas}} \sim 10\text{-}100$ million Kelvin
 - Electron scattering from nuclei produces X-rays, thermal bremsstrahlung.
- Compton scattering occurs between CMB photons and the hot electrons
 - $\sim 1\%$ of CMB photons will interact with the hot electrons
 - Energy will be transferred from the hot electrons to the low energy CMB photons, changing the shape of their intensity vs. frequency plot.
 - Measurements made at low frequencies will have a lower intensity, since photons which originally had these energies were scattered to higher energies. This distorts the spectrum by $\sim 0.1\%$.
- Estimates of cosmological parameters (ie. H_0 and Ω_b) can be made by combining these measurements.

X-ray image of Abell 262



SZE Image of MS 1054



Sunyaev-Zeldovich effect

Kompaneets equation: how the radiation changes with diffusion

$\delta n / \delta y = 1/x_e^2 * \delta / \delta x_e * x_e^4 * (\delta n / \delta x_e + n + n^2)$, where $x_e = h\gamma/k_B T_e$
and y is the Compton y -parameter, $y = \int n_e \sigma_T k_B T_e / (m_e c^2) dl$

variables defined:

n_e = number density of the electron gas

T_e = temperature of the electron gas

σ_T = Thompson cross-section for scattering

assumptions

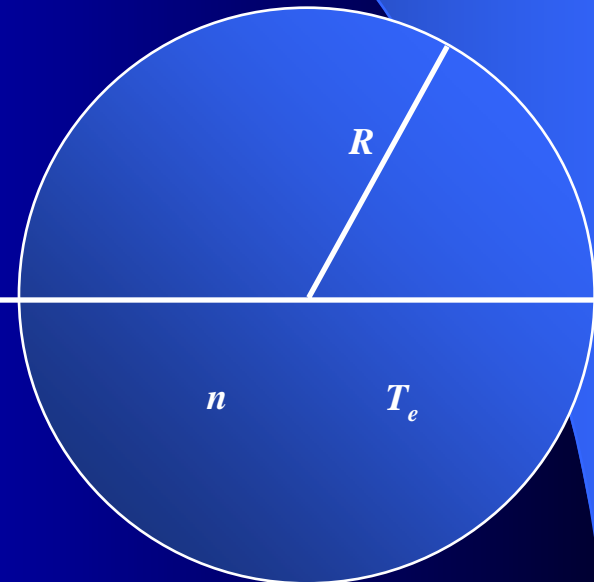
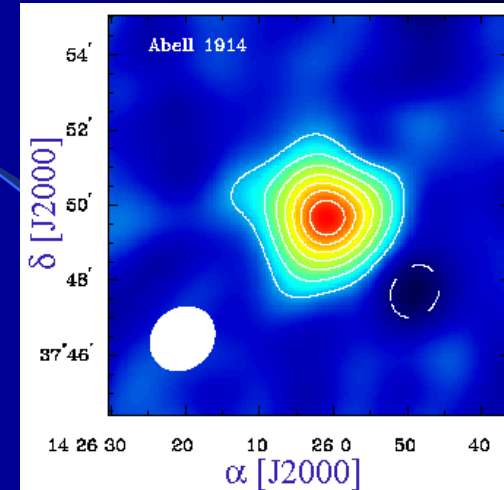
1. T_{gas} is much hotter than T_{rad}
2. CMB radiation behaves as a blackbody
3. each photon will only scatter once

Measured Quantities

- Cluster redshift, z
- Temperature decrement through the center of the galaxy, ΔT
- Angular diameter of the cluster, Θ_d
- X-ray flux from the center of the cluster, b_x
- Temperature of the electron gas, T_e
- Temperature of the CMB

Measuring the CMB Decrement from a Cluster

- Consider simplest model of cluster
 - Spherical with radius R
 - Constant gas number density n
 - Constant temperature T_e
- Sunyaev-Zel'dovich Effect decrement ΔT
 - Directly related to the density
 - Directly related to the cluster path length
 - Directly related to the temperature of the gas, T_e



