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CLUSTERS, GROUPS, AND THE DIFFUSE X-RAY BACKGROUND

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Most of the baryons in the present-day universe are thought to reside in intergalactic space at temperatures of 10^{6-7} K. X-ray emission from these baryons contributes a modest (10%-20%) fraction of the ~ 1 keV background whose prominence depends on the amount of non-gravitational energy injected into intergalactic space by supernovae and AGNs. Because the virialized regions of groups and clusters cover a large percentage of the sky, observing the baryons belonging to individual intercluster filaments may prove quite difficult. However, information about the global properties of the intergalactic medium is contained in the surface-brightness distribution of the diffuse X-ray background.

1 Introduction

Most of the baryons in the universe remain undetected. We believe they exist because primordial nucleosynthesis predicts a baryonic matter density amounting to a few percent of the critical density ($\rho_{\rm cr}$), while the baryons associated with stars and gas in galaxies make up less than half a percent of $\rho_{\rm cr}$ (e.g., Fukugita, Hogan, & Peebles 1998). Within clusters of galaxies the intergalactic baryons are obvious because gravitational compression causes them to glow prominently in X-ray light. Elsewhere they are are much more difficult to see.

Simulations indicate that the bulk of the universe's baryons currently reside outside of clusters in the form of diffuse 10^{6-7} K gas associated with groups and filaments of galaxies (e.g., Cen & Ostriker 1999; Davé et al. 2000). The low surface brightness of this warm, diffuse gas has so far made it very challenging to study. Apart from some tantalizing regions of enhanced X-ray surface brightness (Wang, Connolly, & Brunner 1997; Kull & Bohringer 1999; Scharf et al. 2000) and a few O VI absorption features (Tripp, Savage, & Jenkins 2000) we have no positive detections of it.

Taken together, the intergalactic baryons lying inside and outside of clusters ought to contribute a non-negligible fraction of the ~ 1 keV X-ray background. If these intergalactic gases were heated by purely gravitational processes, they would contribute around 30% of the observed ~ 1 keV X-ray background (Pen 1999; Wu, Fabian, & Nulsen 1999). However, the point-source contribution to the background at these energies is now estimated to be at least 80% (Miyaji, Hasinger, & Schmidt 2000; Mushotzky et al. 2000), meaning that $< 20\%$ of this background can be truly diffuse. Non-gravitational energy input, perhaps by supernovae, can alleviate this discrepancy because it injects entropy into the intergalactic gas, making it harder to compress.

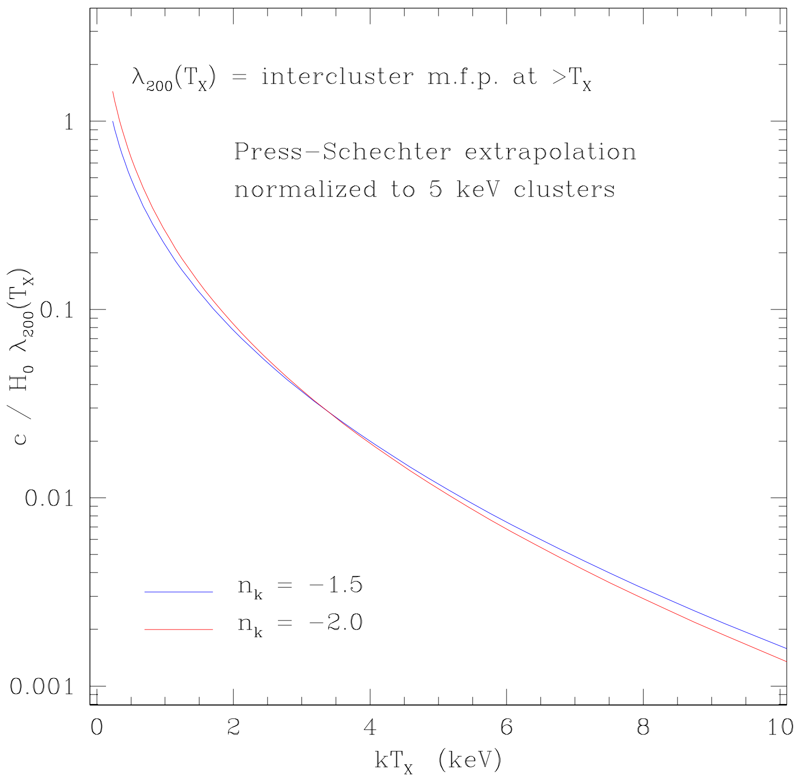

Figure 1: Hubble length c/H_0 in units of the mean free path λ_{200} between the virialized regions of clusters hotter than T_X. Note that the quantity $c/H_0\lambda_{200}$ approaches unity on group scales, implying that the virialized regions of groups cover a high percentage of the sky.

As a result, the mean density and emissivity of gas that has fallen into potential wells are lower, decreasing its contribution to the X-ray background.

