TESTING $\Omega_0$ WITH X–RAY CLUSTERS: A PHYSICAL APPROACH

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The X-ray emission from clusters of galaxies is one of the most pursued observational probe to investigate the distribution of dark matter and the related density parameter $\Omega_0$. The crucial link to derive the statistics of observables from a dynamical theory is constituted by the physics for the diffuse baryons (or ICP) responsible of the X–ray emission. Here we present a physical model for the ICP which leads to a definite $L$–$T$ relation. Then we perform a physically based cosmological test, pointing out three cold dark matter universes: a Tilted critical CDM, a flat CDM with $\Omega_0 = 0.3$, and an Open CDM with $\Omega_0 = 0.5$, which are discussed on the basis of the RDCS survey.

1 Introduction

Groups and clusters of galaxies constitute cosmic structures sufficiently close to equilibrium and with sufficient density contrast ($\delta \approx 2 \times 10^2$ inside the virial radius $R$) as to yield definite observables. They are dominated by dark matter (hereafter DM), while the baryon fraction is observed to be less than 20%. The great majority of these baryons are in the form of diffuse plasma (ICP) with densities $n \sim 10^{-3}$ cm$^{-3}$ and virial temperatures $kT \sim 5$ keV, and are responsible for powerful X–ray luminosities $L \sim 10^{44}$ erg/s by optically thin thermal bremsstrahlung. As the plasma is a good tracer of the potential wells, much better than member galaxies, the X–ray emission is a powerful tool to investigate the mass distribution out to moderate and high redshifts. The ICP temperature directly probes the height of the potential well, with the baryons in the role of mere tracers; on the other hand, the luminosity with its strong dependence on density ($L \propto n^2$) reliably probes the baryonic content and distribution. Statistically, an average $L$–$T$ correlation is observed along with substantial scatter, and this provides the crucial link to relate the X-ray luminosity functions with the underlying statistics of the DM.

A physical model for the diffuse baryons is difficult to achieve. In fact, the simple self similar model (Kaiser 1986), which assumes the ICP amount to be proportional to the DM's at all $z$ and $M$, leads to a relation $L \propto T^2$, conflicting with the observed correlation for rich clusters. The latter is close to $L \propto T^{3.5}$ (David et al. 1993; Mushotzky & Scharf 1997). Here we propose a physical model for baryons, which leads to a prediction for the $L$–$T$ relation (see Cavaliere, Menci & Tozzi 1997, CMT97) and allows a non parametrical approach to the search for cosmological parameters. The results, presented in §3, are a synthesis from Cavaliere, Menci & Tozzi (1998, CMT98).
2 A physical model for the ICP

Respect to the self–similar model, we indicate the missing ingredient in the stellar energy feedback by supernovae. We assume that such non gravitational heating is efficient in depleting the potential wells of the clusters progenitors, at \( z \simeq 1 \div 2 \), and in pre–heating the intergalactic medium to temperatures in the range \( T_1 = 0.1 \div 0.8 \) keV, as recently observed in the outer cluster atmosphere (Henriksen & White 1996).

We describe clusters evolution as a sequence of hierarchical merging episodes of the DM halos; the history of such episodes is followed in the framework of the hierarchical clustering by Monte Carlo simulations based on merging trees consistent with the Press & Schechter (1974) statistics. In the ICP, shocks of various strengths (depending on the temperature ratio between the accreted gas and the plasma in the main progenitor) are associated to such merging events. The shocks provide the boundary conditions for the ICP to re–adjust to a new hydrostatic equilibrium.

2.1 Hydrodynamical equilibrium

In the framework of the hierarchical clustering it is possible to check the assumption of equilibrium. Roettiger, Stone & Mushotzky (1997) showed that after a major merging event, i.e., with a mass ratio less than \( 2^{1.5} \), the non thermal contribution to the pressure is negligible after two Gyrs from the epoch of merging. Adopting this as a conservative rule to identify disturbed clusters at redshift \( z = 0 \), we find that the fraction of such clusters (for which the hydrodynamical equilibrium does not fully apply) is always less than 20% in most CDM universes.