Temperature Decrement

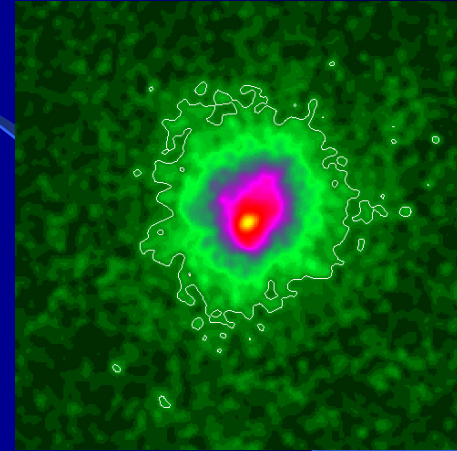
$$\Delta T = -T_{\text{CMB}} 2y \text{ or } \Delta T \approx T_{\text{CMB}} 2Rn$$

Constant Density Gas Sphere Mohr

Measuring X-ray Emission from a Cluster

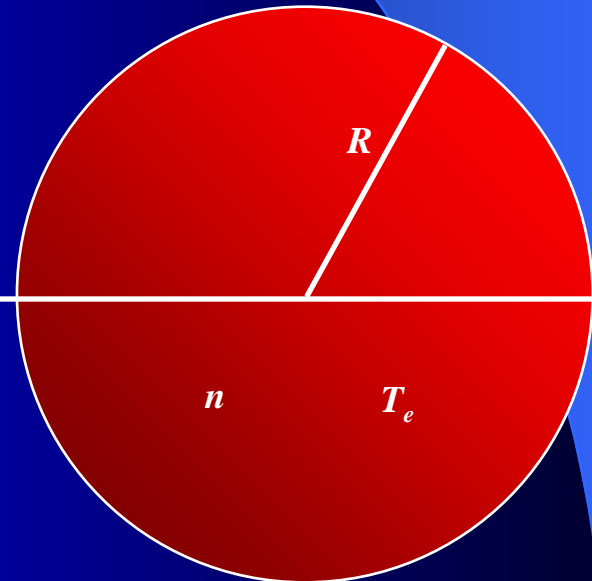
- Model of the cluster
 - Sphere of radius, R
 - Central number density of the electron gas, n
 - Temperature of the gas, T_e
- X-ray surface brightness b_x
 - Directly related to square of density
 - Directly related to the cluster path length

