Analytic Approaches to Understanding the Distribution
and Evolution of Intracluster Gas

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**Abstract.** I will briefly review various analytic approaches to understanding the contents and properties of the hot X-ray emitting gas contained in clusters and groups. Special emphases are given to the following three issues: (1) Reconstruction of the gas distribution in groups and clusters from a (joint) analysis of X-ray, SZ and gravitational lensing observations; (2) Test of the analytic density profiles of dark halos suggested by numerical simulations and empirical models with current X-ray data; And (3) the effects of preheating and radiative cooling on the X-ray properties of groups and clusters.

1. **Introduction**

Groups and clusters serve as a reservoir of baryons in the present-day universe. They exist in the form of hot plasma with temperature close to the virial temperature ($10^6$-$10^8$ K) of the underlying gravitational potential wells as a result of gravitationally-driven shocks and adiabatic compression. Since the discovery of diffuse X-ray emission associated with clusters of galaxies, many efforts have been made towards exploring the distribution and evolution of the hot gas in clusters. This is significant not only for our understanding of the matter composition and dynamical properties of clusters but also for test of various theories of structure formation. In recent years, a combination of multi-wavelength observations (e.g. optical, X-ray, radio, gravitational lensing, etc.), theoretical analysis and hydrodynamical simulations has greatly improved our knowledge of the intragroup/intracluster gas. In this review I will concentrate on the analytic approaches to determining and modeling the distribution and evolution of the diffuse X-ray emitting gas in groups and clusters.

2. **Observational approaches**

2.1. **X-ray observations**

In principle one is able to analytically derive the gas distribution of clusters by direct inversion of the X-ray surface brightness profile $S_x$. Under the assumptions of spherical symmetry and thermal Bremsstrahlung, we have (e.g. Cowie,
Henriksen & Mushotzky (1987)

\[ n_e^2(r) \Lambda(T) = \frac{4(1+z)^4}{r} \frac{d}{dr} \int_{r}^{\infty} S_x(R) \frac{RdR}{\sqrt{R^2 - r^2}}, \]  

(1)

where the emissivity \( \Lambda \) is roughly proportional to \( T^{1/2} \) for clusters. The electron density profile \( n_e(r) \) can thus be obtained in combination with high resolution spectral observation. In the case of isothermality and for conventional \( \beta \) model \( S_x \propto (1 + r^2/r_c^2)^{-3\beta+1/2} \), The above equation reduces to the well-known functional form of

\[ n_e(r) = n_0 \left( 1 + \frac{r^2}{r_c^2} \right)^{-3\beta/2}. \]  

(2)

Even for the double \( \beta \) model suggested by some authors (e.g. Ikebe et al. 1996; 1999; Xu et al. 1998; Mohr, Mathiesen & Evrard 1999; Xue & Wu 2000c; Ettori 2000) aiming at a better description of the central excess emission associated with cooling flows, an analytical form of gas density can also be achieved. Yet, the accuracy of the derived gas density profile may suffer from uncertainties not only in the determination of temperature profile but also in the extrapolation of the available X-ray data to the outer-skirts of clusters. Moreover, the inversion of the X-ray surface brightness profiles becomes complicated if the hot gas in clusters actually has an asymmetrical distribution. Another technique, which has been widely used in the analysis of X-ray clusters, is to deproject the X-ray surface brightness by specifying \textit{a priori} the gravitational potential of a cluster and demanding additionally hydrostatic equilibrium (Fabian et al. 1980, 1981; White, Jone & Forman 1997). Strictly speaking, such a method is not a purely observational approach to the reconstruction of the distribution of intracluster gas.

