3. X-ray observations

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3.1 Detection and identification of clusters in X-rays

[S:4.1, V:II.B, R:548]

→ X-rays: $10^{16} \lesssim \nu \lesssim 10^{19}$ Hz, $1 \lesssim \lambda \lesssim 100$ Å, $0.1 \lesssim E = h\nu \lesssim 100$ keV

→ Clusters of galaxies are the most common X-ray sources. They are extremely luminous in X-rays $L_X = 10^{43-45}$ erg/s. X-ray emission from clusters is extended and not time-variable.

→ Detected in X-ray emission lines of highly ionized metals (e.g. iron) $\Longrightarrow$ metal enriched plasma

→ Cluster X-ray emission is thermal emission from the hot ($2 \times 10^7 - 10^8$ K) gas of the intracluster medium (ICM).

→ X-rays cannot be observed by ground-based telescopes because they are efficiently absorbed by the earth's atmosphere. Need to observe from very high altitude $\Longrightarrow$ rockets (1960-1970) $\Longrightarrow$ satellites (1970-today).

→ Satellites: UHURU (1971), Einstein Observatory (1979), ROSAT (1990), XMM-Newton (1999), CHANDRA (1999), SUZAKU (2005). Increasing sensitivity, spatial (and spectral) resolution.

→ Highest resolution: spectral $E/\Delta E \sim 50$ (XMM), spatial ~ 0.5 arcsec (CHANDRA)

→ Advantage of X-ray selection of clusters: reveals bound systems; X-ray luminosity correlated with mass; X-ray emissivity proportional to gas density squared.

→ Cluster X-ray photometric samples mainly determined by area and flux limit.

3.2 X-ray luminosity function of cluster of galaxies

[S:4.2, R:556]

→ differential Luminosity Function (LF): $n(L_X)dL_X$ number of clusters with X-ray luminosity between L_X and $L_X + dL_X$. Integral LF $N(L_X) = \int_{L_X}^{\infty} n(L_X)dL_X$.

→ The cluster X-ray LF is well described by the Schechter function

$$n(L_X)dL_X = N_*(L_X/L_X^*)^{-\alpha_X} \exp(-L_X/L_X^*)d(L_X/L_X^*), \qquad (3.2)$$

where L_X^* is a characteristic luminosity and α_X is the faint-end slope.

→ L_X in some specified energy range ($E = h\nu$). For instance, 'soft' X-rays (0.5-2 keV).

→ Best-fit values $\alpha_X \sim 1.8$ and $L_X^* \sim 4 \times 10^{44}$ erg/s in soft X-rays 0.5-2 keV.

→ Cluster X-ray LF better determined than galaxy optical LF.

3.3 X-ray spectra of clusters

[S:4.3, V:II.B.2-3, BW:2]

→ Spectral X-ray observations of clusters fundamental to determine emission mechanism

→ It is thermal emission from diffuse hot intracluster gas:

$$I_\nu \propto \exp(-h\nu/k_B T) \qquad (3.3)$$

where T is the gas temperature; thermal velocity of protons $\sim \sqrt{k_B T/m_p} \sim \sigma$, where σ is the velocity dispersion of galaxies in the cluster; no low-energy photoabsorption (optically thin); emission lines from heavy elements (iron).

→ Intensity I_ν in units of $\mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}}$. Spectrum made by continuum + line emission.

→ The continuum is due to thermal bremsstrahlung $I_\nu \propto \exp(-h\nu/k_B T)$ if single-temperature gas. Temperature $2 \times 10^7 - 10^8\,$K, so bremsstrahlung emission is truncated at $\lesssim$ 10 keV (often T is expressed in keV: $k_B T = 1keV$ if $T \simeq 1.16 \times 10^7\,$K). So X-ray spectra can be used to measure temperature of ICM.

→ Observations in the hard X-rays ($\gtrsim$ 20 keV) can constrain the contribution from non-thermal emission (inverse Compton and synchrotron: $I_\nu \propto \nu^{-\alpha_{syn}}$)

→ The most important emission line in the cluster X-ray spectra is the "7 keV Fe line" from mainly Fe^{+24} and Fe^{+25} [e.g. Kβ line: $n = 1$ (K shell), $\Delta n = 2$ (β). Shells: K,L,... Δn: α, β,...]