The next step is computing the disposition of the ICP in equilibrium in a DM potential well. Then we simply use the hydrostatic equilibrium equation \( (dP/dr)/n = -GM(<r)/r^2 \), where \( n(r) \) is the gas density profile, \( M(<r) \) is the mass contained within the radius \( r \) (dominated by DM) and \( P \) is the pressure. To solve the equation we need the boundary condition, i.e., the density of the gas at the virial radius \( n(R) \), and the state equation, that we write for a polytropic gas as \( P \propto T^{\gamma} \), where \( \gamma \) is the polytropic index treated as a free parameter. The resulting profile is:

\[
n(r) = n(R) \left[ 1 + \beta \left( \frac{\gamma - 1}{\gamma} \right) \left( \phi(R) - \phi(r) \right) \right]^{1/(\gamma-1)},
\]

where \( \phi \equiv V/\sigma_r \) is the adimensional gravitational potential, and \( \beta \equiv \mu m_H \sigma_r /kT_2 \), with \( \sigma_r \) the line–of–sight velocity dispersion of the DM particles. Here \( T_2 \) is ICP the temperature inside the virial radius. The above equation can be considered a generalized \( \beta \)–model (Cavaliere & Fusco–Femiano 1978), which reconduces to the usual isothermal case for \( \gamma \to 1 \). Thus, before computing the ICP distribution, we need the boundary condition \( n(R) \).

2.2 Physics of shocks

We expect the inflowing gas (with velocity \( v_1 \)) to become supersonic close to \( R \). In fact, many hydrodynamical simulations (see, e.g., Takizawa & Mineshige 1997) show shocks to form, to convert most of the bulk energy into thermal energy, and to expand slowly remaining close to the virial radius. So we take \( R \) as the shock position, and focus on nearly static conditions inside, with the internal bulk velocity \( v_2 << v_1 \).

The post-shock state is set by conservations across the shock not only of the energy, but also of mass and momentum, as described by the Rankine-Hugoniot conditions (see Landau & Lifshitz 1959). These provide at the boundary the temperature jump \( T_2/T_1 \), and the corresponding density jump \( g \equiv n(R)/n_1 \), which reads:

\[
g \left( \frac{T_2}{T_1} \right) = 2 \left( 1 - \frac{T_1}{T_2} \right) + \left[ 4 \left( 1 - \frac{T_1}{T_2} \right)^2 + \frac{T_1}{T_2} \right]^{1/2}
\]
for a plasma with three degrees of freedom. Here \( n_1 \) is the baryon density external to the virial radius, and it is assumed to be unbiased respect to the universal value, i.e., \( n_1 = \Omega_B \rho \) where \( \rho \) is the total density. Eq. \( \text{(2)} \) includes both weak shocks (with \( T_2 \approx T_1 \), appropriate for small groups accreting preheated gas, or for rich clusters accreting comparable clumps), and strong shocks (appropriate to “cold inflow” as in rich clusters accreting small clumps and diffuse gas). Given the nearly static post-shock condition \( v_2 << v_1 \), it is possible to show that in the case of strong shocks \( k T_2 \approx -V(R)/3 + 3k T_1/2 \) holds, where the second term is the contribution from non-gravitational energy input (CMT98). This leads to a factor \( \beta(T) \) which decline from \( \sim 1 \) for rich clusters, to \( \sim 0.4 \) for poor groups, where the nuclear competes with the gravitational energy (see fig. 1a). A specific gas profile depends on the choice for the potential well (in the following we use forms given by Navarro, Frenk & White (1996), but this is not mandatory). A general result is that the corresponding baryonic fraction lowers down with the mass scale by a factor of three from clusters to groups (see fig. 1b).

