

Longair

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X-ray observations of hot gas in Galaxy clusters

We will show here how the X-ray emission from the intracluster hot gas can be used to determine

- (i) the distribution of hot gas
- (ii) the total gravitating mass

Assume spherical symmetry.

- II - that the gas is in hydrostatic equilibrium within the potential formed by the total cluster mass

With P and ρ the pressure and density of the gas and $M(\leq r)$ the total gravitating mass within r :

$$P = \frac{\rho K T}{\mu m_H} \quad \frac{dP}{dr} = - \frac{G M(\leq r) \rho}{r^2}$$

$$\frac{dp}{dr} \downarrow$$

$$\frac{\rho K T}{\mu m_H} \left(\frac{1}{P} \frac{dp}{dr} + \frac{1}{T} \frac{dT}{dr} \right) = - \frac{G M(\leq r) \rho}{r^2}$$

$$M(\leq r) = - \frac{K T r^2}{G \mu m_H} \left[\frac{d(\log \rho)}{dr} + \frac{d(\log T)}{dr} \right]$$

If the variation of gas density and Temperature are known, we can obtain the mass distribution within the cluster.

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How hot is the gas confined in a galaxy cluster, assuming hydrostatic equilibrium?

Gas equation of state $P = N_e k T$

$$\text{Hydrostatic eq: } \frac{dP}{dr} = - \frac{GM(\leq r)}{R^2} P$$

$$\text{roughly } \frac{P}{R} = \frac{GM}{R^2} p \Rightarrow N_e k T = \frac{GM}{R} N_e m_p$$

$$\Rightarrow T = \frac{GM m_p}{R} \approx \boxed{3 \cdot 10^7 M_{\odot 14} R_{\text{mpc}}^{-1} \text{ K}}$$

$$kT \sim 6 \text{ keV } M_{\odot 14} R_{\text{mpc}}^{-1}$$

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$$r - - - - - \sqrt{a}$$

To measure the Temperature profile $T(r)$
 find from observations the cutoff frequency ν_c
 of Bremsstrahlung as a function of r and
 and recall $h\nu_c = kT$

Now if $\epsilon_{ff}(\nu, r)$ is the spectral emissivity then

$$I_\nu(a) = \frac{1}{2\pi} \int_a^\infty \frac{\epsilon_{ff}(\nu, r) r}{(r^2 - a^2)^{1/2}} dr$$

Inverting this Abel integral we obtain:

$$\epsilon_{ff}(r, \nu) = \frac{4}{r} \frac{d}{dr} \int_r^\infty \frac{I_\nu(a) a}{(a^2 - r^2)^{1/2}} da$$

Knowing ϵ_{ff} one finds $\rho(r)$ of the gas
 because $\epsilon_{ff} \propto n_e n_i$

- > You see the visible galaxy mass
- > You measure the mass of the hot gas
- > You obtain from $\rho(r)$ and $T(r)$ the total gravitating mass.

Cooling flows and their problems

How long does it take for hot gas to cool via Bremsstrahlung?

$$t_{\text{cool}} = \frac{E}{\left| \frac{dE}{dt} \right|} = \frac{3nKT}{1.4 \cdot 10^{-23} \text{ g} \cdot n_e \cdot T^{1/2}} = 10^{10} \frac{T_8^{1/2}}{\eta^{-2}} \text{ years}$$

$\sim \text{Hubble time}$

In clusters, the cooling time decreases (because $n \uparrow$ faster than $T^{1/2} \downarrow$). Inside a cooling radius r_{cool} the cooling time is shorter than the cluster age. At $r > r_{\text{cool}}$ the gas has no time to cool. As gas cools, it slowly drifts inward.

The energy per unit mass available for being radiated is

$$W = E + PV = \frac{5}{2} nKT . \quad \text{if } N \text{ is the rate at which particles drift inward at any radius}$$

$$L_{\text{cool}} = \frac{5}{2} \dot{N}KT = \frac{5}{2} \frac{\dot{m}}{\mu m_p} KT$$

This gives you the mass deposition \dot{m}

BUT In many clusters something heats up the core
(examples)

What? AGN, buoyant radio cavities, dead radio galaxies.

No consensus yet