





Thermal sources

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Clusters of Galaxies



Chandra 900 ks image of Perseus cluster, unsharp-masked at right (Fabian et al. 2006)





Clusters of Galaxies



MS0735+7421 in radio (red) and X-rays (blue) – Gitti et al.





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Thermal Emission from Clusters



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Free-free absorption in 1946+708

Peck & Taylor (2001) Spectral index map from 1.3/5 GHz VLBI observations

free-free optical depth: $\label{eq:tff} \tau_{ff} \sim T^{-3/2} \; n_e{}^2 v^{-2} \; d$ $\label{eq:tff} N_e \sim 8 \; x \; 10^{22} \; cm^{-2}$ ionization $\sim 10\%$





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Planetary Nebulae - NGC 7027



Hjellming et al.





Star forming regions - Orion nebula (M42)











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The Microwave Background







The Microwave Background



We can only see the surface of the cloud where light was last scattered



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Sunyaev-Zeldovich effect

- The Sunyaev-Zeldovich effect
 - Photons of the CMB are scattered to higher frequencies by hot electrons in galaxy clusters, causing a negative brightness decrement.
 - Decrement is proportional to integral of electron pressure through the cluster, or electron density if cluster is isothermal.
 - Electron density and temperature can be estimated from X-ray observations, so the linear scale of the cluster is determined.
 - This can be used to measure the cluster distance and combined with z to get H_0 .





Sunyaev-Zeldovich effect







SZ images



FIG. 2.—–SZE (contours) and X-ray (color scale) images of each cluster in our sample. Negative contours are shown as solid lines. The contours are multiples of 2 σ and the FWHM of the synthesized beams are shown in the bottom left corner. The X-ray color scale images are raw counts images smoothed with Gaussians with $\sigma = 15''$ for PSPC data and $\sigma = 5''$ for HRI data. There is a color scale mapping for the counts above each image. The 30 GHz image statistics are summarized in Table 4.



Reese et al. astro-ph/0205350

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Thermal SZ effect

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DETERMINATION OF THE COSMIC DISTANCE SCALE FROM SUNYAEV-ZEL'DOVICH EFFECT AND CHANDRA X-RAY MEASUREMENTS OF HIGH-REDSHIFT GALAXY CLUSTERS

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ABSTRACT

We determine the distance to 38 clusters of galaxies in the redshift range $0.14 \le z \le 0.89$ using X-ray data from *Chandra* and Sunyaev-Zeldovich effect (SZE) data from the Owens Valley Radio Observatory and the Berkeley-Illinois-Maryland Association interferometric arrays. The cluster plasma and dark matter distributions are analyzed using a hydrostatic equilibrium model that accounts for radial variations in density, temperature, and abundance, and the statistical and systematic errors of this method are quantified. The analysis is performed via a Markov chain Monte Carlo technique that provides simultaneous estimation of all model parameters. We measure a Hubble constant of $H_0 = 76.9^{+3.9}_{-3.4} + 10.0$ km s⁻¹ Mpc⁻¹ (statistical followed by systematic uncertainty at 68% confidence) for an $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$ cosmology. We also analyze the data using an isothermal β -model that does not invoke the hydrostatic equilibrium assumption and find $H_0 = 73.7^{+4.6}_{-3.8} + 9.5_{-7.6}$ km s⁻¹ Mpc⁻¹; to avoid effects from cool cores in clusters, we repeated this analysis excluding the central 100 kpc from the X-ray data and find $H_0 = 77.6^{+4.8}_{-4.3} + 10.1_{-3.8}$ km s⁻¹ Mpc⁻¹ (statistical followed by systematic uncertainty at 68% confidence). The consistency between the models illustrates the relative insensitivity of SZE/X-ray determinations of H_0 to the details of the cluster model. Our determination of the Hubble parameter in the distant universe agrees with the recent measurement from the *Hubble Space Telescope* Key Project that probes the nearby universe.

Subject headings: cosmic microwave background - distance scale - X-rays: galaxies: clusters

Online material: color figures, machine-readable table





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SZ profiles



NRAC

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SZ Results



Fig. 3.—Angular diameter distances of the 38 clusters (*circles*). The error bars are the total statistical uncertainties, obtained by combining the X-ray and SZE data modeling uncertainties (Table 2) and the additional sources of random error described in § 3.3 and Table 3. The systematic errors of Table 3 are not shown. The dashed line is the angular diameter curve using the best-fit Hubble constant $H_0 = 76.9$ km s⁻¹ Mpc⁻¹ and $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$. The squares are from the low-redshift sample of Mason et al. (2001), and they are not included in the fit.



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kSZ Effect

The Doppler effect of line of sight cluster velocity -> observed shift of the CMB spectrum.