2.3 The \( L-T \) correlation

The X-ray luminosity of a cluster with temperature profile \( T(r) \) and density profile \( n(r) \) can be written:

\[
L \propto \langle g^2(T) \rangle \int d^3r \frac{n^2(r)}{n^2(R)} T^{1/2}(r),
\]

Eq. \( \text{(3)} \)
Figure 3: Predicted counts for TCDM (a), OCDM (b) and ΛCDM (c). Data by Rosati et al. (1998), and Piccinotti et al. (1982) for the point at high fluxes.

where the statistical effect of the merging histories has to be taken into account. In fact, for a cluster or a group of a given mass (or temperature), the effective compression factor squared \( \langle g^2 \rangle \) is obtained upon averaging eq. 4 over the sequence of the DM merging events; in such events, \( T_2 \) is the virial temperature of the receiving structure, and \( T_1 \) is the higher between the stellar preheating temperature and the virial value prevailing in the clump being accreted. The averaged \( \langle g^2 \rangle \) is lower than the \( g^2 \) computed with a single temperature \( T_1 \), because in many events the accreted gas has a temperature higher than the preheating value. In addition, an intrinsic variance is generated from the merging histories (see fig. 2a).

In agreement with the observations, the shape of the average \( L - T \) relation flattens from \( L \propto T^5 \) at the group scale (where the nuclear energy from stellar preheating competes with the gravitational energy) to \( L \propto T^3 \) at the rich cluster scales (see fig. 2b). At larger temperatures the shape asymptotes to \( L \propto T^2 \), the self-similar scaling of pure gravity. Notice the intrinsic scatter due to the variance in the dynamical merging histories, but amplified by the \( n^2 \) dependence of \( L \). The average normalization rises like \( \rho^{3/2}(z) \), where \( \rho \) is the effective external mass density which increases as \((1+z)^2\) in filamentary large scale structures hosting most groups and clusters (see Cavaliere & Menci 1997). We check that the shape of the \( L-T \) relation is little affected by changes of \( \gamma \) (we assume a fiducial value \( \gamma = 1.2 \), see CMT98).

3 A physically based cosmological test

We adopt the Press & Schechter rendition of the hierarchical clustering. For each CDM universe we first check agreement with local constraints on the luminosity function \( N(L) \) and on the temperature function \( N(T) \); then the test is performed on the flux counts \( N(> F) \) in the ROSAT band, which include the effect of the evolution (the higher \( z \) sample of RDCS by Rosati et al. 1998). While the normalization \( \sigma_8 \) is fixed by the constraints from COBE for a given CDM spectrum, the predictions for the faint counts are sensitive to \( \Omega_0 \).

We focus on three popular CDM universes. The first is the critical TCDM, for which we adopt the tilted spectrum with primordial index \( n_p = 0.8 \), with amplitude \( \sigma_8 = 0.66(1 \pm 0.08) \), and with a high baryonic fraction \( \Omega_B = 0.15 \) (the Hubble constant is \( h = 0.5 \)). The tilt is
Figure 4: The 99% confidence contours for both the computed local luminosity function (solid lines) and the computed number counts (dotted lines), in the $L_{44} - \sigma_8$ plane ($L_{44} = L_o/10^{44}$ erg/s). The boxes indicate ±1 standard deviations in $\sigma_8$ (corresponding to the COBE uncertainty) and in $L_{44}$. a) TCDM, consistent with the counts within 2 standard deviations below $\sigma_8$; b) $\Lambda$CDM; c) OCDM ($\Omega_o = 0.5$).

chosen so as to minimize one of the main problems of the Standard CDM, namely, the excess of small-scale power. The high baryon fraction is chosen to solve the so called “baryonic crisis” (White et al. 1993). We note that the slope of predicted counts is sufficiently flat to fit both the bright and the faint data by lowering $\sigma_8$ to within the COBE uncertainty (in fig. 3 we adopt $\sigma_8 = 0.6$).

