Autocorrelation function of the soft X-ray background produced by warm-hot gas in dark halos

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ABSTRACT

We calculate the angular two-point autocorrelation function (ACF) of the soft X-ray background (SXRB) produced by the warm-hot intergalactic medium (WHIM) associated with dark halos, motivated primarily by searching for missing baryons and distinguishing different physical processes of the WHIM in dark halos. We employ a purely analytic model for the halo population which is completely determined by the universal density profile and the Press-Schechter mass function. We then adopt a phenomenological approach to nongravitational processes of the WHIM such as preheating and radiative cooling. It shows that the power spectra of the SXRB predicted by three WHIM models, namely, the self-similar model, preheating model and cooling model demonstrate remarkably different signatures in both amplitude and shape, with the peak locations moving from $\ell \approx 4 \times 10^4$ for the self-similar model to a smaller value of $\ell \approx (3-5) \times 10^3$ when nongravitational processes are taken into account. The corresponding ACFs for preheating and cooling models become shallower too as compared with the prediction of the self-similar model. This may permit an effective probe of the physical processes of the WHIM in massive halos in conjunction with the observationally determined power spectrum or ACF of the SXRB from diffuse WHIM. However, a direct comparison of our theoretical predictions with existing data (e.g. the ACF determined from ROSAT observations) is still difficult because of the dominant contribution of AGNs in the soft X-ray sky. We discuss briefly the implication of our results for resolving the missing baryon problem in the local universe.

Subject headings: cosmology: theory — diffuse radiation — intergalactic medium — X-ray: general

1. Introduction

Hydrodynamical simulations of structure formation suggest that most of baryons in the local universe may exist in the form of diffuse warm-hot intergalactic medium (WHIM) at
temperatures of $T \sim 10^5$–$10^7$ K (Cen & Ostriker 1999). The WHIM is believed to be associated with groups and poor clusters that are further embedded in large-scale structures. As a result, the gravitationally heated WHIM may manifest itself as large-scale X-ray filamentary structures through thermal bremsstrahlung emission (Scharf et al. 2000; Zappacosta et al. 2002). However, the majority of the baryons may escape direct detection due to the sensitivity limit of current X-ray instruments. A newly proposed approach is to search for the resonant absorption from the WHIM in large-scale filamentary structures (Cen et al. 2001). It seems that strong evidence for the detection of absorption lines associated with the local WHIM has already been discovered (Fang et al. 2002; Nicastro et al. 2002a,b).

It has been realized in recent years that the WHIM may also contribute a non-negligible fraction of the cosmic soft X-ray background (SXRB) (e.g. Pen 1999; Davé et al. 2001; Voit & Bryan 2001a; Bryan & Voit 2001; Croft et al. 2001; Wu & Xue 2001) and therefore, measurements of the strength and power spectrum of the SXRB may allow us to set stringent constraints on both the amount and distribution of the WHIM in the local universe. In fact, a tight limit on the SXRB from diffuse gas, after discrete sources are removed, has been obtained with advanced X-ray detectors such as ROSAT, Chandra and XMM (e.g. McHardy et al. 1998; Hasinger et al. 1998, 2001; Mushotzky et al. 2000; Giacconi et al. 2001, 2002; Tozzi et al. 2001; Hornschemeier et al. 2001; Rosati et al. 2002; Bauer et al. 2002; etc.). In particular, the angular two-point autocorrelation (ACF) and harmonic power spectrum of the SXRB have been measured over a broad angular scale ranging from ten degrees to a few arcminutes (Barcons et al. 1989; Carrera et al. 1991; Soltan 1991; Soltan & Hasinger 1994; Soltan et al. 1996, 1999; Carrera, Fabian, & Barcons 1997; Soltan, Freyberg & Trümper 2001; Śliwa, Soltan & Freyberg 2001; Soltan, Freyberg & Hasinger 2002), in which the signature of the diffuse WHIM has been clearly detected at arcminute scales (Soltan et al. 2001). This is actually comparable with the angular resolution achieved very recently by cosmic microwave background (CMB) anisotropy measurements, in which the excess power relative to primordial anisotropy at arcminute scales is interpreted as the scattering of CMB photons by the hot electrons within clusters, namely, the Sunyaev-Zel’dovich (SZ) effect (Dawson et al. 2001; Bond et al. 2002). In a sense, the power spectra of both SXRB and CMB at arcminute scales provide equally important information on the amount and distribution of the WHIM in the universe, although X-ray and SZ signals have very different connections with the WHIM. For example, the diffuse X-ray emission is sensitive to the clumping structures of the WHIM and is also subject to the WHIM enrichment. Moreover, the unresolved SXRB after discrete sources are removed is primarily produced by the WHIM in the local universe. By contrast, SZ signals are rather insensitive to the location of the WHIM. At this point, the SXRB may be more suited for the study of the missing baryons.