Analyses of the temperature-luminosity relation of clusters and groups likewise suggest that a significant amount of non-gravitational heating has occurred (Kaiser 1991, Evrard & Henry 1991). The energy injected per particle appears to be comparable to the potential depth of a typical group, which would severely affect the properties of groups (e.g., Ponman, Cannon, & Navarro 1999). Models in which early energy injection by supernovae preheats the intergalactic medium can plausibly account for this non-gravitational heating. Thus, the degree to which the intergalactic baryons have been disturbed may reflect the star-formation history of the universe. The motivation for detecting intergalactic baryons outside of clusters is therefore two-fold: detecting this matter would verify that the baryons implied by primoridal nucleosynthesis do indeed exist in the low-z universe and measuring their entropy level would provide a key constraint on supernova energy injection into intergalatic space.

2 Quantifying Confusion

Detecting true intercluster baryons and distinguishing the separate contributions of clusters, groups, and filaments to the diffuse X-ray background may prove quite challenging because the virialized regions of clusters and groups turn out to cover much of the sky. Figure 1 shows the results of a simple calculation that illustrates this point. One can define the quantity $\lambda_{200}(T_X)$ to be the mean free path between clusters hotter than T_X, where the virial radius of the cluster is taken to be the radius r_{200} within which the mean density is 200 times the critical density. Surveys of massive low-redshift clusters show that $\lambda_{200}(5\,\mathrm{keV})$ is $\sim 100c/H_0$. However, a Press-Schechter extrapolation of the cluster mass function to lower masses shows that the quantity

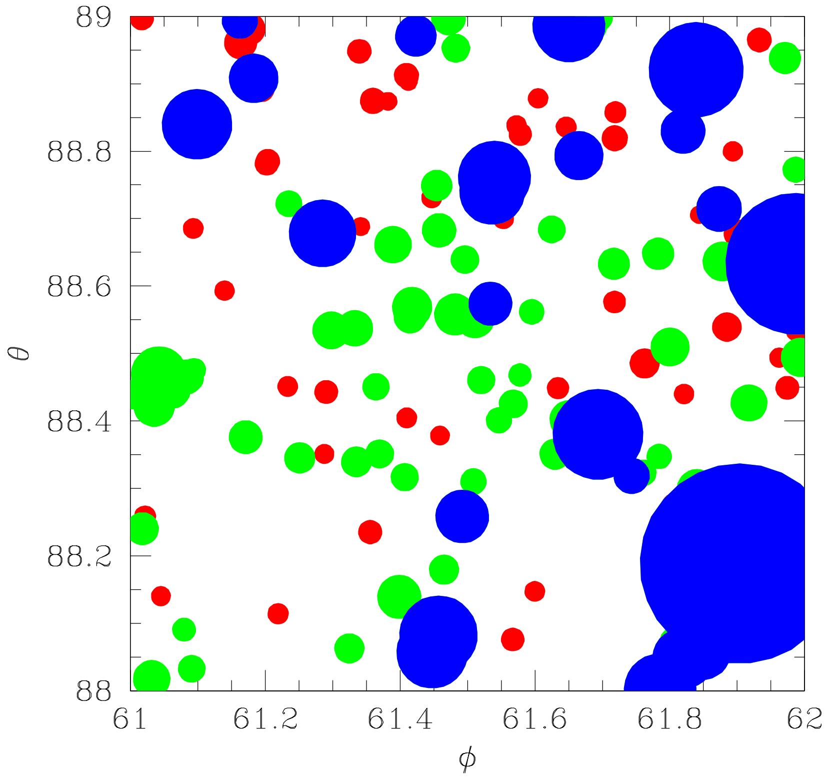

Figure 2: Virial regions of projected groups and clusters more massive than $2.7 \times 10^{13}\, M_\odot$ in a typical square degree of the ΛCDM Hubble Volume simulation. Blue (black) dots indicate clusters at $0 < z < 0.5$, green (light grey) dots indicate clusters at $0.5 < z < 1.0$, and red (dark grey) dots indicate clusters at $1.0 < z < 1.45$.

$c/H_0\lambda_{200}$ grows to be of order unity on group scales ($\sim 0.5 - 1$ keV), meaning that the mean free path between such objects is roughly a Hubble length. In other words, the virialized regions of groups should cover much of the sky.

A more concrete assessment of group confusion can be performed using data from the Hubble Volume simulations of the Virgo Consortium (see Evrard, this volume). Using the Hubble Volume cluster catalogs, which list the masses and locations of virialized objects down to $2.7 \times 10^{13}\, M_\odot$, we have computed the covering factor of such objects in both a ΛCDM ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$) and a τCDM ($\Omega_M = 1.0$, $\Omega_\Lambda = 0.0$) cosmology. In both cases, the aggregate solid angle of groups and clusters out to $z \sim 1.5$ is $\sim 2\pi$ steradians, yielding a total covering factor ~ 0.35 after overlap corrections are accounted for (Voit, Evrard, & Bryan 2000). Figure 2 shows how clusters and groups cover a typical square degree of the simulated sky.