The second is an open CDM universe. After Liddle et al. (1996), we focus first on the representative OCDM cosmogony, with $\Omega_o = 0.5$, $h = 0.65$ with $\Omega_B = 0.07$, which yield $\sigma_8 = 0.76 (1 \pm 0.08)$. It is seen that the counts show excesses over the data. The underlying reason is that in open cosmologies long lines of sight and slow dynamical evolution conspire to yield a slope of the counts too steep to account for both faint and bright counts.

The third universe ($\Lambda$CDM) has a flat geometry with $\Omega_o = 0.3$ and $\Omega_\Lambda = 0.7$, $\Omega_B = 0.05$ and $h = 0.7$. The normalization is $\sigma_8 = 1.1 (1 \pm 0.08)$. In this intermediate condition faint counts are higher respect to TCDM, yet lower than in the $\Omega_o \approx 0.5$ case, to yield a moderate excess (fig. 3c).

For a synthetic presentation, we also show in fig. 4 the effects of varying $\sigma_8$ and the normalization of the $L-T$ relation, i.e., the average luminosity $L_{44}$ corresponding to 4.5 keV. In TCDM and in $\Lambda$CDM the counts are consistent with the observations on considering the uncertainties in the present COBE normalization and the intrinsic uncertainty in the $L-T$ relation, while, on the other hand, in OCDM the counts are inconsistent with local data by a significant excess.

4 Discussion and conclusion

We presented a physically based approach to cosmological tests with clusters of galaxies. We describe the X-ray emission from clusters with a specific model for the diffuse baryons. In this sense this approach is alternative to the parametrical approach (see Borgani this meeting).

The results of our model depend on two parameters, the external temperature $T_1$ and density $n_1$, which are not free. Specifically, we use for $T_1$ the range $0.1 \div 0.8$ keV provided by the stellar preheating. The value of $n_1$ for rich clusters is related to the DM density by the universal baryonic fraction. Thus we compute the expression of the bolometric luminosity for a given temperature. The average of the square of the density jump factor $\langle g^2 \rangle$ over the merging histories coupled with $\beta(T)$ is what gives to the statistical $L - T$ correlation the curved shape shown in fig. 2b. In addition, our approach predicts an intrinsic variance of dynamical origin
due to the different merging histories, and built in the factor $g^2$.

With the ICP state so described, we proceeded to constrain the cosmological parameters. After the observations by Rosati et al. (1998), we have computed the X-ray observables for groups and clusters of galaxies. On the basis of local data, the set of acceptable CDM universes is restricted to three disjoint domains: $\Omega = 1$ for the Tilted CDM with high baryon content; $\Omega_o \approx 0.5$ for standard CDM; $\Omega_o \approx 0.3$ for CDM in flat geometry. However, only the TCDM and the $\Lambda$CDM universes give acceptable faint counts. As an overall remark, a common feature of all the above universes is constituted by some excess in the counts. This may indicate some non–trivial incompleteness in the canonical hierarchical clustering, worth keeping under scrutiny. We recall that in the adiabatic models for the ICP (Evrard & Henry 1991, Kaiser 1991) the evolution of the $L-T$ relation is reduced or even negative, thus alleviating the excess. However, the anti–evolution required in OCDM would be very difficult to justify (the adiabatic models are largely discussed in CMT98).

Now the question is: to what extent enlarging the data base on X–ray clusters will help in further constraining cosmology? We argue that the variance intrinsic to the hierarchical clustering, and amplified by the ICP emissivity, sets an effective limitation. Richer, faint surveys will hardly provide a sharper insight into cosmology unless one reduces both the uncertainty concerning $\sigma_8$ and the larger one concerning $L_o$. However, we stress that such efforts will find soon a more proper aim than constraining $\Omega_o$. This is because MAP, and subsequently PLANCK, will accurately measure on still linear scales not only the perturbation power spectrum but also directly $\Omega_o$. Once the cosmological framework has been fixed, the study of groups and clusters in X-rays will resume its proper course, that is, the physics of systems of intermediate complexity which is comprised of the DM and of the ICP component.

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