→ Beside Fe 7 keV line, many lower energy lines from highly ionized Ni, Fe, C, N, O, Ne, Mg, Si, S...

→ Line equivalent width

$$EW \equiv \int \frac{I_\nu - I_{\nu,cont}}{I_{\nu,cont}} d(h\nu) \tag{3.4}$$

(in keV). Measures of EW of iron lines allows to determine metal abundance of cluster gas . Iron abundance $n_{\rm Fe}/n_{\rm H} \sim 10^{-5} \sim 0.3$ solar value ([Fe/H]=-0.5).

→ Also metallicity gradient: higher metallicity in the core.

3.4 Spatial distribution of X-ray emission form clusters

[S:4.4, V:II.B.1]

→ Extended X-ray emission peaked on the cluster center (on the cD or BGC if there is a central dominant galaxy)

→ β model: both the distribution of gas and the distribution of galaxies are assumed to be isothermal, in hydrostatic equilibrium in the cluster gravitational potential. Galaxy distribution with isotropic velocity dispersion. The parameter β is the ratio between gas (T_{gas}) and galaxy ($T_{gal,equiv} = \mu m_p \sigma^2 / k_b$), where μ is the mean gas particle mass in units of the proton mass m_{p} and k_B is the Boltzmann constant. Thus

$$\beta \equiv \frac{\mu m_p \sigma^2}{k_B T_{gas}}, \tag{3.5}$$

where σ is the 1-dimensional galaxy velocity dispersion. $\Longrightarrow \rho_{gas} \propto \rho_{gal}^{\beta}$ (derive from hydrostatic equilibrium equation).

→ If galaxy distribution is King analytic model then

$$n_{gas}(r) = n_{gas,0} \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-3\beta/2} \tag{3.6}$$

($\rho_{gas} = \mu m_p n_{gas}$).

→ The X-ray surface brightness is

$$S_X(R) = 2 \int_R^{\infty} \frac{\epsilon r dr}{\sqrt{r^2 - R^2}}, \tag{3.7}$$

where $\epsilon = n_i n_e \Lambda(T)$ is the emissivity and $\Lambda(T)$ is the cooling function $\Lambda(T) \propto T^{1/2}$ for bremsstrahlung (n_i and n_e are the ion and electron number densities and $n_{gas} = n_i + n_e$). In the case of β model one obtains

$$S_X(R) \propto \left[1 + \left(\frac{R}{r_c} \right)^2 \right]^{-3\beta + \frac{1}{2}}. \tag{3.8}$$

→ Best fit values for beta models of clusters $\beta \simeq 2/3$. Thus at $r \gg r_c$ $\rho_{gas} \propto r^{-2}$ while $\rho_{gal} \propto r^{-3}$ (gas distribution more extended).

→ Gas mass diverges at large radii for $\beta \leq 1$. The integrated X-ray luminosity converges for $\beta > 0.5$.

→ Morphology of X-ray emission: regular/irregular; with or without a central dominant galaxy; with or without cool core.

3.5 Thermal emission mechanisms in X-rays

[S:5.1.3, S:5.2, BW:2]

3.5.1 Ionization and X-ray emission

→ $T \sim 10^8$ K, $n_e \sim 10^{-3}$ cm^{-3}

→ Assumptions: Coulomb collision timescale short $\Longrightarrow$ Maxwell-Boltzmann distribution at temperature $T_e = T_i$; low density $\Longrightarrow$ collisional excitation and deexcitation slower than radiative decay; gas is optically thin; ionization determined by electron-ion collisions (negligible ion-ion collisions); plasma in ionization equilibrium.

→ H and He fully ionized with primordial composition $X = 0.75$ and $Y = 0.25$ (H and He fraction in mass) $\Longrightarrow n_H = 6n_e/7$, $n_{\rm He} = n_e/14$, where n_H and $n_{\rm He}$ are H and He number densities $\Longrightarrow n_i \simeq 0.93n_e$, $n = n_i + n_e \simeq 1.93n_e$ and $\mu \simeq 0.59$ (derive). By definition, in fully ionized plasma $n_H = n_p$ (proton number density).

→ The equilibrium ionization state depends only on the electron temperature.

