Detection of the Entropy of the Intergalactic Medium: Accretion Shocks in Clusters, Adiabatic Cores in Groups

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ABSTRACT

The thermodynamics of the diffuse, X-ray emitting gas in clusters of galaxies is linked to the entropy level of the external intergalactic medium at the epoch of accretion. In particular, models that successfully reproduce the properties of local X-ray clusters and groups require the presence of a minimum value for the entropy of the pre-collapse, intergalactic medium. Such an entropy floor can be generated by non-gravitational phenomena, such as SNe heating, stellar winds and radiative processes. However, there is no consensus on the level, the source or the time evolution of this entropy.

In this paper we propose that the best way to investigate the entropy distribution of the local universe is via the detection of the shock fronts expected at the virial boundary of rich clusters, and the extended isentropic gas distribution in the center of low mass clusters and groups. In particular we describe a strategy to look for accretion shocks with the next generation of X-ray facilities (in this case XMM). The measurement of the entropy level exterior to the shock, and observations of the transition from the shock (clusters) to the adiabatic (groups) regime, will be crucial probes of both the physics of clusters and the relationship of stellar processes to the state of the intergalactic medium.

*Subject headings:* galaxies: clusters: general – intergalactic medium – X–rays: galaxies
1. Introduction

The complex thermodynamic evolution of the hot, X-ray emitting, gas in clusters of galaxies is at the forefront of current efforts to understand these largest virialized systems. X-ray observations of cluster number counts, luminosity functions and temperature distributions indicate little apparent evolution in clusters back to redshifts as high as $\sim 0.7$ (e.g., Henry 1997, Rosati et al. 1998). These results provide one of the strongest challenges to high density cosmological models in which cluster evolution is expected to be occurring rapidly at low redshifts.

However, these tests are strongly dependent on the thermodynamic evolution of the intracluster medium (ICM, see Borgani et al. 1999 and references therein). In particular, the X-ray properties of clusters depend on the entropy of the pre-collapse intergalactic medium (IGM) at the epoch of accretion. An ubiquitous minimum entropy, or entropy floor, in the external gas would break the self-similar behaviour of purely gravitational models, in agreement with the X-ray data. In terms of the global X-ray observables luminosity ($L$) and temperature ($T$), self-similar models predict $L \propto T^2$, while $L \propto T^\alpha$, with $\alpha \sim 3$, is observed (David et al. 1993, Mushotzky & Scharf 1997, Allen & Fabian 1998, Arnaud & Evrard 1998, Markevitch 1998), with evidence for a further steepening at group scales (Ponman et al. 1996). Not only can the inclusion of an entropy minimum successfully reproduce the observed $L \propto T^3$ relationship, but it can also explain the flat density distribution observed in the cores of clusters and the low evolution of the $L$–$T$ relation at high redshifts (see Cavaliere, Menci & Tozzi 1997, Bower 1997, Balogh, Babul & Patton 1999, Tozzi & Norman 1999b, hereafter TNb). Recently an entropy floor has been detected in the core of groups (Ponman, Cannon & Navarro 1999 - hereafter PCN) providing direct evidence for the entropy excess emerging in objects with temperatures between 1 and 3 keV. Evidence for a breaking of self-similarity also comes from the observation of a dramatic change in
the chemical and spatial distribution properties of the gas at the scale of groups, below the observed temperature of 1 keV (Renzini 1997, 1999).

However, there is no general consensus on the origin of an IGM entropy floor. In hierarchical models of structure formation the local ICM is simply the high redshift IGM accreted into cluster and group scale potential wells. An examination of the equation of state of the IGM based on observations of the Lyα forest (Schaye et al. 1999; Ricotti, Gnedin & Shull 1999) yields an entropy level which is at least an order of magnitude lower than that observed in the core of low temperature clusters, and needed to explain the local properties of X–ray clusters and groups. Physical processes which could raise the entropy of the early IGM are SNe feedback processes, linked to the history of star formation, or radiative processes driven by quasars (see Valageas & Silk 1999; Wu, Fabian & Nulsen 1999; Menci & Cavaliere 1999). It is, however, very difficult to model a priori such processes. Thus, direct observations of the entropy properties of both the ICM and the IGM are currently the best way to improve our understanding of the energetic processes at play.