The theoretical framework of evaluating the ACF of the SXRB was established many
years ago by Barcons & Fabian (1988). Similar technique was simultaneously developed by Cole & Kaiser (1988) for the computation of the SZ power spectrum. Furthermore, an extensive investigation of the harmonic power spectrum of the SXRB has been recently made by Śliwa et al. (2001). Essentially, the ACF or power spectrum of the SXRB can be effectively predicted and compared with observations, provided that the distribution and evolution of the WHIM as well as the cosmological background are specified. However, major uncertainties in such an exercise arise from our poor knowledge of nongravitational processes of the WHIM if we accept the prevailing cosmological model (e.g. the concordance model) and hierarchical theory of structure formation (e.g. the ΛCDM model). This is because the WHIM is easily disturbed by many complicated physical processes in addition to gravity and thermal pressure, which include (non)gravitational heating, radiative cooling, star formation and energy feedback, magnetic fields, etc. The reliability of our theoretical predictions of the intensity and ACF of the SXRB is closely connected with the question of how well one can handle these non-gravitational mechanisms. Based on the analysis of the SXRB intensity alone, it has been shown that the SXRB produced by the gravitationally heated and bound WHIM in groups and clusters within the standard framework of hierarchical formation of structures vastly exceeds the upper limits set by current X-ray observations, arguing for the presence of nongravitational heating process during the evolution of the WHIM (e.g. Pen 1999; Wu, Fabian & Nulsen 2001; Bryan & Voit 2001; Wu & Xue 2001). On the other hand, it may become possible to use the unresolved SXRB as a probe of the underlying physical processes of the WHIM (Xue & Wu 2003). Yet, there is still no agreement about the significance of nongravitational heating on the SXRB produced by the WHIM (e.g. Croft et al. 2001; Davé et al. 2001; Phillips, Ostriker & Cen 2001). This partially reflects the difficulty in handling the complex processes of the WHIM evolution.

In this study, we will focus on the nongravitational effect of the WHIM on the evaluation of the power spectrum and ACF of the SXRB. Using hydrodynamical simulations without inclusion of nongravitational heating, Croft et al. (2001) attempted to construct the ACF of the SXRB. Their result is in quantitative agreement with the extrapolated ACF of the SXRB measured at scales of > 20 arcminutes by Soltan et al. (1999), which is, however, dominated by AGNs. By contrast, a recent investigation of Zhang & Pen (2002), based purely on analytical models, has shown that the ACF of the SXRB at arcminute scales can be significantly modified by the presence of nongravitational heating process. Further investigation is thus needed to clarify the situation. Recall that there is growing observational evidence for the existence of nongravitational process in groups and clusters, which includes the significant departure of the observed X-ray luminosity - temperature relation of groups and clusters from the prediction of the self-similar model (e.g. Edge & Stewart 1991; David et al. 1993; Wu, Xue & Fang 1999; Helsdon & Ponman 2000; Xue & Wu 2000 and references
therein) and the entropy excess in the central cores of groups and clusters (Ponman, Cannon & Navarro 1999; Lloyd-Davies, Ponman & Cannon 2000).