→ Continuum X-ray emission due to free-free (bremsstrahlung) and free-bound (recombination). Bremsstrahlung dominant.

→ Line X-ray emission due to radiative deexcitation of collisionally excited inner shell electrons $\Longrightarrow$ radiative recombination.

→ Line ratios useful to determine temperature, abundance and ionization state of the cluster gas.

→ The combined emissivity from this mechanisms can be expressed as

$$\epsilon_\nu = n_p n_e \sum_{X,i} \frac{n(X)}{n(H)} f(X^i, T_e)\Lambda_\nu(X^i, T), \tag{3.9}$$

where X^i is a ion of the generic element X, f is the ionization fraction and Λ_ν is the emission per ion at unit electron density. The bolometric emissivity can be written

$$\epsilon = \int \epsilon_\nu dh\nu = n_e n_i \Lambda(T), \tag{3.10}$$

where Λ is the radiative cooling function, strongly dependent on metallicity for $T \lesssim 3 \times 10^7$ K. (units of ϵ: $erg\, s^{-1}\, cm^{-3}$ or $W\, m^{-3}$)

→ It is useful to define the Emission Integral $EI \equiv \int n_e n_p dV$. The normalization of the spectrum depends on EI. The shape on the abundance and on $d(EI)/dT_e$.

→ The clearest evidence for thermal emission in clusters is the presence of metal lines, especially iron 7 keV line. Inverse Compton does not produce lines.

3.5.2 Thermal bremsstrahlung

→ $T \sim 10^8$ K, $n_e \sim 10^{-3}$ cm^{-3} gas with Maxwell-Boltzmann distribution $\Longrightarrow$ thermal bremsstrahlung (free-free) with emissivity

$$\epsilon_\nu \equiv \frac{dL}{d\nu dV} \propto Z^2 n_e n_i g(Z, T_e, \nu) T_e^{-1/2} \exp(-h\nu/k_B T_e), \tag{3.11}$$

where T_e is the electron temperature, k_B is the Boltzmann constant, n_e (n_i) is the electron (ion) number density, Z is the charge of ions and g is the Gaunt factor (of the order of unity) accounting for quantum mechanical effects.

→ Bolometric bremsstrahlung emissivity, neglecting temperature and frequency dependence of g (derive)

$$\epsilon = \int \epsilon_\nu d(h\nu) \propto T_e^{1/2} n_e n_i. \tag{3.12}$$

Total X-ray luminosity

$$L_X = \int \epsilon dV. \tag{3.13}$$

13/10/2009

4. Microwave observations of clusters

4.1 Clusters in microwaves

[Bibl: S:3.5, V:II.C]

→ Millimetric/submillimetric band: $30 \lesssim \nu \lesssim 300$ GHz, $0.1 \lesssim \lambda \lesssim 10$ mm.

→ Clusters of galaxies do not emit significantly in the microwaves, but can be detected by their effect on the Cosmic Microwave Background (CMB): known as Sunyaev-Zeldovich (SZ) effect

4.2 Thermal Sunyaev-Zeldovich effect

→ CMB: black body radiation at $T_{CMB} = 2.725$ K. CMB spectrum:

$$I_\nu = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{k_B T_{CMB}}\right) - 1}. \tag{4.2}$$

→ Free electrons of cluster hot gas scatter CMB photons $\Longrightarrow$ distortion of CMB spectrum. The optical depth is

$$d\tau_T = \sigma_T n_e dl, \tag{4.3}$$

where n_e is the electron number density and

$$\sigma_T = \frac{8\pi}{3} \left[\frac{e^2}{m_e c^2}\right]^2 \tag{4.4}$$

is the Thomson electron scatter cross section. For typical values $n_e \sim 10^{-3}$ and $l \sim 1Mpc \implies$

$$\tau_T = \int \sigma_T n_e dl \sim 10^{-2} \tag{4.5}$$

$\implies 1\%$ probability of scattering.