In the nonrelativistic limit, the spectral signature of the kinetic SZE is a pure thermal distortion of magnitude of the CMB signal:



Kinetic SZ Results







TIDAL INTERACTIONS IN M81 GROUP

Stellar Light Distribution



21cm HI Distribution









Arp 220 - A starburst Galaxy



HI image from the VLA



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Sirius at 43 GHz with the VLA





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Solar activity in the radio







Thermal Sources

- The Cosmic Microwave Background
- Dust
- Planets, comets, asteroids
- Emission lines (HI, CO, other atomic and molecular)
- Stellar winds and outflows
- Sun (Quiet Sun) and other stars
- Supernovae
- HII regions
- Starburst galaxies (thermal component from HII regions)
- Clusters of galaxies (free-free)
- Clusters of galaxies Sunyaev-Zeldovich effect
- Accretion disks



Further Reading

http://www.nrao.edu/whatisra/mechanisms.shtml http://www.nrao.edu/whatisra/ www.nrao.edu

Synthesis Imaging in Radio Astronomy ASP Vol 180, eds Taylor, Carilli & Perley

This lecture is on the course web page:

http://www.phys.unm.edu/~gbtaylor/astr423





Review for Midterm #2

• Everything since midterm #1





Exam 2 Equations

Constants and astronomical quantities:

$c = 3 \times 10^{10} \text{ cm s}^{-1}$
$h = 6.626 \times 10^{-27} \text{ erg s}$
$G = 6.67 \times 10^{-8} \text{ cm}^3 \text{ g}^{-1} \text{s}^{-2}$
$\sigma = 5.67 \times 10^{-5} \mathrm{g s^{-3} K^{-4}}$
$k = 1.38 \times 10^{-16} \mathrm{erg} \mathrm{K}^{-1}$
${ m M}_{\odot} = 1.99 imes 10^{33} { m g}$
$T_{\odot} = 5800 \mathrm{K}$
$M_H = 1.67 \times 10^{-24} \mathrm{g}$
$m_e = 9.11 \times 10^{-28} g$
$1 \text{ AU} = 1.496 \times 10^{13} \text{ cm}$
1 pc = 3.26 ly = 3.086×10^{18} cm = $206,265$ AU
$10^{-23} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$
T[K]=T[C]+273
$T[F] = \frac{9}{5}T[C] + 32$
206,265 arcseconds

Useful equations:

 $\lambda_{max} = \frac{0.29 cm K}{T}$ Wien's Law and $F = \sigma T^4$ Stefan - Boltzmann Law

 $B_{\nu}=\frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$ Planck Function

 $T_b = \frac{\lambda^2 S_{\nu}}{2k\Omega}$ Brightness Temperature

K.E. = 3/2kT (per particle) and $V = \sqrt{(3kT/m)}$ (average velocity of particle)

 $\theta = 1.02\lambda/D$ (in radians) resolution for diameter or baseline length, D

 $V = \frac{\lambda_{aba} - \lambda_0}{\lambda_0} c$ doppler velocity

 $\nu_G = \frac{eB}{2\pi m} = 2.8 \frac{B}{\text{Gauss}} \text{MHz}$ gyro frequency

 $\nu_c = 1.5 \gamma^2 \nu_G$ synchrotron characteristic frequency

Synchrotron Lifetime = $\frac{16.4yr}{B^2\gamma}$ where B is in Gauss

 $E=\gamma mc^2$ Relativistic energy of a particle

 $T_b(s) = T_{back}(s_0)e^{-\tau_\nu(s)} + T_{emit}(1 - e^{-\tau_\nu(s)})$ radiative transfer $\tau(\nu) = 3.014 \times 10^{-2}\nu^{-2}T_e^{-1.5}EMg_{ff}$ free-free optical depth with ν in GHz, T_e in K and EM in pc cm⁻⁶

 $EM=\int n_e^2 ds$ emission measure and $RM=812\int Bn_e ds$ rad ${\rm m}^{-2}$ rotation measure





Practical Spectral Line Correlators

- The FX architecture
 - F : Fourier transform
 - X : Use a complex-correlator for each frequency channel
 - Then integrate
- The XF architecture
 - X : Measure correlation function at many lags
 - Integrate
 - F : Fourier transform
- Other architectures possible





XF Spectral Response (2)



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FX Spectral Response (2)



A Data Editing Example







Editing

•Typical calibrator visibility function after a priori calibration

- Calibrator is resolved
- Will need to image
- One antenna low
- Use calibrator to fix

•Shows why flux scale (gain normalization) should only be set by a subset of antennas





Plot file version 32 created 02-JUN-1995 13:29:38 Amplitude vs UV dist for BW12X.MULTI.1 Source:0923+392 Ants * -* Stokes RR IF# 1 Chn# 2



Calibration Summary

- Determining calibration is as important as determining source structure—can't have one without the other
- Calibration dominated by antenna-based effects, permits separation of calibration from astronomical information
- Calibration formalism algebra-rich, but can be described piecemeal in comprehendible segments, according to well-defined effects
- Calibration determination is a single standard fitting problem
- Calibration an iterative process, improving various components in turn
- Point sources are the best calibrators
- Observe calibrators according requirements of components
- Data examination and editing an important part of calibration





What is Polarized Light?