2.2. Combination of X-ray and optical observations

The pioneering effort to derive the empirical \( \beta \) model of gas density in clusters can be traced back to 1976 when Cavaliere & Fusco-Femiano (1976, 1978) combined the Jeans equation for galaxies

\[ \frac{1}{n_{\text{gal}}(r)} \frac{d[n_{\text{gal}}(r) \sigma_f^2(r)]}{dr} = - \frac{d\Phi(r)}{dr}, \]  

(3)

with the hydrostatic equation for gas

\[ \frac{1}{\rho_{\text{gas}}} \frac{d[n_{\text{gas}}(r) kT(r)]}{dr} = - \frac{d\Phi(r)}{dr}, \]  

(4)

and reached

\[ n_{\text{gas}}(r) \propto n_{\text{gal}}^{\beta_{\text{spec}}}(r) \propto \left( 1 + \frac{r^2}{r_c^2} \right)^{-3\beta_{\text{spec}}/2}, \]  

(5)

in which an isotropic, constant velocity dispersion of galaxies and a constant gas temperature have been adopted, and the last equality in the above equation assumed a simplified King model for the radial variation of galaxy number density,
This does reproduce the functional form of the empirical $\beta$ model except the power index: Direct fitting of the X-ray surface brightness of clusters gives a mean value of $\langle \beta \rangle \approx 0.6 - 0.7$, while the average spectral parameter $[\beta = \sigma^2/(kT/\mu m_p)]$ seems to be slightly larger, $\langle \beta_{\text{spec}} \rangle \approx 1$. This so-called $\beta$ discrepancy has attracted the attention of many investigators (e.g. Bahcall & Lubin 1994; Gerbal, Durret & Lachièze-Rey 1994; Bird, Mushotzky & Metzler 1995; Wu, Fang & Xu 1998; Xue & Wu 2000c; etc.), and several possible reasons including observational selection effect have been extensively discussed in the literature.

2.3. Combination of X-ray and S-Z measurements

Silk & White (1978) were the first to suggest the utilization of the nonparametric reconstruction of the radial profiles of density $[n_e(r)]$ and temperature $[T(r)]$ of intracluster gas by combining the X-ray and SZ measurements. The basic idea is to inverse the observed X-ray and SZ temperature surface brightness profiles of clusters:

$$n_e^2(r)T^{1/2}(r) \propto \frac{1}{r} \frac{d}{dr} \int_r^\infty S_X(R) \frac{R dR}{\sqrt{R^2 - r^2}}, \quad (6)$$

$$n_e(r)T(r) \propto \frac{1}{r} \frac{d}{dr} \int_r^\infty S_{SZ}(R) \frac{R dR}{\sqrt{R^2 - r^2}}, \quad (7)$$

where $S_{SZ}(R)$ is the SZ surface brightness across clusters. And a simple combination of the two functions gives straightforwardly the gas density $n_e(r)$ and temperature $T(r)$. This method requires no assumptions about the dynamical properties of clusters and the equation of state for intracluster gas, and can therefore be regarded as an ideal and ultimate tool to probe the gas distribution in clusters under spherical approximation.

Despite its elegant mathematical treatment further developed by Yoshikawa & Suto (1999) based on some theoretical models, the pioneering suggestion of Silk & White (1978) has not yet been put into practice. This has been primarily limited by the instrumental sensitivity and resolution of detecting the temperature variations of the cosmic microwave background (CMB) behind clusters. So far, marginal detections of the radial SZ temperature distributions have been reported only for a few clusters (see Birkinshaw 1999), which can hardly be used for the purpose of reconstructing the gas temperature profiles because of the sparse data points and the large associated uncertainties. A preliminary analysis of the central gas temperatures of 31 clusters provided by the two methods has been made, based on the $\beta$ model for the gas density profiles (Zhang & Wu 2000). It turns out that there is a good agreement between these two independent temperature estimates.

2.4. Combination of X-ray, SZ and weak lensing measurements

Weak gravitational lensing technique provides a robust constraint on the shape of the gravitational potential of clusters. With this additional observation, one will be able to reconstruct the intracluster gas distribution even if it is not spherical (e.g. Cooray 1998; Zaroubi et al. 2001; Fox & Pen 2002).
The X-ray surface brightness in a given energy band is simply

\[ S_x(r) = \frac{1}{2\pi(1+z)^3} \int_r^\infty n_e^2 \Lambda(T, n_e) d\ell. \] (8)