Two prevailing nongravitational scenarios will be considered in the present investigation: preheating and radiative cooling. Both of them tend to suppress the X-ray emission of the WHIM heated by purely gravitational shocks and compression, and become indistinguishable at present in the explanation of the observed X-ray properties of groups and clusters (Voit & Bryan 2001b; Voit et al. 2002; Borgani et al. 2002; Xue & Wu 2003). Nonetheless, it has been argued that radiative cooling alone is probably insufficient to account for the unresolved SXRB (Wu et al. 2001; Xue & Wu 2003), while preheating model or a combined model of cooling and heating may be able to produce an SXRB intensity below the observational limit (Wu et al. 2001; Voit & Bryan 2001b; Xue & Wu 2003). In the present study we will demonstrate how the ACF of the SXRB is affected by preheating and radiative cooling processes. To achieve this, we will employ a simple analytic model to determine the new distribution of the WHIM in dark halos when preheating or radiative cooling is added, as was done by our recent work (Xue & Wu 2003). Incorporating our WHIM models with the distribution and cosmic evolution of dark halo model described by the universal density profile and the Press-Schechter (PS) (Press & Schechter 1974) formalism, we will be able to work out the power spectrum and ACF of the SXRB and discuss the feasibility of measurement. Throughout this paper we assume a flat cosmological model ($\Lambda$CDM) of $\Omega_M = 0.35$, $\Omega_\Lambda = 0.65$ and $h = 0.65$.

2. Halo approach to the ACF of the SXRB

In terms of thermal bremsstrahlung, the X-ray surface brightness of a halo of mass $M$ at redshift $z$ is

$$I(z, M, \theta) = \frac{1}{4\pi (1+z)^4} \int \epsilon(R, Z) d\chi,$$

where $\epsilon$ is the emissivity that is calculated using the Raymond-Smith (1977) code at the soft X-ray energy band 0.5-2.0 keV for an evolving metallicity model of $Z = 0.3Z_\odot(t/t_0)$, $t_0$ is the present age of the universe, $R$ is the radius from the halo center and $R = \sqrt{D_\Lambda^2 \theta^2 + \chi^2}$, $D_\Lambda$ is the angular diameter distance to the halo, and the integral is performed along the line-of-sight $\chi$. The Fourier transform of the X-ray surface brightness distribution $I(z, M, \theta)$ in the case of spherical symmetry for the distribution of the WHIM in a halo is

$$I_\ell(z, M) = 2\pi \int I(z, M, \theta)J_0(\ell \theta) \theta d\theta,$$
where $J_0$ is the cylindrical Bessel function. The distribution and evolution of halo population are described by the PS theory:

$$\frac{d^2 N}{dVdM} = \sqrt{\frac{2\bar{\rho}}{\pi M\sigma^2}} \frac{d\sigma}{dM} \exp \left(-\frac{\delta_c^2}{2\sigma^2}\right),$$

(3)

where $\bar{\rho}$ is the mean cosmic density, $\delta_c$ is the linear over-density of perturbations that collapsed and virialized at redshift $z$, $\sigma$ is the linear theory variance of the mass density fluctuations at mass $M = 4\pi\bar{\rho}R^3/3$. We parameterize the power spectrum of fluctuation $P(k) \propto k^nT^2(k)$ and take the fit given by Bardeen et al. (1986) for the transfer function of adiabatic CDM model $T(k)$. The primordial power spectrum is assumed to be the Harrison-Zel’dovich case $n = 1$. The mass variance for a given $P(k)$ is simply

$$\sigma^2(M) = \frac{1}{2\pi^2} \int_0^\infty k^2 P(k)W^2(kR)dk,$$

(4)

in which $W(x) = 3(sin x - x cos x)/x^3$ is the Fourier representation of the window function. The amplitude in the power spectrum is determined using the rms fluctuation on an $8\ h^{-1}$ Mpc scale, $\sigma_8$, which will be assumed to be $\sigma_8 = 0.9$.