In this respect, the regions around rich clusters offer a unique way to approach this problem. The enhanced density expected around actively accreting clusters of galaxies should make this gas detectable in emission in the X–ray band. In this paper we present a strategy to image accretion shocks at the ICM/IGM interface, considering the most general predictions for the X–ray properties of clusters assuming the presence of an entropy floor. The expected properties of the accretion shock regions and of the interior and exterior gas are described for a range of scenarios corresponding to different entropy levels. We then assess the feasibility of observing such accretion shock regions in real systems, using simulated XMM observations scaled to a nearby cluster (Abell 2029), and present the expected observed entropy profiles. The simulations illustrate the requirements of the X-ray observations. We also present detailed observational requirements for investigations of lower
luminosity, lower mass systems, mapping the transition from shock-dominated clusters to adiabatic regimes in poor groups.

2. Entropy-based models, shocks, and adiabatic compression

The evolution of the ICM is governed by both dynamics (and the underlying cosmology) and gas thermodynamics. A complete treatment of the physics of the gas necessarily includes shock heating and adiabatic compression (see the 1D models of Bertschinger 1985, Knight & Ponman 1997, Takizawa & Mineshige 1998, and the 3D numerical simulations of Evrard 1990, Roettiger et al. 1993, Metzler & Evrard 1994, Bryan & Norman 1998). An expanding accretion shock at the interface of the inner virialized gas with a cooler, adiabatically-compressed, external medium, located approximately at the virial radius of the cluster, is a longstanding prediction from such gravitationally-driven models. However, as discussed in the Introduction, gravitationally-driven models predict X-ray properties which scale self-similarly with mass and fail to reproduce X-ray observations of clusters.

The presence of a minimum entropy in the pre-collapse IGM has been advocated for some time as a way to naturally break the purely self-similar behaviour (Kaiser 1991, Evrard & Henry 1991). More recently, such a minimum entropy has been detected (PCN) and all of its consequences have been re-visited. Entropy-based models are able to explain the detailed shape of the $L-T$ relation, predict its evolution, and help in explaining the cores and temperature profiles observed in clusters. In fact, a non-negligible entropy in the IGM introduces a mass scale where strong accretion shocks no longer form. Below this mass (at the scale of groups) is an effectively adiabatic regime, where gas is just compressed into the potential wells at constant entropy. The observed $L \propto T^3$ relationship is essentially produced by the resulting flattening of the density distribution in cluster cores, which leads to the asymptotic relation $L \propto T^5$ when shocks turn off completely (see Balogh, Babul &
We note that in the class of models discussed here the entropy of each accreted shell of gas is kept constant after the accretion, i.e., non-gravitational heating processes are neglected inside virialized regions. The latter assumption is reasonable for two reasons; first, for a given energy amount, the entropy change is smaller for higher densities. Second, a large part of the cosmic star formation, and of the nuclear activity due to the AGN, occurred at redshifts $z \geq 2$, which is larger or comparable to the redshifts of formation for the majority of clusters and groups. Of course, in a more comprehensive model, the onset of the entropy floor and its eventual evolution, turns out to be crucial since it will deeply affect subsequent star formation processes, establishing links between, for example, the cluster X-ray counts and the past star formation rate (Menci & Cavaliere 1999). Finally, we note that the cooling is sensitive to the gas density ($t_{\text{cool}} \propto \rho^{-1}T^{1/2}$) and is important in the center of rich clusters, but it is not enough to erase the entropy minimum especially in low mass systems (see discussion in TNb).

The mass scale of shock formation is governed by the value of the IGM entropy $\propto \log(K)$, where $K \equiv kT/\mu m_H \rho^{2/3}$ (Here we assume that $\mu = 0.59$ for a primordial IGM). The value of $K = K_*$ that produces a good fit to the local $L-T$ relation is at least $K_* = 0.3 \times 10^{34}$ erg cm$^2$ g$^{-5/3}$, which corresponds to $0.01(1+z)^2$ keV for the IGM at the background density. Higher values of $K_*$ also lead to a good fit to the observed $L-T$ relation, but for $K_* > 2 \times 10^{34}$ erg cm$^2$ g$^{-5/3}$, groups with virial masses lower than $10^{14} h^{-1} M_\odot$ become unbound. For a given entropy level, the temperature of the gas at the universal background density is derived as $kT \simeq (K_*/30 \times 10^{34})(1+z)^2$ keV. These temperatures can therefore be traced back to the energy injected per particle if the heated gas were at the background density (see PCN). However, the energy injection is likely to occur in overdense environments (see Loewenstein 1999).
The observed entropy floor in the core of groups is about $K_{cl} \simeq 0.15 \times 10^{34} \text{erg cm}^2 \text{g}^{-5/3}$ (corresponding to $S \equiv kT/n_e^{2/3} \simeq 100 \hbar^{-1/3} \text{keV cm}^2$ in the definition of PCN). However, such a value can be different in the external IGM if substantial entropy evolution occurred between the epoch of accretion of the gas in groups and $z = 0$. In particular, the entropy level can be higher at $z = 0$, as measured, for example, in the Lyα clouds (see discussion).