The SZ temperature variation caused by a cluster is

\[ \frac{\Delta T_{SZ}}{T_{CMB}} = g(x) \frac{\sigma_T}{m_e c^2} \int n_e kT_e d\ell, \] (9)

where \( g(x) \) denotes the spectral dependence and is approximately equal to \(-2\) in the Rayleigh-Jeans regime, \( x = h_\nu / kT_{CMB} \), and \( T_{CMB} = 2.728 \) K is the temperature of CMB. Under the assumption of spherical symmetry, the inversion of these two equations yields the radial profiles of gas density \( n_e \) and temperature \( T(r) \), as has been discussed above. However, if the gas distribution deviates from spherical symmetry, additional constraints must be postulated. The equation of hydrostatic equilibrium is certainly the first choice:

\[ \nabla p = -\rho_{gas} \nabla \phi. \] (10)

Here \( \phi \) represents the gravitational potential of the cluster, which should be either determined by other independent observations or specified by numerical simulations or theoretical models. Weak gravitational lensing permits a direct reconstruction of the projected cluster mass \( \Sigma(\theta) \), which is related to the two-dimensional potential \( \psi \) through

\[ \nabla^2 \psi = \frac{2\Sigma(\theta)}{\Sigma_c} = 2\kappa, \] (11)

where \( \Sigma_{crit} = (c^2/4\pi G)(D_s/D_d D_{ds}) \) is the critical surface density, and \( \kappa \) is called convergence. Finally,

\[ \psi(\theta) = \frac{1}{2\pi G \Sigma_{crit}} \int \phi d\ell. \] (12)

With this additional constraint from gravitational lensing, one can now reconstruct the gas distribution if the cluster possesses an axial symmetry. Strictly speaking, such a combined analysis is not a purely observational method because it demands the condition of hydrostatic equilibrium for the intracluster gas.

3. Tests of analytic density profiles for dark halos

High-resolution cosmological simulations suggest that the dark matter density profile is well described by a self-similar, two-parameter functional form (e.g. Navarro, Frenk & White 1997):

\[ \rho_{DM}(r) = \frac{\rho_{crit}\delta_c}{(r/r_s)^\alpha(1+r/r_s)^{3-\alpha}}. \] (13)

The parameters \( \delta_c \) and \( r_s \) set the scale of the mass distribution in density and length, and \( \alpha \) is the logarithmic power-law slope near the center, with \( \alpha = 1 - 1.5 \).
(Navarro et al. 1997; Moore et al. 1998). Other empirical density profiles advocated in the literature include Hernquist profile $\rho_{DM}(r) = (M/2\pi a)\left((r/a)(1 + r/a)^3\right)$ and Burkert profile $\rho_{DM}(r) = \rho_0\left((1 + r/r_0)(1 + r^2/r_0^2)\right)$. Now our strategy is to find the distribution of the intracluster gas if it is in hydrostatic equilibrium with the underlying gravitational potential of dark matter defined by one of the above analytical forms:

$$1 \mu m_p n_{gas}(r) \frac{d[n_{gas}(r)kT(r)]}{dr} = -\frac{GM_{tot}(r)}{r^2}.$$  \hspace{1cm} (14)

This enables one to work out the gas distribution once the equation of state is specified. Eventually, an examination of the predicted and observed X-ray surface brightness distributions of clusters will provide a critical test for the proposed dark matter profiles. In the case of isothermality for the gas and an NFW profile for the dark matter distribution, one has $n_{gas}(r) \propto (1 + r/r_s)^{b/(r/r_s)}$ where $b = 4\pi G \mu m_p \rho_s r_s^2/kT$ (Makino, Sasaki & Suto 1998). This functional form can be approximately fitted by the $\beta$ model except the small core sizes as compared with X-ray observations of clusters. Inclusion of the temperature gradient parameterized by the polytropic form seems to provide a more plausible prediction (Suto, Sasaki & Makino 1998) but a direct comparison with observations is hampered by the poorly constrained temperature profiles at present. Alternatively, one can also assume that the gas distribution is self-similar, i.e., $n_{gas} = (f_b/\mu m_p)\rho_{DM}(r)$ where $f_b$ is the universal baryon fraction. This is justified by a number of hydrostatic simulations at least outside the central cores of clusters (e.g. Bryan & Norman 1998; Eke, Navarro & Frenk 1998; Pearce et al. 2000; etc.). As a result, we can predict the radial profile of gas temperature