The power spectrum of the SXRB can be separated into the Poisson term, which arises from the correlation within a single halo

$$P^p(\ell) = \int dz \frac{dV}{d\Omega dz} \int dM \frac{d^2 N}{dMdV} [I_\ell(z,M)]^2,$$

(5)

and the clustering term, which arises from the correlation between two different halos

$$P^c(\ell) = \int dz \frac{dV}{d\Omega dz} P^{m}(\ell/\tau, z) \left[ \int dM \frac{d^2 N}{dMdV} b(M, z) I_\ell(z,M) \right]^2,$$

(6)

where we have introduced the halo-halo biasing $b(M, z)$ relative to linear matter power spectrum such that the power spectrum of halo $M_1$ and halo $M_2$ can be approximated by $P^{hh}(z, M_1, M_2, k) = b(z, M_1)b(z, M_2)P^{m}(z, k)$, the small-angle approximation has also been assumed so that $k \approx \ell/\tau$, $\tau$ is the comoving distance, and $dV/d\Omega$ denotes the comoving volume per steradian. We calculate $b(z, M)$ in terms of the prescription of Mo & White (1996). Finally, the angular two-point ACF of the SXRB is simply

$$\omega(\theta) = \frac{1}{2\pi^{\ell^2}} \int_0^\infty [P^p(\ell) + P^c(\ell)] J_0(\ell\theta)\ell d\ell.$$

(7)

The mean SXRB intensity $\bar{T}$ is given by

$$\bar{T} = \int dz \frac{dV}{d\Omega dz} \int dM \frac{d^2 N}{dMdV} \left[ \frac{L_X(z, M)}{4\pi D_L^2(z)} \right],$$

(8)

where $L_X$ is the total soft X-ray luminosity of a halo of mass $M$ at redshift $z$, and $D_L$ is the luminosity distance.
3. WHIM models

A set of analytic models for the WHIM distribution in dark halos have been derived by Xue & Wu (2003). Here we choose three models corresponding to three typical physical processes of the WHIM: (1) Self-similar model: The WHIM simply follows the dark matter distribution, in which no radiative cooling and no extra heating are added to the WHIM; (2) Preheating model: An extra, constant energy budget is added to the WHIM for all halos; And (3) Cooling model: Radiative cooling of the WHIM is included. We briefly summarize the properties of the three models below.

3.1. Dark halos

We begin with the underlying dark matter profile in a halo of mass $M$ at redshift $z$. We adopt the universal density profile suggested by numerical simulations (Navarro, Frenk & White 1997; NFW)

$$\rho_{DM}(r) = \frac{\delta_{ch}\rho_{crit}}{(r/r_s)(1 + r/r_s)^2},$$

(9)

where $\delta_{ch}$ and $r_s$ are the characteristic density and length of the halo, respectively, which can be fixed through the so-called concentration parameter $c = r_{vir}/r_s$ using the empirical fitting formula found by numerical simulations (Bullock et al. 2001)

$$c = \frac{10}{1 + z} \left( \frac{M}{2.1 \times 10^{13} M_\odot} \right)^{-0.14}.$$

(10)

The influence of the $c$ scatter on the ACF of the SXRB will not be considered in this study, which roughly reflects the effect of different formation time of dark halos. The virial mass $M$ is defined as

$$M = \frac{4}{3} \pi r_{vir}^3 \Delta_c \rho_{crit},$$

(11)

where $\Delta_c$ denotes the overdensity parameter and for a flat, $\Lambda$CDM cosmological model, $\Delta_c = 18\pi^2 + 82[\Omega_M(z) - 1] - 39[\Omega_M(z) - 1]^2$, $\Omega_M(z) = \Omega_M(1+z)^3/E^2$ and $E^2 = \Omega_M(1+z)^3 + \Omega_\Lambda$. Finally, we specify the virial temperature of a dark halo in terms of the cosmic virial theorem (Bryan and Norman 1998):

$$kT = 1.39 \text{ keV} f_T \left( \frac{M}{10^{15} M_\odot} \right)^{2/3} \left( h^2 E^2 \Delta_c \right)^{1/3}.$$

(12)