Abell 2319



X-ray brightness

$$b_x \approx 2Rn^2$$



Constant Density Gas Sphere

Mohr

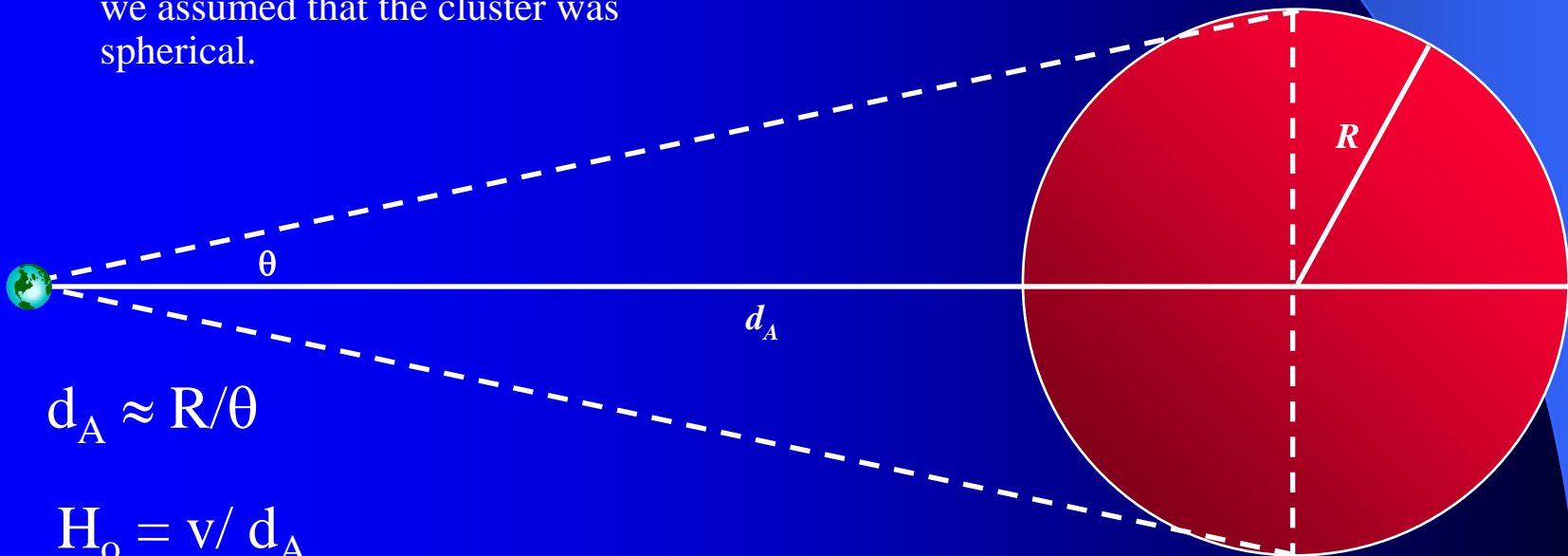
Measuring the Size of a Cluster

- Combined observations of b_x and ΔT measure the path length along the line of sight.
- Use the radius of the cluster and the angular size to make an estimate at the cluster distance. Remember, we assumed that the cluster was spherical.

$$\Delta T/T_{\text{CMB}} = 2Rn$$

$$b_x \approx 2Rn^2$$

$$R = (\Delta T/T_{\text{CMB}})^2 / 2 * b_x$$



$$d_A \approx R/\theta$$

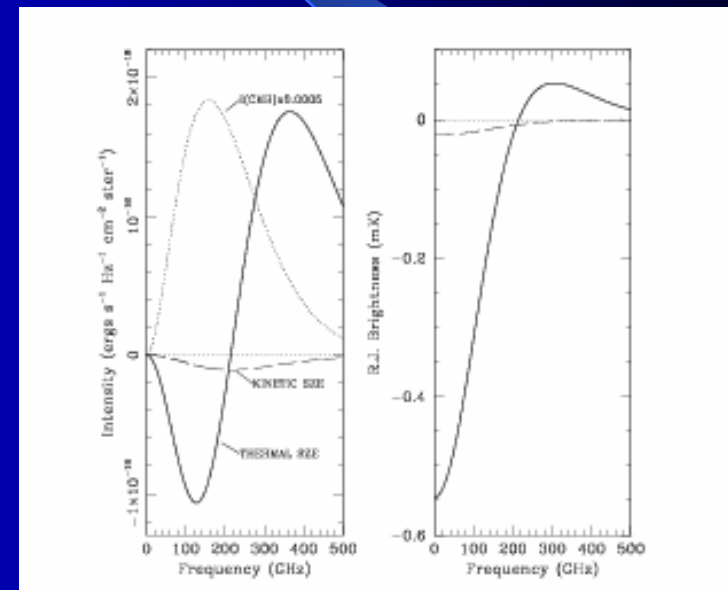
$$H_0 = v/d_A$$

Distance independent of redshift!

Mohr

Sunyaev-Zel'dovich signal

- SZE distortion of the CMB signal. Note the decrement on the low frequency side, and the increment at higher frequencies.
- The amplitude of the distortion is proportional to T_e , although shape is independent of T_e . The relativistic equation has a slightly more complicated shape.