$$kT(r) = \left(\frac{\mu m_p G}{\rho_{DM}(r)}\right) \int_r^\infty \rho_{DM}(r) \frac{M(r)}{r^2} dr, \hspace{1cm} \text{(15)}$$

in which we have neglected the self-gravity of the intracluster gas and set $n_{gas}(r)kT(r)$ to approach 0 when $r \rightarrow \infty$. One can equally use the central temperature $T(0)$ as the boundary condition and/or the polytropic state of equation to get more general form of the temperature profile (e.g. Komatsu & Seljak 2001). Another possible way to derive the temperature profile is to combine the high-resolution surface brightness measurement $S_x$ with the equation of hydrostatic equilibrium for a given dark matter distribution such as the NFW profile (Wu & Chiuheh 2000; Xue & Wu 2000a). Yet, high quality, spatially-resolved spectral measurements will be needed to test these predictions.

The striking similarity between the predicted X-ray surface brightness of clusters by NFW profile in the case of isothermality and the conventional $\beta$ model has stimulated several authors to determine the two free parameters in the NFW profile through a direct fitting of the observed data of clusters to theoretical prediction (e.g. Makino & Asano 1999; Ettori & Fabian 1999; Wu & Xue 2000a,b; Xu, Jin & Wu 2001; etc.). Although the best fit values of $r_s$ and $\delta_c$ have been given for a few tens of X-ray clusters, great caution must be exercised if these data are used for cosmological purposes (Wu & Xue 2000a; Sato et al. 2000; Cheng & Wu 2001). Note that the fitting process is sensitive to the data points at the central regions of clusters, in which the presence of central cooling
flows in most of clusters may lead to large uncertainties in the determination of $r_s$ ($r_s \approx r_c/3$).

In a word, current measurements of the X-ray surface brightness of clusters are still insufficient to distinguish various proposed analytic models for dark matter distribution in clusters except the Burkert profile. This last empirical profile is based on the fitting of the rotation curves of the dark matter dominated dwarf galaxies (Burkert 1995). Such a model resembles an isothermal profile in the inner region with a constant core $r_0$, while in the outer region the mass profile diverges logarithmically with $r$, in agreement with the generalized NFW profile. The model has recently received considerable attention because of the existence of the soft inner matter distributions of the dark halos claimed by some observations (e.g. Flores & Primack 1994; de Blok & McGaugh 1997; Tyson & Kochanski & dell’Antonio 1998; etc.). In despite of its success on galactic scales, the Burkert profile predicts too large core radii of dark matter profiles for clusters to be reconciled with the measurements of strong gravitational lensing (Wu & Xue 2000b; Xue & Wu 2001). Meanwhile, its predicted X-ray surface brightness of clusters fails in the fitting of the observed data (Xu et al. 2001).

4. Physical motivations

While gravity plays a dominant role in the overall distribution and evolution of the hot gas in groups and clusters, the gas also suffers from the influence of nongravitational effects such as radiative cooling, nongravitational heating, nonthermal pressure, etc. In low mass groups and the central regions of clusters the nongravitational effects could even govern the behavior of the gas. Indeed, it has been realized that some peculiar X-ray features of groups and clusters are associated with nongravitational processes, although the essential physics still remains a subject of intense debate. In the following discussion, we will focus on the impacts of preheating and radiation cooling on the X-ray properties of groups and clusters.

4.1. Observational evidence

There is growing observational evidence for the presence of nongravitational heating and/or radiative cooling in groups and clusters which suppresses the X-ray emission of the gas heated by purely gravitational shocks and adiabatic compression. A summary of the observational facts is given below:

- The steepening of the X-ray luminosity - temperature relation of groups and clusters (David et al. 1993; Wu, Xue & Fang 1999; Xue & Wu 2000b and references therein);
- The existence of the entropy floor in the central cores of groups and clusters (Ponman, Cannon & Navarro 1999);
- The flattening of the X-ray surface brightness profiles of poor clusters and groups (Ponman et al. 1999);
- The upper limit on the X-ray background from the diffuse gas bound in groups and clusters (Pen 1999; Phillips, Ostriker & Cen 2001; Wu & Xue 2001 and references therein);
• The scale-dependence of the gas and stellar mass fractions and the mass-to-light ratios of groups and clusters (Mohr et al. 1999; Bryan 2000; Bahcall & Comerford, 2002; Wu & Xue 2002b; Girardi et al. 2002; etc.);
• A monotonic increase in the gas mass fraction of clusters with cluster radii (White & Fabian 1995; Ettori & Fabian 1999; Markevitch et al. 1999; Wu & Xue 2000c; etc.);
• The failure of detection of X-ray halos surrounding spiral galaxies (Benson et al. 2000).