We will take the normalization factor to be $f_T = 0.8$ below.
3.2. Self-similar model

We assume that the WHIM particles in halos simply follow the dark matter distribution:

\[ n_e(r) = \frac{f_b}{\mu_e m_p} \rho_{DM}(r), \] (13)

where \( n_e \) is the number density of electrons, \( f_b \) is the universal baryon fraction, and \( \mu_e = 1.13 \) is the mean electron weight. We further assume that the WHIM is isothermal with temperature \( T = T_{\text{vir}} \). Consequently, the X-ray surface brightness profile \( I(z, M, \theta) \) can be straightforwardly obtained. To avoid the divergence of \( I(z, M, \theta) \) towards the centers of the halos, the NFW profile is replaced by a flat core for the central regions of radius \( 0.01 r_{\text{vir}} \). Adopting a temperature profile given by the equation of hydrostatic equilibrium alters the result only slightly. It is well known that this model yields a significant overestimate of the SXRB intensity. Here we use this model as a reference point.

3.3. Preheating model

We employ a phenomenological approach to constructing the preheating model by simply raising the entropy \( S^0(r) \) of the WHIM in the self-similar model to a certain level regardless of whatever the energy sources would be:

\[ S(r) = \Delta S + S^0(r). \] (14)

We fix the constant entropy floor \( \Delta S \) using the observed X-ray luminosity and entropy distributions of groups and clusters. It turns out that a constant floor of \( \Delta S = 120 \text{ keV cm}^2 \) reproduces nicely both the X-ray luminosity - temperature relation and central entropy measurement of groups and clusters (Xue & Wu 2003). The new distribution of the WHIM with preheating can be obtained by combining the equation of hydrostatic equilibrium

\[ \frac{1}{\mu m_p n_e(r)} \frac{d[n_e(r)kT(r)]}{dr} = - \frac{G M_{DM}(r)}{r^2} \] (15)

and the new entropy profile \( S(r) = kT(r)/n_e^{2/3}(r) \). The latter acts as the equation of state for the preheated WHIM.

3.4. Cooling model

Radiative cooling is completely governed by the conservation of energy:

\[ \frac{3}{2} n_t kT = \epsilon(n_e, T, Z) t_c, \] (16)
where \( n_t \) is the total number density of the WHIM. Setting the cooling time \( t_c \) to equal the cosmic age at the halo redshift gives the cooling radius \( r_{\text{cool}} \) and total mass \( M_{\text{cool}} \) of the cooled material. Following the prescription of Voit & Bryan (2001b) and Wu & Xue (2002a), we can find the distribution of the remaining WHIM after cooling by solving the equation of hydrostatic equilibrium under the conservation of total baryonic mass and entropy. Two uncertainties in this model arise from the metallicity \( Z \) and the cooling time \( t_c \). Note that \( t_c \) has a cosmological dependence if \( t_c \) is set to equal the age of the universe.

4. Results

Figure 1a - 1c show the ACFs of the SXRB over angular scales from 0.01° to 1° predicted by our self-similar model, preheating model and cooling model, respectively. A glimpse of these plots reveals that overall features of the resulting ACFs look quite similar for all three models: The ACFs of the SXRB are dominated by the Poisson distribution of the WHIM halos, and the contribution of halo clustering is essentially negligible. Moreover, the ACFs of the SXRB are governed by nearby halos within redshift \( z \approx 0.2 \). In other words, if the local population of groups and poor clusters can be properly removed in the measurement of the SXRB, the ACF amplitude will be significantly reduced especially at large angular separations \( \theta > 0.1° \) where the halo clustering becomes the dominant component. Yet, there is a remarkable difference between the ACF predicted by the self-similar model and those by preheating and cooling models. Namely, the ACF power in the self-similar model arises primarily from poor groups in mass range between \( 10^{13} \) and \( 10^{14} \) M\(_{\odot} \), while more massive groups and poor clusters (\( 10^{14}-10^{15} \) M\(_{\odot} \)) play a prominent role in the ACFs of the SXRB for preheating and cooling models. This is because either the WHIM cannot be trapped in low-mass halos in the scenario of preheating or most of the WHIM in low-mass halos was converted into the cooled materials in radiative cooling model.