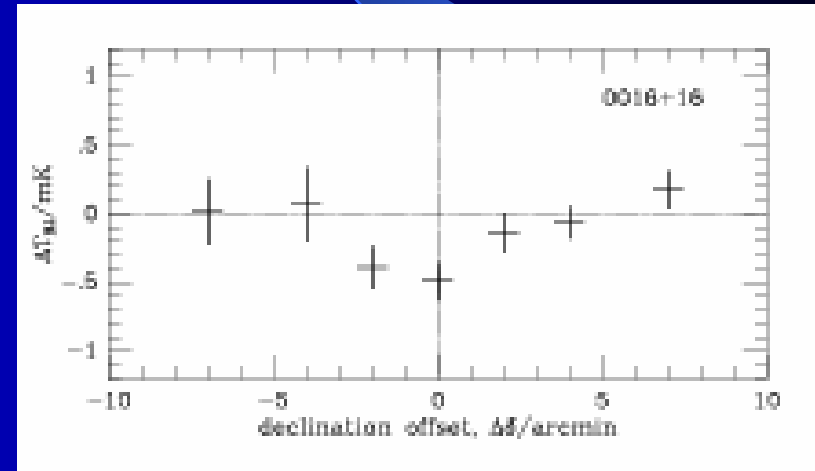


Single Dish Radiometers Used to measure the SZ effect

- Chibolton 25-m telescope
- OVRO 40 m telescope
 - Plot shown to the right demonstrates one of the first detections of the SZE, a profile of CL 0016+16.

Errors in single dish radiometers

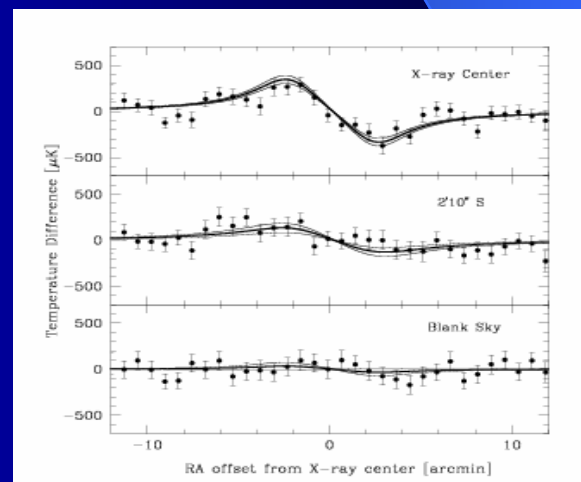
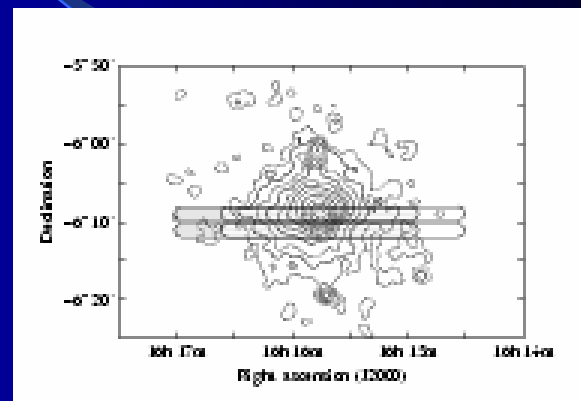
- atmospheric signals
- Calibration by measuring the planets (6%)
- Low resolution, can not subtract point sources along the line of sight of the cluster.



Bolometers used to measure the SZ effect

Sunyaev-Zel'dovich Infrared Experiment (SuZIE)

- Observes 4 pixels simultaneously, at frequencies of 143, 217 and 350 GHz.
- Three bolometers are in each pixel, which observe the same part of the sky. Therefore the atmospheric noise is correlated between each channel.
- Bolometers attached to balloons are a partial solution to the atmospheric noise problem. Instruments such as PRONAOS are taking this approach.
- Abell 2163 measurements taken across center of the X-ray peak, 2' 10" South of the X-ray peak, and one free of sources X-ray sources.
- Shows the temperature difference the bolometer will read as it scans a cluster.



Interferometers Used to Measure the SZ effect: 1

Ryle Array

- This 8 element array is located in Cambridge, UK, and operates at 15 GHz (2 cm.)



Berkeley Illinois Maryland Association (BIMA)

- This millimeter-wave array is located in Hat Creek, CA. John Carlstrom (U Chicago) and collaborators measure the SZE using the 10 antenna at 30 GHz (1cm.).