The expected break scale between adiabatic and shock regimes can be estimated by studying the dependence of the infall velocity $v_i$ of the accreting IGM on the total mass of the system. Approximating the infall as an adiabatic flow, we can estimate the infall velocity at the shock radius, where the gas is expected to be shocked and reach hydrostatic equilibrium. To determine if the accreting gas is shocked or not, we do not need to establish the redshift $z_*$ when an energy $kT_*$ is injected into the IGM. Here for simplicity we assume that the entropy floor is established in all of the IGM at one epoch $z_*$ larger than the redshift of the collapse of a typical cluster, and it stays constant until the present epoch. The effect of a constant entropy minimum $K_*$ on the infalling IGM is to introduce a compression term proportional to the square of the sound speed $c_s^2 = \gamma K_* \rho_e^{2/3}$, where $\rho_e$ is the external baryonic density and $\gamma = 5/3$ is the adiabatic index for a monoatomic gas. In fact, part of the gravitational energy goes into compression, to give for the infall velocity (see Tozzi & Norman 1999a):

$$\frac{v_i^2}{2} = \frac{v_{ff}^2}{2} - \frac{c_s^2}{\gamma - 1} + \frac{c_s^2}{\gamma - 1} \left(\frac{\rho_{ta}}{\rho_e}\right)^{\gamma-1},$$  \hspace{1cm} (1)

where $v_{ff}$ is the free fall velocity. The third term on the right hand side results from the initial condition $v_i = 0$ for a gas shell at the turnaround radius, when the gas had a density $\rho_{ta}$. The compression term carries an increasing fraction of the total gravitational energy when the system mass is lower, or, since the sound speed is proportional to $K_*^{1/2}$, when the entropy is higher.
The infall velocity can then be compared with the sound speed in the infalling gas, to test whether \( v_i > c_s \) and shocks can develop. In Figure 1 the infall velocity computed at the shock radius is plotted as a function of the virialized mass, which in turn is a function of the redshift (here we assumed the average mass growth of the main progenitor). At early epochs, when the virialized mass is still low, the compression term is important and the infall velocity is lower than the sound speed. In this case, the accretion of the IGM proceeds entirely adiabatically, giving rise to an adiabatic core. As soon as the virialized mass grows, the infall velocity becomes larger than the sound speed, marking the epoch when shocks dominate (here we neglected the small velocity of the shock front in the cluster rest frame). Then, the infall velocity asymptotically approaches the free fall velocity of the system. In Figure 1 an external constant entropy of \( K_\star = 0.3 \times 10^{34} \text{ erg g}^{-5/3} \text{ cm}^2 \) has been assumed for a low density (\( \Omega_0 = 0.3 \)) flat cosmology, for objects of \( 10^{14}h^{-1}M_\odot \) and \( 10^{15}h^{-1}M_\odot \). At lower masses, the transition from the adiabatic to the shock regime occurs later, giving rise to a relatively larger adiabatic core.

In the above picture only the entropy level is needed to determine the transition between the adiabatic and the shock regime. In fact, the external density, which determines the sound speed in the IGM, is given by mass conservation within the average mass accretion rate set by the adopted cosmology, plus the assumption that all the accreted baryons are diffuse (see TNb for the detailed model). In reality, the mass growth has substantial intrinsic scatter, and the average accretion rates are better used to describe statistically the cluster population, rather than a single object.

The effect of the accretion shocks in massive systems is to raise the entropy over its minimum level. In principle, a knowledge of both the temperature and density of the ICM at different radii would allow the reconstruction of the history of entropy production in clusters. At present, the detection of modest radial temperature profiles in clusters show
that the entropy is actually increasing outwards from the center. The use of spatially resolved data will allow a more detailed reconstruction of the entropy profiles, showing how the shock strength increases as the virial mass increases with time (i.e., with radius) and the shock front moves to larger and larger radii, leaving behind an isentropic core in which the entropy is the same as that of the gas shell at the epoch of accretion.

In summary, the detection of accretion shocks and a measurement of the external entropy level in present day clusters, together with a weakening of shocks at the scale of groups, and the growing size of the central adiabatic core would be direct evidence for this scenario of cluster formation.