3 Surface-Brightness Statistics

Because the covering factor of virialized gas in groups and clusters is of order unity, identifying individual intercluster filaments and isolating their contribution to the diffuse background could prove quite difficult, even with ideal data. Likewise, group-group overlap will complicate the compilation of luminosity and temperature functions for high-redshift groups. Motivated by these confusion problems, we have begun to investigate the texture of the diffuse X-ray background, including projection effects, in hopes of extracting information about intergalactic baryons from the statistical properties of the X-ray background.

Hydrodynamical simulations of large-scale structure are currently limited to box sizes much less than a Hubble volume. Individual X-ray filaments can appear quite obvious in a ~ 100 Mpc box (e.g., Pierre, Bryan, & Gaustad 2000); however, a typical line of sight through the universe

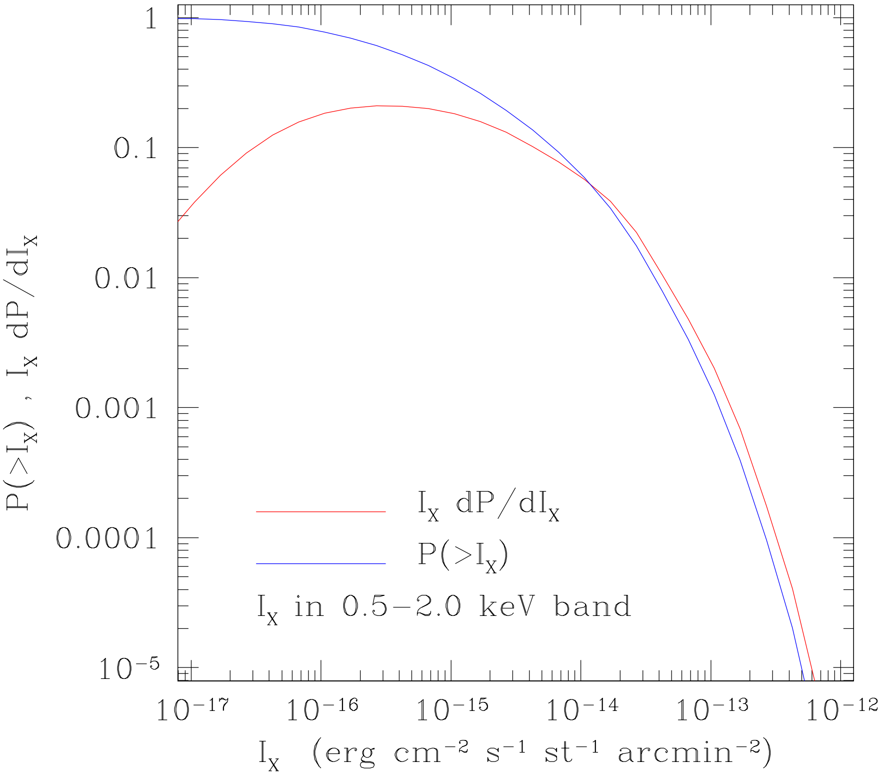

Figure 3: Simulated surface-brightness distribution functions for hot, diffuse gas integrated from $z = 0$ to $z = 0.5$. The median and mode of this distibution are at $I_X \approx 3 \times 10^{-16}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,arcmin^{-1}}$, while the mean is closer to $10^{-15}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,arcmin^{-1}}$.

extends through tens of such boxes spanning a wide range of redshifts. For any two-dimensional projection of a simulated box of comoving size L at redshift z, one can calculate the probability $P(> I_X, L, z)$ that a given line of sight will have a $0.5 - 2$ keV surface brightness exceeding I_X. We have computed $P(> I_X, L, z)$ from the simulation of a 100 Mpc box described in Pierre et al. 2000, and we reconstructed $P(> I_X)$, the total projected surface brightness out to high redshift, by convolving these surface brightness distributions over redshift space. Implicit in this convolution is the assumption that structures greater than 100 Mpc contribute little to the integrated background.

Figure 3 shows the resulting surface brightness distribution. The function $I_X dP(> I_X)/dI_X$ peaks at $I_X \approx 3 \times 10^{-16}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,arcmin^{-1}}$, indicating that this is the median value of the projected surface brightness. In the range $10^{-14} - 10^{-15}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,arcmin^{-1}}$, the function $I_X dP(> I_X)/dI_X$ has a slope similar to the surface-brightness profile beyond the core radius of a cluster. Above $10^{-14}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,arcmin^{-1}}$, where cluster cores would be expected to dominate, $I_X dP(> I_X)/dI_X$ drops off steeply, echoing the steep drop in the abundance of clusters as the mass scale rises.

One quantity of particular interest in this type of analysis will be $I_X^2 dP(> I_X)/dI_X)$, which peaks at the surface-brightness levels that contribute the most flux to the mean background. Preliminary simulations indicate that the position of this peak is sensitive to the amount of energy injected into the intergalactic medium. If the minimum entropy within clusters and groups is large, then their intergalactic gas is more difficult to compress, preferentially lowering the emissivity of high-density regions. This effect pushes the peak of $I_X^2 dP(> I_X)/dI_X$ to lower values of I_X and could turn out to be a method of measuring preheating that is not prone to the uncertainties of selecting and measuring the properties of X-ray groups.

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