$\rightarrow$ $E_e \gg E_\gamma \implies$ inverse Compton $\implies$ distortion of CMB spectrum. Frequency change:

$$\frac{\Delta\nu}{\nu} = \frac{4k_B T_e}{m_e c^2}. \tag{4.6}$$

$\rightarrow$ The distorted spectrum is not black body. Define brightness temperature T_b of a source as the temperature of a black body having the same intensity as the source at a given frequency ν. In terms of T_b the spectral distortion is

$$\frac{\Delta T_b}{T_b} = \frac{\Delta I_\nu}{I_\nu}\frac{d\ln T_b}{d\ln I_\nu} = f(x)y, \tag{4.7}$$

where $x \equiv h\nu/k_B T_b$, the Compton y-parameter is

$$y \equiv \int \frac{k_B T_e}{m_e c^2} d\tau_T = \int \frac{k_B T_e}{m_e c^2} n_e \sigma_T dl \tag{4.8}$$

and $f(x) = [x\coth(x/2) - 4]$ if nonrelativistic.

$\rightarrow$ In the Rayleigh-Jeans regime (low frequency, $x \ll 1$)

$$T_b \equiv \frac{I_\nu c^2}{2k_B \nu^2}, \tag{4.9}$$

and $f(x) \rightarrow -2 \implies$

$$\frac{\Delta T_b}{T_b} = -2y = -\int \frac{2k_B T_e}{m_e c^2} n_e \sigma_T dl \tag{4.10}$$

$\rightarrow$ Intensity decreases at $\nu < 218$ GHz and increases at at $\nu > 218$ GHz. Usually measurements at low frequency $\implies$ "microwave diminution"

$\rightarrow$ In the hottest clusters relativistic corrections become important

→ SZ effect is small ($\Delta T_b/T_b \sim 10^{-3}$) $\Longrightarrow$ difficult to observe.

→ SZ effect independent of cluster distance (redshift) $\Longrightarrow$ detection of high-redshift clusters.

4.3 Observations of the Sunyaev-Zeldovich effect

→ Radio telescopes. BIMA radio telescope (30 GHz).

→ SZ brightness is independent of redshift. But not all high-redshift clusters can be resolved $\Longrightarrow Y$ parameter:

$$Y = \int y dA \propto \int n_e T_e dV, \tag{4.11}$$

where dA is projected cluster area element.

→ $Y \propto M_{gas} < T_e >$

4.4 Hubble constant with SZ effect

→ SZ + X-ray $\Longrightarrow$ independent estimate of distance $\Longrightarrow$ estimate of H_0 (derive). Absorption $A \propto n_e D_A \theta$, emission $E \propto n_e^2 D_A \theta$ $\Longrightarrow A^2/E \propto D_A \theta^3$ (θ angular size of cluster, D_A angular diameter distance).

→ Combining the SZ effect for a spherical cluster

$$\frac{\Delta T_b}{T_b} \propto T_e n_e \Delta l \sim T_e n_e D_A \theta \tag{4.12}$$

with the X-ray flux f_X is

$$f_X \propto \frac{n_e^2 T_e^{1/2} \Delta V}{D_L^2} \propto \frac{n_e^2 T_e^{1/2} \theta^3 D_A}{(1+z)^4} \tag{4.13}$$

[because $D_L = (1+z)^2 D_A$ and $\Delta V \propto \theta^3 D_A^3$], we get (derive)

$$D_A \propto \frac{(\Delta T_b)^2}{T_b^2} \frac{\theta}{f_X T_e^{3/2} (1+z)^4}. \tag{4.14}$$

→ at low redshift $D_A \simeq cz/H_0 \implies$ estimate of H_0. At higher redshift estimates of deceleration parameter q_0

4.5 Kinetic Sunyaev-Zeldovich effect

→ If a cluster is moving w.r.t. the CMB (or Hubble flow) $\implies$ additional spectral distortion of CMB.

→ If $\tau_T \ll 1 \implies$ brightness temperature change is almost independent of frequency

$$\frac{\Delta T_b}{T_b} = -\frac{v_r}{c}\tau_T, \tag{4.15}$$

where v_r is the radial component of the cluster peculiar velocity. Here $v_r > 0$ corresponds to a recession velocity exceeding that of the Hubble's law.

→ $v_r > 0 \implies$ negative temperature variation; $v_r < 0 \implies$ positive temperature variation;

→ Temperature change independent of $\nu \implies$ Planck spectrum.

→ Kinetic SZ effect much weaker than thermal SZ effect.

→ Measures of kinetic SZ effect are done at $\nu \sim 218$ GHz, where the thermal SZ effect is null.