3. Physics of accretion shocks

3.1. Accretion processes

It is important to distinguish between accretion shocks of diffuse material falling into the quasi-static, virialized hot gas of a cluster, and the bow shocks developed through the merging of cluster subunits of comparable mass (indicated by ASCA and ROSAT observations, cf. Henriksen & Markevitch 1996, Donnelly et al. 1998). In the latter case strong non-equilibrium features appear (hot spots) and the plasma is vigorously stirred. However, the occurrence of large, violent mergers is expected to be relatively rare in (for example) Cold Dark Matter (CDM) dominated cosmologies within the framework of the extended Press-Schechter theory (see Lacey & Cole 1993). Most of the mass growth of a typical cluster occurs by accretion of small clumps and diffuse matter onto a main progenitor, the relative amounts of which depend on the details of the cosmology and mass power spectrum. In most CDM models, dynamically quiet clusters always constitute a significant fraction of the total population, especially at $z = 0$. It is these systems that are
most likely to exhibit well defined accretion shocks.

In the usual, extended Press-Schechter theory, the distinction between diffuse and clumped matter is subtle, since formally all matter, at all epochs, has collapsed into virialized halos of some mass. Thus, some of the baryons can be shocked many times in the small sub-halos, before being engulfed into the main progenitor. However, the presence of an entropy minimum offers a natural way to discriminate between ‘diffuse’ and ‘clumped’ baryons, where ‘clumped’ means shock heated through a gravitational process before inclusion into the main progenitor. In fact, the entropy prevents most of the baryons from being shocked on small scales. The complexity that gravitational heating adds to the non-gravitational heating in establishing the entropy level in the infalling IGM, can be fully captured only in N-body hydrodynamical simulations. In any case, the entropy which is generated in gravitational processes does not break the self similarity.

From Figure 1 we can see that for low mass systems ($M < 10^{14} M_\odot$) and $K \simeq 0.3 \times 10^{34}$ erg cm$^2$ g$^{-5/3}$, a growing fraction of the accreted baryons retains the pre-collapse entropy level. This fraction approaches unity at the scale of poor systems and groups, providing self-consistency with our expectations of isentropic gas in groups as described in §2.

The entropy is expected to be much larger than the external average level in the outskirts of hot, massive clusters, where the gas has been strongly shock heated. In fact, massive clusters are likely to be still accreting significant amounts of matter in most cosmologies, since they are the last objects to form in any hierarchical universe. The total accretion rate of matter for a cluster of 8 keV (roughly corresponding to a mass of $\simeq 10^{15} h^{-1} M_\odot$) is expected to be on average quite high at $z = 0$. The predicted average mass growth in baryons, computed in the extended PS framework, is about $f_b 0.24 \times 10^{15} M_\odot$/Gyr for $\Omega_0 = 1$ (with a tilted, cluster normalized CDM spectrum) and $f_b 0.08 \times 10^{15} M_\odot$/Gyr for $\Omega_0 = 0.3$ and $\Lambda = 0.7$. Here $f_b$ is the universal baryonic fraction.
after the exclusion of the baryons already locked in stars.

Therefore, for most clusters a significant accretion rate is expected at the present epoch. These rates are correspondingly higher at higher redshifts for the same masses. However, in this current work we will focus on $z \simeq 0$.

### 3.2. The cluster entropy profile

When present, the accretion shock is likely to occur at approximately the virial radius, where the gas density can typically be a factor $\simeq 100$ lower with respect to that at the cluster center. A simple relation exists between the density jump and the temperatures of the hot internal, and colder external, gas (Landau & Lifshitz 1959, see Cavaliere, Menci & Tozzi 1997):

$$\frac{\rho_i}{\rho_e} = 2 \left(1 - \frac{T_e}{T_i}\right) + \sqrt{4 \left(1 - \frac{T_e}{T_i}\right)^2 + \frac{T_e}{T_i}},$$

(2)

where $\rho_i$ and $T_i$ are the internal gas density and temperature. The external density $\rho_e$ and temperature $T_e$ refer to the infalling gas just prior to being shocked. Note that $T_e$ is not simply the temperature of the field IGM. The accreted IGM will experience adiabatic compression prior to reaching the accretion shock, thus $T_e = \mu m_p K_\star \rho_e^{2/3}$. The overdensity $\rho_e/\rho_c$ is expected to be $\geq 10$ for very rich clusters, yielding, for example, $kT_e \geq 0.2$ keV for entropy levels $K_\star \geq 1$ erg g$^{-5/3}$ cm$^2$.