We compare in Figure 2 the ACFs of the SXRB predicted by our three WHIM models. In addition to their difference in amplitude, the ACFs in preheating and cooling models become shallower in shape than the ACF in the self-similar model. This arises from the fact that both preheating and radiative cooling tend to flatten the radial profiles of the WHIM inside dark halos, and the effect is more remarkable for low-mass halos (e.g. Balogh, Babul & Patton 1999; Babul et al. 2002; Wu & Xue 2002a,b; Voit et al. 2002), which is consistent with the result of Zhang & Pen (2002) that the more an extra energy is added to the WHIM, the shallower the ACF of the SXRB would be. Yet, the most efficient way of distinguishing different WHIM models is perhaps to work directly with the power spectrum of the SXRB produced by the WHIM. To see this, we have also illustrated in Fig. 2 the SXRB power
spectra predicted by the three WHIM models. Indeed, the inclusion of nongravitational processes (preheating or cooling) results in a dramatic change in the SXRB power spectrum, with the peak location moving from $3 \times 10^4$ for self-similar model to $\sim 3-5 \times 10^3$ for preheating and cooling scenarios. Apparently, this is because X-ray emission is sensitive to the dense WHIM in the central cores of dark halos, while both preheating and cooling yield a flattening of the WHIM distribution in halos. As a result, the SXRB power spectrum is peaked toward smaller $\ell$ in the presence of nongravitational processes as compared with the prediction of the self-similar model. Future measurement of the SXRB power spectrum by diffuse WHIM at 1-10 arcminute scales should allow us to place stringent constraints on the spatial distribution and physical processes of the WHIM. Recall that the SZ power spectrum at $\ell < 10^4$ is rather insensitive to the physical processes of the WHIM.

We now compare our predictions with the existing results of X-ray observations, hydrodynamical simulations and other theoretical work. Figure 3 shows our model predictions with and without ‘local’ population within $z = 0.2$, along with the observationally determined ACFs of the SXRB by Soltan et al. (2001) and the numerically simulated result by Croft et al. (2001) without inclusion of preheating. However, a direct comparison of our theoretically expected ACFs with these observational and simulated data is inappropriate because the latter have included contributions from both point sources like AGNs and extended sources such as galaxies, groups and clusters. A reasonable comparison can be made only if the major component of the SXRB, i.e. AGNs, is properly removed. In addition, the ACF constructed by Soltan et al. (2001) has excluded the pointings centered at local extended sources. This also complicates our comparison with theoretical predictions because the inclusion of nearby clusters can change the predicted ACF substantially. In a word, the current measurements of the SXRB ACF still do not facilitate a meaningful comparison with theoretical expectation. For a preheating model, we can indeed compare our prediction with a similar theoretical investigation by Zhang & Pen (2002). It appears that the two results are roughly consistent with each other except at very large angular separations.

5. Discussion and conclusions

Using a halo approach to the abundance and evolution of dark halos and a phenomenological approach to including nongravitational heating and radiative cooling for the WHIM, we have calculated the power spectra and ACFs of the SXRB produced by diffuse WHIM associated with dark halos. Because both nongravitational heating and radiative cooling tend to produce a flattening of the WHIM distribution in halos, the resulting ACFs of the SXRB thus become shallower in shape as compared with the one given by the self-similar
model. In particular, the corresponding SXRB power spectra exhibit a signature that differs dramatically from the one in the self-similar model, with the peak location moving from \( \sim 3 \times 10^4 \) for the self-similar model to \((3-5) \times 10^3\) for preheating and cooling models. Therefore, measurement of the SXRB power spectrum can be used as an effective tool for the probe of different physical processes of the WHIM at various scales. Unfortunately, the current measurement based on ROSAT observations is still unable to facilitate such an investigation because the available ACF of the SXRB is primarily produced by AGNs (Soltan et al. 2001). One possible way is to subtract the AGN component from the SXRB power spectrum using the 3D spatial correlation function of the AGNs that can be constructed separately. Yet, this may also introduce large uncertainties.