Owens Valley Radio Observatory (OVRO)

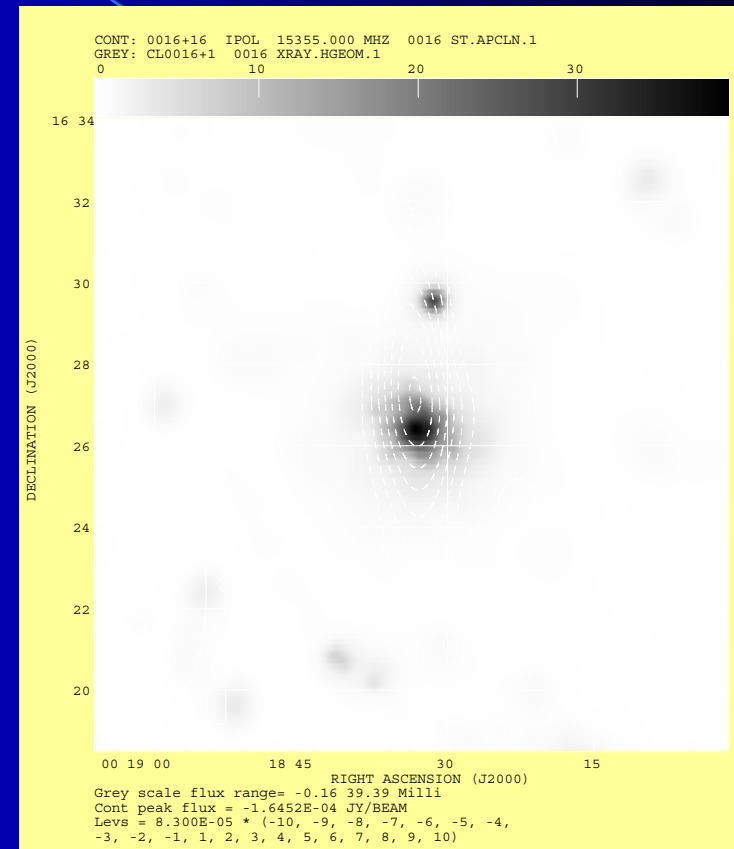
- This millimeter-wave array is located in Bishop, CA and run by Caltech. John Carlstrom and Steve Meyers (Caltech) use the 6, 10.4 meter antennas with 30 GHz detectors (1 cm.).



- ** These interferometers are only sensitive to the angular scales required to image clusters with $z > 0.1$