To compute the internal density at the shock boundary, we could use the detailed and self-consistent density and temperature profile of the ICM resulting from a minimum entropy model. However, since the final conclusions are robust to variations in the profile, for simplicity we choose to approximate the gas density internal to the shock with a standard $\beta$ model (Cavaliere & Fusco Femiano 1976):
\[ \rho = \rho_c \left(1 + \left(\frac{r}{r_c}\right)^2\right)^{-\frac{3}{2}\beta}, \]  

(3)

where \( r_c \) is the core radius. For a flat internal temperature profile, the observed X-ray surface brightness at the shock radius \( r_s \) can be written as:

\[ \Sigma = \Sigma_c \left(1 + \left(\frac{r_s}{r_c}\right)^2\right)^{-3\beta+1/2}. \]  

(4)

In this case a simple inversion from surface brightness to density is given by:

\[ \frac{\rho}{\rho_c} = \left(\frac{\Sigma}{\Sigma_c}\right)^{1/(2-1/3\beta)}. \]  

(5)

For a \( \beta \) model, the discontinuity in the surface brightness expected at the shock is approximately \( (\rho_i/\rho_e)^{2-1/3\beta} \). In the case in which there is no shock \( (\rho_i/\rho_e = 1) \) and the temperature profile decreases adiabatically as \( T \propto \rho^{2/3} \), we can use the same functional form, replacing \( \beta \) with an effective \( \beta' \) which accounts for the mild dependence of the emissivity \( \epsilon \) on temperature. In the case of pure bremsstrahlung \( \epsilon \propto T^{1/2} \) and \( \beta' = \frac{7}{6}\beta \).

In the simulations in §4 below we include the contribution from line emission, which is significant at low temperatures, especially in the wide energy band of XMM (0.1 – 12 keV).

The entropy jump can therefore be detected when both the X-ray surface brightness (from which density is determined) and the temperature are measured at the shock radius.

### 3.3. Shock heating vs adiabatic compression: three cases

As described in §2, the two dominant, gravitationally–driven, mechanisms for changing the thermodynamic state of cluster gas are shock heating and adiabatic compression. While shock heating occurs principally at the accretion radius, adiabatic compression will occur both interior and exterior to this radius. As shown, adiabatic compression of
gas during accretion (prior to being shocked) will raise the external gas temperature to values dependent on the initial entropy. The entropy floor that provides a good fit to the observed $L-T$ relation is within the range $0.3 - 2 \times 10^{34}$ erg g$^{-5/3}$ cm$^2$, which corresponds approximately to pre–shock (adiabatically–raised) temperatures of $kT_e \sim 0.05 - 0.5$ keV. Furthermore, the gas density immediately exterior to the shock will be no more than a factor of $\sim 4$ lower than that at the inner shock boundary, following equation 2.

It is also a consequence of the increasing shock strength at larger radii that positive gradient entropy profiles and a mildly negative (radially decreasing) temperature gradient is expected, in good agreement with observations of clusters (Markevitch 1998). In fact, if accretion has not been interrupted, the entropy rise is expected to stop only at the interface between the accreted gas (in hydrostatic equilibrium) and the infalling IGM. For simplicity, we will consider an isothermal distribution of gas within the shock radius, since the predicted temperature profiles for large clusters, especially at large radii, can be well approximated as constant (the predicted polytropic index is $\gamma_p \simeq 1.1$, see TNb).

We consider here three basic scenarios for conditions at the cluster accretion radius. The first case is that expected to apply to massive clusters surrounded by a high entropy IGM; a strong shock front with a warm external plasma with a temperature of around 1 keV. Such a value is somewhat higher than expected because we assumed a shock radius 20% smaller than the predicted average value, allowing more compression of the pre–shocked gas. This is the most favourable case from the observational point of view, and provides a crucial test for the basic picture. The second case envisages a strong shock front with a cold, low-emission external plasma ($kT_e < < 0.1$ keV). In this case the non-detection of an external gas halo would not provide any direct constraint on the external entropy level. However, with the assumption of a strong shock located where the emission fades, it is possible to derive a lower limit to the external density (a factor of 4 lower than the internal,
detected gas density) and thus an upper limit to the entropy. Finally, the third case is expected to represent lower mass groups: pure adiabatic compression with a continuously, decreasing temperature profile at constant entropy (with $T \propto \rho^{2/3}$) smoothly fading into the external IGM.

4. Simulated Observations and Feasibility

Current X-ray data lack the necessary combination of both spatial and spectral resolution to have routinely detected the accretion shock and entropy profiles of clusters. ROSAT for example, while its limiting surface brightness was quite low (a typical background level $\sim 1 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcmin}^{-2} \text{ 0.5-2 keV}$), had a point spread function width from $\sim 20 - 60 \text{ arcsec}$ and insufficient spectral sensitivity to constrain temperatures to the precisions required. Attempts to push the capabilities of the ASCA X-ray satellite to their limits and observe this accretion shock in archival data of nearby clusters failed, mainly due to the poor ASCA point-spread function (Gendreau & Scharf, private communication).