These independent observations as a whole suggest that there exists some nongravitational mechanism which removes the content of hot gas from groups and clusters, and the effect is more significant in the central regions and low-mass systems. As a consequence, late-type galaxies contain almost no hot gas at present. The prevailing physical scenarios proposed thus far are preheating and radiative cooling. The former invokes an extra energy source to preheat the gas to a certain entropy floor so that the heated gas cannot be compressed by the shallower gravitational potential wells of low-mass systems like poor clusters and groups, while the latter requires a considerably high efficiency of cooling to convert hot gas into cooled material (i.e. stars) inside the systems. Both processes result in a decrement of the hot gas in groups and clusters, and have been shown to explain equally well the observed X-ray properties of groups and clusters (e.g. Voit et al. 2002; Muanwong et al. 2002; Borgani et al. 2002).

4.2. Preheating

The preheating scenario was proposed a decade ago by several authors (David, Forman & Jones 1991; Evrard & Henry 1991; Kaiser 1991; White 1991): If the gas was preheated before falling into the gravitational potentials of groups and clusters dominated by dark matter, the entropy of the gas would be raised up to a certain level so that the gas became harder to compress. The resulting entropy floor breaks the self-similarity between dark matter and gas, and the flattened radial distribution of the hot gas developed. For low-mass systems like groups, the gas may even extend well beyond the virial radii. This leads to a significant decrease of the gas density and therefore, the X-ray emission. An energy budget of 0.4 - 3 keV per gas particle, depending on the epoch and environment of preheating, is required to reproduce the observed entropy floor and $L_x-T$ relation. There are two potential energy sources of heating which have been explored extensively in the literature: SN explosions and AGN activity. However, a number of recent studies have found that an unreasonably high efficiency of energy injection into the intragroup/intracluster medium from supernovae should be required in order to bring the gas to the energy level seen in the X-ray luminosity and entropy distributions of groups and clusters (Wu, Fabian & Nulsen 1998, 2000; Valageas & Silk 1999; Tozzi 2001; etc.). Although the energy supply by AGN activity is sufficiently large (Valageas & Silk 1999; Nath & Roychowdhury 2002), it still remains unclear how the kinetic energy of the AGN activity is deposited onto the baryons.

A phenomenological treatment of the problem is to simply put the energy budget problem aside, and work directly with the observed entropy distribution of intragroup/intracluster gas. Together with some physically motivated, analytic models and empirical relations revealed by hydrodynamical simulations,
one may be able to explain/reproduce the gross observational properties of the
intragroup/intracluster gas. Many investigations of these issues have been made
over past years. The shock model suggested by Cavaliere, Menci & Tozzi (1997;
1998) has successfully reproduced the steepening of the $L_x$-$T$ relation and the
flat cores of gas distribution in the central regions of groups and clusters. The
model attempts to link the preheated infalling gas with the virialized gas of a
dark halo at the boundary through the Rankine-Hugoniot equation. The new
distribution of the gas can be obtained by numerically solving the equation of
hydrostatic equilibrium under the boundary condition. However, one must re-
dply on Monte Carlo techniques in order trace the hierarchical merging history
of dark halos.