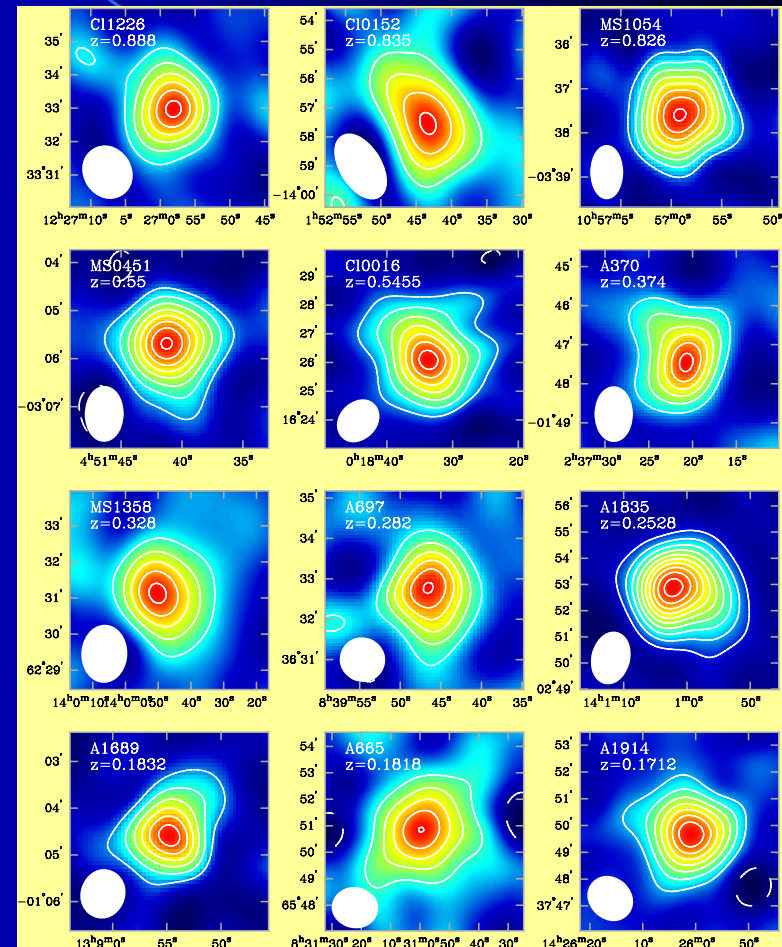
First Interferometric SZ detections

- Ryle telescope, using an array of 5, 15 m., 15-GHz dishes in Cambridge. Antennae arranged to achieve the smallest baselines (100 m.).
- N-S resolution is compromised because the Ryle Telescope is an E-W instrument.
- This plot shows the Ryle telescope image of C1 00016+16. Contours mark the SZE, while the gray background is the ROSAT image.



BIMA/OVRO observations of the SZ effect: 2

- These data have been taken on interferometers retrofitted with 30 GHz receivers.
- The array is set to small baselines, to ensure a large beam size.



Interferometers Used to Measure the SZ effect

Cosmic Background Imager (CBI)

- Located at the ALMA site in Chajantor, Chile. These 13 antennae operate at 26-36 GHz.



Degree Angular Scale Interferometer (DASI)

- A sister project to the CBI, located at the South Pole.



** These interferometers are suited to measure nearby clusters.

X-ray Telescopes Used to Measure the SZ effect: 1

ROSAT

- X-ray satellite in operation between 1990 and 1999. Mainly, its data has been used in conjunction with the radio observations to make estimates of H_0 and Ω_b . Uncertainties of the X-ray intensity are $\sim 10\%$.

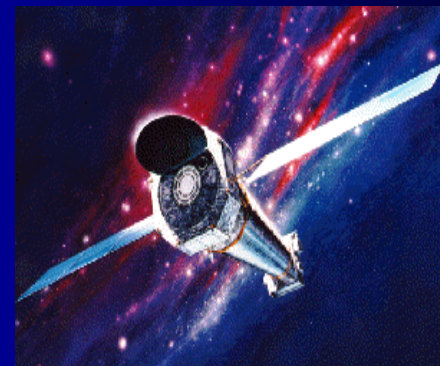
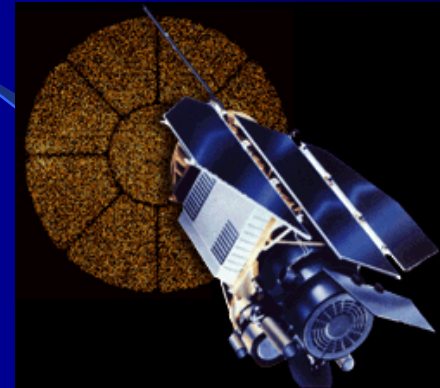
Chandra X-ray Observatory

- Provides x-ray observations of the clusters to make estimates of the gas temperature. Chandra currently has the best resolution of all x-ray observatories.

XMM-Newton

- ESA's X-ray telescope. Has 3 European Photon Imaging Cameras (EPIC).

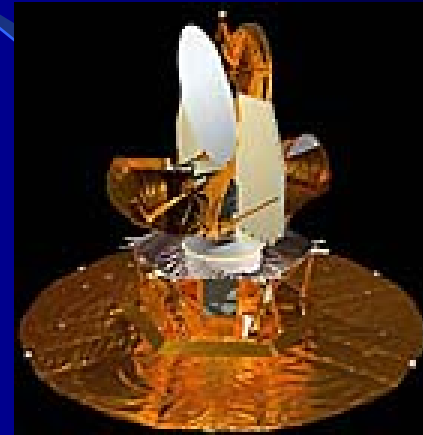
** The data from Chandra and XMM-Newton should reduce the uncertainty in the X-ray intensities.