Upcoming missions should however be well suited to detecting cluster accretion shocks. Chandra’s high spatial resolution ($\sim 1 - 10 \text{ arcsec}$) and good spectral resolution may allow details of the spatial structure of a shock region to be investigated. With an effective area of $\sim 4600 \text{ cm}^2$ at 1 keV, XMM has approximately 10 times higher throughput than ROSAT, and combined with a $\sim 6 - 15 \text{ arcsec}$ PSF and excellent spectral resolution is ideally suited to this task. XMM would, for example, detect an accretion shock in the nearby Perseus cluster ($z = 0.018$, $L_{2-10\text{keV}} = 2.8 \times 10^{44} \text{ erg s}^{-1}$) with an exposure of the order of 10 ksec. However, in this case, the area to be searched is extremely large compared to the field of view of XMM. With poorer spatial resolution, but exceptional spectral resolution, ASTRO-E should allow searches to be made for line emission species both inside and outside of shock regions.
We suggest that the best strategy will be to look for the diffuse emission of the post-shock and pre-shock gas using the large effective area and the good spatial and spectral resolution of XMM (Dahlem et al. 1999). We present here simulated observations of Abell 2029 with XMM. At a redshift of $z = 0.0767$ and with $L_{2-10\text{keV}} = 2.07 \times 10^{45}$ erg s$^{-1}$ ($h = 0.5$) and $kT = 7.8$ keV (David et al. 1993) this system presents an optimal angular scale ($\sim 30$ arcmin) and surface brightness. In addition Abell 2029 is a strong cooling flow cluster, and, at least in the inner regions, appears to be in equilibrium with no sign of merging of cluster subunits (Sarazin et al 1998). A shock radius of $1.1h^{-1}$ Mpc is assumed and a core radius of $0.164h^{-1}$ Mpc, corresponding to $\sim 16$ and $\sim 2.5$ arcmin respectively. Assuming $\beta = 2/3$, we obtain an estimated surface brightness at the shock of $\Sigma_{0.1-12\text{keV}} = 1.05 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ arcmin$^{-2}$.

Using QUICKSIM (Snowden 1998) we have simulated a 20 ksec XMM observation of a $\beta$ profile distribution with different density and temperature structures according to cases 1, 2 and 3 (see §3.3 above). The simulated cluster is orientated such that the XMM field of view is centred on the shock radius. We simulate both the PN and two MOS EPIC cameras. The internal and cosmic background count rates in the 0.1 – 12 keV band at the coordinates of Abell 2029 are estimated to be $3.67 \times 10^{-3}$ ct s$^{-1}$ arcmin$^{-2}$ (PN) and $1.11 \times 10^{-3}$ (MOS) and are included. The resulting outputs are spatially and spectrally analyzed with XSELECT and XSPEC, assuming an absorbed Raymond-Smith spectrum. Background counts are subtracted for all spatial data bins using a simulated observation of blank sky, to account for vignetting effects.

The spectral fits are performed in concentric annuli, centred on the cluster core. The neutral hydrogen column density is fixed ($N_H = 3 \times 10^{20}$ cm$^{-2}$ to match the value at A2029) and the redshift is fixed, while the temperature, normalization and metallicity are allowed to vary. To measure the gas temperature with a precision of $\sim 10 - 20\%$ requires
at least $\sim 2000 - 4000$ source photons respectively for low ($\sim 1$ keV) and high ($\sim 8$ keV) temperatures. This is a consequence of lower temperature spectra having more photons on the exponential cutoff, where the impact of temperature is strongest. The metallicity is always poorly constrained in these simulations. We choose the widths of the radial bins in order to accumulate enough photons to match these criteria.

In Figure 2 we plot the observed surface brightness, temperature and entropy profiles, for the three different cases described in §3.3. The spatially resolved spectral analysis has in this case been performed only on the PN data, which contains the majority of the signal. It is apparent from this simulation that in 20 ksec XMM can clearly distinguish between the three cases. In the first case, when a warm gas surrounds the cluster (see first row of Figure 2), the entropy level is clearly determined interior and exterior to the shock radius. In particular the entropy jump is clearly visible at more than 90 % confidence. In the case of a very cold external medium (second row) there is no detection outside the shock radius, and thus no direct constraint on the entropy level.

The case of adiabatic compression, with a slowly decreasing temperature profile at constant entropy, is shown in the third row. Physically, to have this profile, a rapidly rising entropy in the external IGM should be assumed, to give the very high value $K_\ast \sim 5 \times 10^{34}$ erg cm$^2$ g$^{-5/3}$. In fact, we note that this case is more by way of illustration since this scenario is expected only at much lower mass systems and the surface brightness should really be scaled down to that of groups.