Balogh, Babul & Patton (1999) and Babul et al. (2002) developed a purely
analytic model which may help to highlight the essential physics behind the pre-
heating process. First of all, the distribution and evolution of the dark matter
component is assumed to be unaffected by preheating and described by the an-
alytic profile suggested by numerical simulations (e.g. NFW profile). Moreover,
preheating adds an initial, universal excess entropy $S_0$ to the gas. For low-mass
halos, the maximum velocity of the infalling flow of the preheated gas induced
by gravity is only subsonic, and the accretion shocks by gravitational collapse
thus become less important. In this case, the isentropically accreted gas with
the state of equation $P = K_0 \rho_{\text{gas}}^{5/3}$ is completely determined by the equation of
hydrostatic equilibrium:

$$
\rho_{\text{gas}}(r) = \rho_{\text{gas}}(r_h) \left[ 1 + \frac{2}{5} \frac{G}{K_0 \rho_{\text{gas}}^{2/3}(r_h)} \int_{r_h}^{r} \frac{M(r')}{r'^2} dr' \right]^{3/2},
$$

and the temperature is $kT(r) = \mu m_p K_0 \rho_{\text{gas}}(r)$, where $r_h$ is the size of the halo
at the epoch of observation. For massive halos, it assumes that an isentropic
core of mass $M_{\text{gas}}(r_c) = (\Omega_b/\Omega_M)M_{\text{isen}}$ within radius $r_c$ would form first. The
rest gas will be heated by shocks as the halo grows more massive. One can use
a generalized equation of state to describe the gas inside and outside the core:

$$
P = K \rho_{\text{gas}}^{5/3},
$$

where $K = K_0$ for $r \leq r_c$, and $K = K_0 (r/r_c)^\alpha$ for $r > r_c$. This last
expression is taken from an empirical formula found by numerical simulations
(Lewis et al. 2000). Again, solving the equation of hydrostatic equilibrium yields

$$
\rho_{\text{gas}}(r) = \rho_{\text{gas}}(r_c) \left[ 1 - \frac{2}{5} \frac{G}{K_0 \rho_{\text{gas}}^{2/3}(r_c)} \int_{r_c}^{r} \frac{M(r')}{r'^{2+3/5}} dr' \right]^{3/2}.
$$

Finally, the key point is to specify the turnover mass ($M_{\text{isen}}$) which separates the
isentropic accretion from the accretion shock. This can be achieved by setting
the total gas mass fraction evaluated by the adiabatic Bondi accretion rate
$\dot{M}_{\text{Bondi}}$ to equal the universal value: $M_{\text{gas}} / M_h = \dot{M}_{\text{Bondi}} t_H(z) / M_h = \Omega_b / \Omega_M$, in
which $t_H$ is the Hubble time. Of course, in order to properly normalize the gas
density $\rho_{\text{gas}}(r_h)$ or $\rho_{\text{gas}}(r_c)$, the universal baryon fraction within $r_h$ or $r_c$ should
be assumed. This may be a major shortcoming for the model since the observed
gas mass fractions $M_{\text{gas}} / M_h$ of clusters seem to increase with temperature (e.g.
Mohr et al. 1999).
4.3. Radiative cooling

Radiative cooling as a natural process was first considered in the formation of galaxies by White & Frenk (1991). The major concern has been whether radiative cooling of the hot gas is sufficient to account for the X-ray observed properties of groups and clusters (Bower et al. 2001; Balogh et al. 2001). Recent hydrodynamical simulations and semianalytic models have, nevertheless, shown that radiative cooling alone turns to be successful in the recovery of the entropy excess and the steepening of the X-ray luminosity-temperature relations detected in groups and clusters (Bryan 2000; Pearce et al. 2000; Muanwong et al. 2001, 2002; Voit & Bryan 2001; Wu & Xue 2002a,b; Borgani et al. 2002; Voit et al. 2002), which may suggest a simple, unified scheme for the evolution of hot gas and the formation of stars in the largest virialized systems in the universe.

A simple yet plausible approach to evaluating the effect of radiative cooling is as follows: We assume that in the absence of cooling the gas has the same distribution as the dark matter in groups and clusters which is described, for example, by the universal density profile. The electron number density of the hot gas thus follows $n_e(r) \propto f_b \rho_{NFW}(r)$. We assign an X-ray temperature to each halo in terms of cosmic virial theorem $M \propto T^{3/2}$. The hot intragroup/intracluster gas would continuously lose energy due to bremsstrahlung emission. The decrease in X-ray temperature $T$ is completely governed by the conservation of energy,

$$\frac{3}{2} n_{\text{gas}} kT = \epsilon(T, Z) t_{\text{cool}}$$

where $\epsilon$ is the emissivity. This defines the so-called cooling time $t_{\text{cool}}$ and radius $r_{\text{cool}}$ within which gas can cool out of the hot phase. If the cooling time is set to equal the age of groups/clusters, or approximately the age of the universe, $t_0$, we will be able to estimate the maximum cooling radii of the systems by the present time, $r_{\text{cool}}^m$, and the corresponding critical gas density, $n(r_{\text{cool}}^m)$.