Light is oscillating electric and magnetic fields
Polarization is labeled by the shape of the trace of the tip of the E vector

Each polarization has an orthogonal state
Incoherent light can contain many polarization states

Stokes Parameters describe partially polarized light

I = RR + LL
Q = RL + LR
For circular feeds
U = i(LR - RL)
V = LL - RR

Alternate representation:

- pol. angle (EVPA) $\phi = 0.5$ atan (U/Q)
- polarized intensity $p = sqrt(Q^2 + U^2)$
 - fractional linear
 - fractional circular

φ = 0.5 atan (U/Q)
p = sqrt(Q² + U²)
m = p / I
v = |V| / I





Faraday Rotation







The Dirty Image



 \rightarrow





The

Dirty Image





...Weighting

• Robust/Briggs weighting: $W_k = 1/[S.\rho(u_k, v_k) + \sigma_k^2]$

 Parameterized filter – allows continuous variation between optimal resolution (uniform weighting) and optimal noise (natural weighting).







The missing information

- As seen earlier, not all parts of the uv-plane are sampled – the 'invisible distribution'
- 1. "Central hole" below u_{min} and v_{min} :
 - Image plane effect: Total integrated power is not measured.



- Upper limit on the largest scale in the image plane.
- **2.** No measurements beyond u_{max} and v_{max} :
 - Size of the main lobe of the PSF is finite (finite resolution).
- 3. Holes in the uv-plane:
 - Contribute to the side lobes of the PSF.











Why does self-calibration work?

 self-calibration preserves the Closure Phase which is a good observable even in the presence of antennabased phase errors

$$\begin{split} \Phi_{ijk} &= \theta_{ij} + \theta_{jk} + \theta_{ki} \\ &= \theta_{ij}^{\text{true}} + \left(\phi_i - \phi_j\right) + \theta_{jk}^{\text{true}} + \left(\phi_j - \phi_k\right) + \theta_{ki}^{\text{true}} + \left(\phi_k - \phi_i\right) \\ &= \theta_{ij}^{\text{true}} + \theta_{jk}^{\text{true}} + \theta_{ki}^{\text{true}} \end{split}$$





Advantages and disadvantages of self-calibration

Advantages

- Gains are derived for correct time, not by interpolation
- Gains are derived for correct direction on celestial sphere
- Solution is fairly robust if there are many baselines
- Disadvantages
 - Requires a sufficiently bright source
 - Introduces more degrees of freedom into the imaging so the results might not be robust and stable
 - Position information may be lost





Model fitting

- Imaging as an Inverse Problem
 - In synthesis imaging, we can solve the forward problem: given a sky brightness distribution, and knowing the characteristics of the instrument, we can predict the measurements (visibilities), within the limitations imposed by the noise.
 - The **inverse problem** is much harder, given limited data and noise: the solution is rarely unique.
 - A general approach to inverse problems is **model fitting**. See, e.g., Press et al., *Numerical Recipes*.
 - 1. Design a model defined by a number of adjustable parameters.
 - 2. Solve the forward problem to predict the measurements.
 - 3. Choose **a figure-of-merit** function, e.g., rms deviation between model predictions and measurements.
 - 4. Adjust the parameters to **minimize the merit function**.
 - Goals:
 - 1. Best-fit values for the parameters.
 - 2. A measure of the goodness-of-fit of the optimized model.
 - 3. Estimates of the uncertainty of the best-fit parameters.





Inspecting Visibility Data

• Fourier imaging

$$V(u,v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \mathcal{A}(l,m) I(l,m) \exp[-2\pi i (ul+vm)] \, dl \, dm$$

- Problems with direct inversion
 - Sampling
 - Poor (*u*,*v*) coverage
 - Missing data
 - e.g., no phases (speckle imaging)
 - Calibration
 - Closure quantities are independent of calibration
 - Non-Fourier imaging
 - e.g., wide-field imaging; time-variable sources (SS433)
 - Noise
 - Noise is uncorrelated in the (u, v) plane but correlated in the image





Non-Thermal Sources

- Man-made signals (RFI)
- Cosmic ray air showers
- Solar Flares (Active Sun), also flare stars and brown dwarfs
- Planetary magnetospheres
- Lightning (from storms on planets and locally as RFI)
- Planetary Radar/Spacecraft telemetry
- Supernova Remnants
- Gamma-ray Bursts and their afterglows
- Pulsars
- Magnetar flares
- Masers
- X-ray binaries/microquasars
- Normal galaxies (cosmic ray population)
- Active Galaxies (including Quasars, Blazars, etc.)
- Intracluster medium (halos and relics)
- Dark-matter decay



Synchrotron Emission



Thermal Sources

- The Cosmic Microwave Background
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- Starburst galaxies (thermal component from HII regions)
- Clusters of galaxies free-free emission
- Clusters of galaxies Sunyaev-Zeldovich effect
- Accretion disks?





Free-Free Emission



$\tau(\nu) = 8.235 \times 10^{-2} \nu_{\rm GHz}^{-2.1} T_e^{-1.35} \rm EM$