One of our initial goals in the present investigation is to study the feasibility of searching for the missing baryons from measurement of the power spectra and ACFs of the SXRB. If the missing baryons are the WHIM associated with groups and poor clusters that are further embedded in large-scale structures as shown by hydrodynamical simulations (Cen & Ostriker 1999; Davé et al. 2001), a comparison of the theoretically predicted power spectrum, ACF or total intensity of the SXRB and the X-ray observed quantities should allow us to set useful constraints on the content and distribution of the missing baryons. Indeed, in the more realistic case of where nongravitational effect is taken into account, the major contribution to the SXRB comes from local groups and poor clusters with masses ranging from \( 10^{14} \) to \( 10^{15} M_\odot \) (see Fig.1b and Fig.1c), and the effect of very massive clusters of \( M > 10^{15} M_\odot \) and low-mass halos below \( 10^{14} M_\odot \) is actually negligible. In other words, the SXRB, after AGNs are removed, is dominated by the baryons in the form of the WHIM and within groups and poor clusters. Of course, our present analytic models of the WHIM are still too simplistic, in the sense that a considerable fraction of the WHIM may reside outside of less massive dark halos like groups and poor clusters due to nongravitational processes such as preheating and/or radiative cooling. The inclusion of the WHIM outside the virial radii of dark halos in an analytic treatment is somewhat difficult because hydrostatic equilibrium may break down even if the NFW profile can be extrapolated to large radii. One of the possibilities of extracting information about the WHIM residing outside of virial radii is to subtract the contribution of the WHIM within virial radii from the observed SXRB in conjunction with theoretical modeling as we have done in this study.

Another approach to improving current work is to cross-correlate the SXRB and the SZ sky, which may allow us to acquire additional knowledge of the distribution and evolution of the WHIM. Recall that X-ray emission and SZ signals have very different dependence on both the radial distribution of the WHIM in halos and the spatial locations of halos themselves. In fact, cross-correlations between the SXRB and other sources (galaxies, clusters, CMB, radio sources, IRAS sources, etc.) have been extensively explored in literature. A combination of
these cross-correlation and auto-correlation analyses of the SXRB may eventually constitute a powerful tool of unveiling the amount and distribution of the missing baryons in the local universe.

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Fig. 1a.— Angular two-point autocorrelation function (ACF) of the soft X-ray background (SXRB) predicted by (a) self-similar model, (b) preheating model and (c) cooling model. Contributions of halos from different mass ranges to Poisson and clustering terms are demonstrated in left panels: thin solid line-(10^{12}−10^{13}M_{⊙}); dashed line-(10^{13}−10^{14}M_{⊙}); dot-dashed line-(10^{14}−10^{15}M_{⊙}); and dotted line-(10^{15}−10^{16}M_{⊙}). ACFs from halos with and without exclusion of local population within z = 0.2 are displayed in right panels, in which dashed and dotted lines represent the contributions of Poisson and clustering terms, respectively.
Fig. 1c.—
Fig. 2.— Comparison of the ACFs (top panel) and power spectra (lower panel) of the SXRB predicted by self-similar model (solid line), preheating model (dashed line) and cooling model (dotted line).
Fig. 3.— The theoretically predicted ACFs of the SXRB are compared with the observationally determined data (Soltan et al. 2001) and the simulated results (Croft et al. 2001; open circles). The model predicted ACFs with and without inclusion of nearby halos within $z = 0.2$ are plotted by solid and dashed lines, respectively. Filled and open squares represent the data with and without inclusion of clusters in the fields of the ROSAT pointing observations used for the determination of ACFs. Note that both observational and simulated data are dominated by AGNs rather than the WHIM. In the middle panel we have also illustrated the result of Zhang & Pen (2002) for preheating model with nongravitational energy put $E = 0.5$ keV per particle (dotted line).