The gas within the maximum cooling radius $r_{\text{cool}}^m$ is assumed to convert into stellar objects. This latter component should also include the contribution of other possible cooled materials (e.g. neutral and molecular gas) which may form out of cooling process. The cooled gas mass within $r_{\text{cool}}^m$ can be obtained by integrating the gas profile $n_{\text{gas}}(r)$ over volume out to $r_{\text{cool}}^m$. Such a simple exercise gives rather a robust estimate of the total stellar mass of a system, $M_{\text{star}}$, as has been shown recently by Yoshida et al. (2002). As a result, one can obtain the stellar and gas mass fractions from $f_{\text{star}} = M_{\text{star}}/M$ and $f_{\text{gas}} = f_b - f_{\text{star}}$, respectively. Because the hot gas cools relatively faster in groups than in clusters due to the difference in their density contrast, temperature or metallicity, poor groups experienced higher efficiency of star formation than rich clusters did. Therefore, a(n) decrease (increase) of stellar (gas) mass fraction from groups to clusters is expected to occur naturally. The predicted scale-dependence of $f_{\text{gas}}$ shows a good agreement with observations (Wu & Xue 2002b). However, the cool gas mass fraction slightly exceeds the observed stellar mass fractions estimated within virial radii by Roussel, Sadat & Blanchard (2000), implying that some of the cooling gas may exit in other forms such as cold clouds. The failure of detecting the cool gas in clusters might construct a challenge to the cooling model (e.g. Miller, Bregman & Knezek 2002). Nevertheless, within the framework of radiative cooling, the mass-to-light should increase from groups
to clusters because $M/L = (M/M_{\text{star}})(M_{\text{star}}/L) = \Upsilon/f_{\text{star}}$, where $\Upsilon \equiv M_{\text{star}}/L$ measures the efficiency with which groups and clusters transform cooled material into light. Indeed, by properly choosing this parameter, one may be able to quantitatively account for the mildly increasing trend of $M/L$ with scale claimed recently by Bahcall & Comerford (2002) and Girardi et al. (2002).

The newly established gas distribution as a result of radiative cooling can be obtained by combining the conservation of entropy and the equation of hydrostatic equilibrium (Bryan 2000; Voit & Bryan 2001; Wu & Xue 2002a; Voit et al. 2002). It appears that both the cores of the gas density profiles and the entropy floors are created in the centers as a result of galaxy formation which has consumed the central hot gas by converting it into stars or other forms of cold materials. Meanwhile, a monotonically increasing gas fraction with radius is expected to occur. Apparently, the effect is more significant in lower temperature systems than in higher ones. It has been shown that the regulated gas distribution in groups and clusters produced by cooling or star formation resembles the conventional $\beta$ model in shape, and the increase of global $f_{\text{gas}}$ with mass provides a natural explanation of the observed radial variation of $f_{\text{gas}}$ (Wu & Xue 2002a; Voit et al. 2002). Finally, a straightforward computation of the X-ray emission of the gas inside groups and clusters permits a recovery of the observed $L_x$-$T$ relation (Bryan 2000; Muanwong et al. 2001, 2002; Voit & Bryan 2001; Wu & Xue 2002a; Voit et al. 2002; Borgani et al. 2002).

In a word, radiative cooling of the hot intragroup/intracluster gas, which is based on the well-motivated physical process, may allow us to resolve some of the puzzles seen in current X-ray observations of groups and clusters, and it seems that energy feedback from star formation comes into effect only in the less massive systems of $M < 10^{13} M_\odot$. Yet, current analytic and numerical models of radiative cooling still have some defects including an overcooling crisis (Balogh et al. 2001). A critical test of the cooling scenario, in addition to the conventional test using X-ray properties of groups and clusters, is the upper limit of the unresolved soft X-ray background. It is unlikely that current cooling model can account for the upper limit of the unresolved soft X-ray background from the diffuse gas of groups and clusters without excess energy from preheating (Wu, Fabian & Nulsen 2001). Indeed, recent hydrodynamic simulations have suggested that neither preheating nor radiative cooling alone is able to reproduce all the X-ray observations. A combination of both may be the right way to resolve the problem (Borgani et al. 2002).