Note that the region of the cluster being observed here is at a radius approximately twice that of the last significant point of Sarazin et al. (1998): the surface brightness profile in clusters has never been tested to such large radii. The observations simulated here could provide a very strong test for minimum entropy models as well as others. We stress again that, even if the shock is absent (because the accretion processes ended long ago) or is
located outside the observed region, the entropy profile of the gas can tell us about the physical processes experienced by the gas during accretion.

The lower luminosity of groups will make observations like these increasingly difficult. In Figure 3 we show, as a function of the total X-ray luminosity, the exposure times needed with XMM to detect the emission interior and exterior to the accretion shock with a signal to noise of 5, and enough photons to derive the temperature to within 20% uncertainty. Here we use the 2 – 10 keV luminosity, and map to $T$ using the 2-10 keV EXOSAT $L$-$T$ relation (David et al. 1993). We have assumed the same redshift as Abell 2029 ($z = 0.0767$), $\beta \approx 0.7$, and an external temperature of about 1 keV. The limits are derived using the signal in the PN + 2MOS detectors, for different choices of the ratio $R_S/R_V$ of the shock to the virial radius (as long as $\rho_i/\rho_e > 1$). We have always assumed the shock fronts to be at the center of the XMM field of view. The small circle represents our simulated observation of Abell 2029. The constraints on the observation times are dominated by the requirement to have 4000 and 2000 photons respectively inside and outside the shock (continuous lines) while the requirement of the 5-sigma emission detection becomes dominant at lower luminosities (dashed lines). It is clear that, with sufficient exposure at lower luminosities, the shock/adiabatic transition can be mapped to a considerable extent, allowing a direct test of the general picture summarized in §2.

Looking further ahead, two possible missions would make the cluster accretion shock a routine observation in studies of clusters. ESA’s X-ray evolving Universe Spectroscopy (XEUS) mission, has design goals for a $3 \times 10^5$ cm$^2$ effective area ($\sim 70$ times larger than XMM) and sub 2-arcsec imaging, with high spectral resolution. NASA’s CONSTELLATION-X with a factor 20-100 times larger area than current missions, plus the ability to perform high-resolution spectroscopy of extended objects, could potentially see line emission from pre-shock gas superimposed on the continuum emission of the shocked
5. Discussion

As mentioned in §1, the entropy level measured in high–z Lyα clouds is low with respect to the level observed in clusters of galaxies. From figure 10b of Ricotti et al. 1999, we can interpolate $K_{\text{Ly}\alpha} \sim 1.6 \times 10^{-2}(1 + z)^{-1} \times 10^{34} \text{ erg g}^{-5/3} \text{ cm}^2$; higher values of this entropy would make the IGM invisible in absorption. Thus, we estimate that the ratio of the entropy $K_{cl}$ observed in the clusters to that observed in Lyα is $K_{cl}/K_{\text{Ly}\alpha} \simeq 10(1 + z)$. The discrepancy is even larger for higher values of $K_* \gamma$ that provide a good fit to the local $L$–$T$ relation and are still allowed by present data.

In the framework of the entropy model, this indicates that the IGM undergoes substantial heating before being accreted in the potential wells of groups and clusters. Furthermore, the chemical properties of the IGM seen in the Lyα forest are also different from those of the ICM in clusters, showing that the ICM was affected by star formation processes and chemical enrichment, with a commensurate amount of entropy production.

A self consistent treatment would be to compute the X–ray emission properties of clusters along with the galaxy formation history as derived from hierarchical structure formation models. This would take into account the feedback effect that the entropy production must have on subsequent galaxy formation. In addition, it would properly take into account the intrinsic stochasticity of the entropy.

It has been pointed out that a uniform entropy production model may require an excessive energy release compared to constraints from observations of high redshift stellar populations (Valageas & Silk 1999, Wu, Fabian & Nulsen 1999). The problem can be solved partially with a “bias” in the entropy production. This bias is expected to go in
the favoured direction (higher entropy in lower mass systems) in all the hierarchical model of structure formations. Lower mass systems evolve by accreting lower mass halos, where the effect of SNe heating and stellar winds is larger due to the shallower potential wells of the host halos. This can assist in attaining the same expected entropy level with a minor global energy release. In this case it will be particularly important to trace the average entropy level or, better, the average entropy profiles, in groups and clusters to search for an eventual trend with scale. This would correspond to a relation between entropy and emission weighted temperature like the one plotted in figure 2 of PCN in the perspective of the forecoming data with better spatial and spectral resolution.