All-Sky Projects Used to Measure the SZ effect: 5

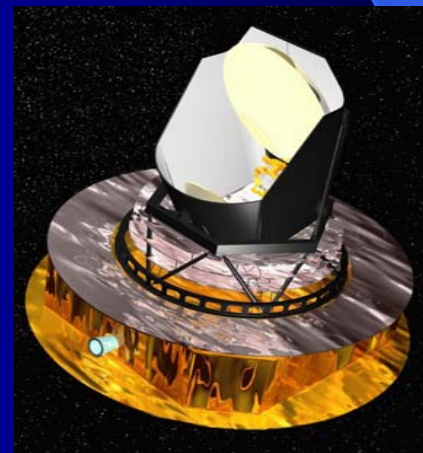
Microwave Anisotropy Probe

- Measures temperature fluctuations in the CMB. Ned can tell you all about this.



Planck satellite

- ESA project designed to image the entire sky at CMB wavelengths. Its wide frequency coverage will be used to measure the SZ decrement and increment to the CMB photons. The expected launch date is ~2007.



Systematic Uncertainties in Current SZE Measurements

- SZE calibration ($\pm 8\%$)
- X-ray calibration ($\pm 10\%$)
- Galactic absorption column density ($\pm 5\%$)
- Unresolved point sources still contaminate measurement of the temperature decrement. ($\pm 16\%$)
- Clusters that are prolate or oblate along the line of sight will be affected. A large sample of clusters should average the orientations. Or SZ method proposed from ROSAT data, in which clusters are barely resolved. ($\pm 14\%$)
- XMM/Chandra data demonstrate substructures within a cluster, known as isothermality and clumping. ($\pm 20\%$)
- Kinetic SZE ($\pm 6\%$)

Total Systematic Uncertainties: $\pm 33\%$

Reese et al. 2001



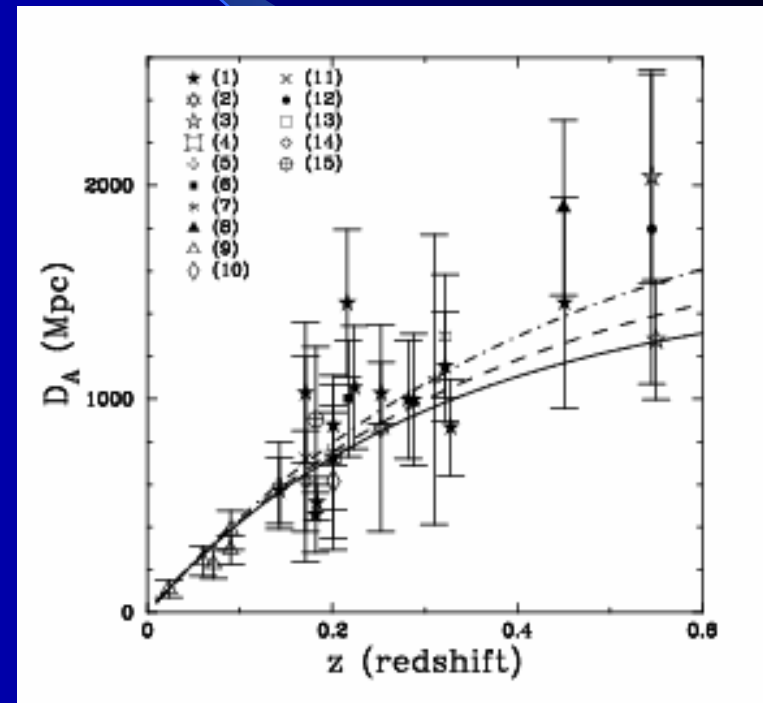
Results of SZE Distance Measurements

- 33 SZ distances vs. redshift

$H_0 = 63 \pm 3$ km/s/Mpc for $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$, fitting all SZE distances

- Results
 - SZE distances are direct (rather than relative)
 - SZE distances possible at very large lookback times
 - Can see the theoretical angular diameter distance relation.
 - High systematic uncertainties (30%)
 - $H_0 = 60$ km/s/Mpc for an open $\Omega_M = 0.3$
 - $H_0 = 58$ km/s/Mpc for a flat $\Omega_M = 1$