4.4. A physically unmotivated model

If we are interested in the cosmological applications rather than the internal dynamics and structures of groups and clusters, we may make a crude estimate of the influence of nongravitational heating or radiative cooling using a simple but physically unmotivated approach (e.g. Holder & Carlstrom 2001; Voit & Bryan 2001): We first evaluate the entropy distribution of the gas $S^0 = kT^0/(n_e^0)^{2/3}$ by assuming that the gas is dissipationless and satisfies the equation of hydrostatic equilibrium. Taking the prevailing NFW profile as an approximation of the underlying dark matter component, i.e. $n_e^0(r) = (f_b/\mu_e m_p)\rho_{\text{NFW}}(r)$ where $\mu_e = 1.131$, we can get the radial profile of the X-ray temperature $T^0(r)$. Now, regardless of the physical mechanism behind the steepening of the $L_x$-$T$ rela-
tion, the consequence of the effect must result in an entropy floor in the central regions of groups and clusters with a value of $S_{\text{floor}} \approx 100 - 400 \text{ keV cm}^2$ at the present epoch. A simple approach is to define the new entropy distribution as the entropy $S^0$ expected from self-similar evolution plus a constant entropy floor $S_{\text{floor}}$:

$$S(r) = \frac{kT(r)}{n_e^{2/3}(r)} = S_{\text{floor}} + S^0(r)$$

This is equivalent to specifying the equation of state for the gas. Now, the new gas distribution is obtained by requiring that the gas is in pressure-supported hydrostatic equilibrium with the underlying gravitational potential dominated by dark matter:

$$\frac{n_e(r)}{n_e(r_{\text{vir}})} = \left[ \frac{S(r_{\text{vir}})}{S(r)} \right]^{3/5} \left[ 1 + \frac{2}{5} \frac{G \mu_e m_p}{n_e^{2/3}(r_{\text{vir}}) S(r_{\text{vir}})^{2/3}} \int_{r}^{r_{\text{vir}}} \frac{M(r')}{S(r')^{3/5} r'^2} dr' \right]^{3/2}$$

One needs to normalize the above expression by properly choosing the gas density at the virial radius $r_{\text{vir}}$. To a first approximation, the total gas density at $r_{\text{vir}}$ or the total gas mass within $r_{\text{vir}}$ can be set to equal the universal baryon fraction $\Omega_b/\Omega_M$. A more plausible approach is to employ the observationally determined $f_{\text{gas}}-T$ relation (e.g. Mohr et al. 1999) or scale-dependence of stellar mass fraction combined with the universal baryon fraction. Although quantitatively crude, this simple analytic model based on the entropy floor detected in groups and clusters enables us to effectively demonstrate the more realistic distribution of the hot gas in today’s groups and clusters. Yet, the model contains no information about evolutionary effect unless the variation of the entropy floor $S_{\text{floor}}$ with cosmic epoch can also be given.

5. Summary

We have entered a new era of exploration of matter and energy in groups and clusters, thanks to the high-sensitivity, high-resolution X-ray observations incorporated with optical, radio, SZ and gravitational lensing measurements. A joint analysis of these independent measurements within next decade will undoubtedly allow us to reconstruct more precisely the distributions of both baryons and dark matter in groups and clusters, which is especially important with respect to the impact on the current debate on the density profiles of dark halos suggested by numerical simulations and empirical models. The physical process of the gas in the formation and evolution of groups and clusters has been another subject of a longstanding debate. The prevailing preheating and radiative cooling scenarios become indistinguishable in the context of current observations, numerical simulations or analytic models. This may indicate that our understanding of physical processes for gas is still incomplete. Clearly caution thus needs to be applied in using groups and clusters for cosmological purpose.

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