Another important aspect of such a relation, is that it can potentially exhibit an evolution of the entropy with epoch. In fact, the entropy level in the cores of groups is related to the entropy of the IGM at the epoch of accretion, and thus it can be different with respect to the value in the external IGM if there is some evolution in the average cosmic value (as, for example, is observed for $K_{Ly\alpha}$). This observation of the “evolution” of the entropy as recorded in the profiles of local clusters and groups, can be seen as well in the evolution of the global properties: a constant entropy leads to an almost constant $L-T$ relation, while an entropy decreasing with epoch leads to a positively evolving $L-T$ (see TNb).

Similar considerations can be applied to other scenarios, like the heating of the IGM by quasars. This model, again, can be tested looking for the entropy distribution, which in this case will be biased according to the distribution of the quasars.

Finally, other models envisage gravitational entropy generation by large scale shocks before the collapse of smaller structures (see Cen & Ostriker 1999 and references therein). However, to make a significant contribution to the IGM entropy irrespective of the scale (which is needed to break the self similarity) this phenomenon requires substantial power
on large scales which may prove inconsistent with observed galaxy formation properties.

6. Conclusions

In this work we have described how the IGM and ICM entropy distribution, at least in the local universe, can be directly measured by observing X-ray clusters of galaxies. Not only should the global emission properties of clusters bear the imprint of the past entropy level in the accreted IGM, but the values of this entropy can be directly measured in the cores of intermediate mass clusters or groups, or in the external IGM just outside the shock radius of very massive clusters, still accreting at $z = 0$. We use our knowledge of the gravitational processes to relate the IGM to the ICM observed in the core of groups, and at large radii in rich clusters, where the X-ray emission is enhanced due to the higher densities. This will allow us to trace the entropy distribution in the Universe as a function of scale and epoch, giving complementary information to the search for the low density, warm–hot gas in the fluctuations of the soft X-ray background (Cen & Ostriker 1999).

In particular, the detection of the external entropy of the pre–shocked gas requires a measurement of both the surface brightness and temperature of cluster gas around the shock radius. With such data, the entropy profile across the shock can be measured, and hence the thermodynamic state of both the ICM and the IGM. The detection of accretion shock signatures in rich clusters, together with the observation of constant entropy profiles in groups, would be consistent with the hypothesis of a minimum entropy IGM, accreted by dark matter halos. If the measured entropy level in the gas around clusters and in groups is similar, the simple scenario of homogeneous entropy production in the IGM at high redshifts will be strongly supported. This would simultaneously help constrain physical models for the generation of the entropy and (in the case of stellar formation processes) the chemical enrichment of the IGM.
Such observations would therefore provide crucial information at the confluence of many different physical processes involving both baryons and dark matter, that put in a common perspective an enormous amount of data, both in the optical and the X-ray band. At present there are no other viable observations which can connect the entropy of the IGM detected in the Ly$\alpha$ forest with the entropy level required to explain X–ray constraints from galaxy clusters and groups. We show how an instrument such as XMM can relatively easily perform the necessary measurements and hope this work encourages future observations which will directly test the cluster physics described here.

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Fig. 1.— The infall velocity at the shock radius of each accreted gas shell as a function of the virialized mass. Here we assumed $K = 0.3 \times 10^{34}$ erg cm$^2$ g$^{-5/3}$ in a low density ($\Omega_0 = 0.3$) flat cosmology, for a final mass at $z = 0$ of $10^{15} h^{-1} M_\odot$ (upper panel) and $10^{14} h^{-1} M_\odot$ (lower panel). The straight line is the free fall velocity $v_i \simeq M^{1/3}$, while the thick line is the infall velocity of the baryons, and the dashed line is the sound speed $c_s$. When $v_i < c_s$ the accretion process is entirely adiabatic, and the accreted gas originate the adiabatic core (dashed line) in the density profiles shown in the small boxes.
Fig. 2.— Simulated observations of Abell 2029 in the three cases discussed in the text. The three columns show the observed surface brightness, temperature and entropy profiles, with relative error bars (90% confidence level). A beta-model with $\beta \simeq 0.7$, normalized to the results of Sarazin et al. (1998), has been used. First row: strong shock with an external warm gas ($kT_e = 1$); second row: strong shock with an external cold gas ($kT_e = 0.01$); third row: adiabatic profile without shock.
Fig. 3.— The exposure times needed to detect the emission internal (left panel) and external (right panel) to the shock, with a $S/N=5$, as a function of the total $2-10$ keV luminosity for objects at the same redshift of Abell 2029 ($z = 0.0767$). Here $\beta = 2/3$ and $kT_e = 1$ keV. The limits are derived using the signal in the PN+2MOS detectors (thin filter). Different curves refer to different value of the ratio $R_S/R_V$. The circle refers to the simulated observations for Abell 2029.