SZE Distance Measurements



Measuring the Baryon Fraction

$$f_g < f_B = \Omega_B / \Omega_M$$

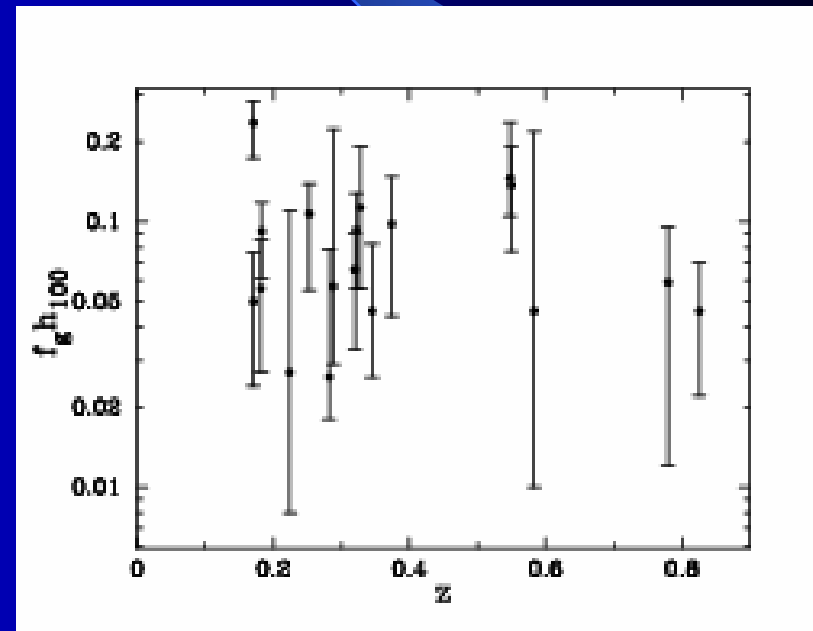
then $\Omega_M < \Omega_B / f_g$

Ω_B is constrained by BBN theory.

Calculate f_g by either measuring the SZE
(proportional to n) or X-ray brightness
(proportional to n^2).

Results of SZE Baryon Fraction Measurements

- Remember, the gas mass fraction sets a lower bound for the baryon fraction.
- SZ derived gas mass fraction at 65", and extrapolate to a fiducial radius of $r_{500}(T,z)$, 500 times the critical mass density.
- The mean gas mass fraction for 18 clusters (Grego et al.) is $0.081 + 0.009 - 0.011 * h_{100}^{-1}$



Conclusions

- **Hot gas in galaxy clusters**
 - **Combined constraints from X-ray emission and SZE**
 - **Direct cluster distances**
 - **Baryon mass fraction**
- **Significant systematic errors, but a good theory for cosmological discriminators**

References

PAPERS

Birkinshaw et al. 1998

Carlstrom et al. 2000

Grego et al. 2000

Reese et al. 2001

TELESCOPES

BIMA, <http://bima.astro.umd.edu/>

OVRO, <http://www.ovro.caltech.edu/>

Ryle telescope, <http://www.mrao.cam.ac.uk/telescopes/ryle/>

CBI, <http://www.astro.caltech.edu/~tjp/CBI/>

DASI, <http://astro.uchicago.edu/dasi/>

Chandra, <http://chandra.harvard.edu/>

XMM-Newton telescope, <http://sci.esa.int/xmm/>

ROSAT, <http://heasarc.gsfc.nasa.gov/docs/rosat/rosgof.html>

MAP, <http://map.gsfc.nasa.gov/>

PLANCK, <http://astro.estec.esa.nl/SA-general/Projects/Planck/>

SuZIE, <http://www.astro.caltech.edu/~lgg/suzie/suzie.html>

SuZIE observes 4 pixels on the sky simultaneously at 143, 217 and 350 GHz.

The three bolometers in a single photometer observe the same patch of sky at different frequencies; this atmospheric noise is well correlated between all three frequency channels.

PRONAOS, http://www.cnes.fr/WEB_UK/activites/connaissance/html/Pronaos/Prons.html

OTHER SITES

<http://astro.uchicago.edu/home/web/mohr/Compton/>