Heating of the IGM

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ABSTRACT

Using the cosmic virial theorem, Press-Schechter analysis and numerical simulations, we compute the expected X-ray background (XRB) from the diffuse IGM with the clumping factor expected from gravitational shock heating. The predicted fluxes and temperatures are excluded from the observed XRB. The predicted clumping can be reduced by entropy injection. The required energy is computed from the two-point correlation function, as well as from Press-Schechter formalisms. The minimal energy injection of 1 keV/nucleon excludes radiative or gravitational heating as a primary energy source. We argue that the intergalactic medium (IGM) must have been heated through violent processes such as massive supernova bursts. If the heating proceeded through supernova explosions, it likely proceeded in bursts which may be observable in high redshift supernova searches. Within our model we reproduce the observed cluster luminosity-temperature relation with energy injection of 1 keV/nucleon if this injection is assumed to be uncorrelated with the local density. These parameters predict that the diffuse IGM soft XRB has a temperature of $\sim 1$ keV with a flux near $10 \text{ keV/cm}^2 \text{ s str keV}$, which may be detectable in the near future.

Subject Headings: cosmology: theory and diffuse radiation – X-rays: general – supernova: general

1. Introduction

The intergalactic medium has been a mysterious subject for many decades. While the baryonic content of the universe is still uncertain, the current Big-Bang nucleosynthesis value of $\Omega_b h^2 = 0.02$ (Burles and Tytler 1998) is much larger than the observed stellar density $\Omega_* h = 0.0025$ (Fukogita et al. 1997). In recent years, the large gas mass in clusters of galaxies (White et al. 1993) has uncovered a diffuse reservoir of baryons. Since the gas
fraction in clusters should be representative of the global mean, this hot diffuse component of baryons could account for the majority of baryons in the universe. Barcons et al. (1991) first applied the soft X-ray background (XRB) constraints to the IGM. Since their work, the major portion of the XRB has been resolved into point sources (Hasinger et al. 1993), strengthening the bound. We here present new aspects to the argument by estimating the temperature with the cosmic virial theorem, and calculating the clumping factor directly through numerical simulations and Press-Schechter estimates. These two ingredients rule out a passively evolving IGM where the energetics are dominated by gravity. We discuss these constraints in more detail in section 2. Using our galaxy as a representative gravitational well, we place constraints on the non-gravitational heat injection required to explain the small observed XRB contribution from our halo in section 4. In section 5 we discuss predictions and implications of the model. It explains the luminosity-temperature relation in clusters of galaxies, and predicts a very sudden heating period for each galaxy.

2. Cosmological X-ray background

The cosmological background flux is

\[
F = \Omega_b^2 \rho_c^2 \epsilon_{\text{ff,bol}} \int_0^{\infty} \frac{T_{1/2} (\delta^2) (1+z)^3}{4\pi d_L^2} \frac{d_A}{dz} \frac{d_L}{dz} \frac{d r}{d z} \frac{d A}{d z} \frac{d z}{dz} \frac{\text{erg}}{\text{cm}^2 \text{s str}}
\]

where \(d_A\) and \(d_L\) denote the angular diameter and luminosity distance respectively, related by \(d_L = (1+z)^2 d_A\). \(\rho_c \equiv 3H_0^2/8\pi G\) is the critical closure density of the universe. \(\delta\) is the local overdensity of the gas which is related to \(\langle \delta^2 \rangle = \xi(0)\) in terms of the correlation function at zero lag. The volume emission coefficient \(\epsilon_{\text{ff,bol}} \sim 1.7 \times 10^{-42} c_Z/0.875m_p^2\) (Rybicki & Lightman 1979) is expressed in terms of the proton mass \(m_p\) at a solar hydrogen-helium mixture with a coefficient \(c_Z \sim Z/Z_\odot (4\text{keV}/T) + 1\) to correct for metal cooling (Raymond et al. 1976). The approximation for \(c_Z\) is accurate to 20% in the interval 0.01 keV < \(T\) < 10 keV. We have assumed a mean gaunt factor \(g_{\text{ff}} \sim 1.2\). We will use the \(Z = Z_\odot/4\) as the lower plausible limit on the intergalactic medium inferred from clusters of galaxies. Higher metallicities strengthen the bounds derived here.

In a flat universe with a powerlaw correlation function \(\xi = (r/r_0)^{-1.8}/(1+z)^2\) the characteristic temperature evolves as \(T_{1/2} \propto (1+z)^{-0.6}\), and is expected to evolve more slowly in a low density model. To simplify (1), we neglect this weak redshift dependence. We express the integrand in terms of \(\tau_0 \equiv t_0 H_0\), the age of the universe in units of the Hubble constant. Recall that \(\tau_0 = 2/3\) for a flat universe and \(\tau_0 = 1\) for an empty universe.
Since $F = \xi(0)\Omega_b\rho_c^2\epsilon_H\tau_0 c/H_0$, we find in differential energy units
\[
F = \xi(0)\left(\frac{\Omega_b h^2}{0.02}\right)^2\left(\frac{T}{0.13 \text{ keV}}\right)^{-1/2}\frac{\tau_0}{h}\exp\left(-\frac{h\nu}{kT}\right)\left(\frac{\text{keV}}{T^2}+1\right)\frac{0.16 \text{ keV}}{\text{cm}^2 \text{ s str keV}}.
\] (2)

X-ray emission is proportional to the square of the density. Its emission weighted temperature is well approximated by the pair weighted temperature given be the cosmic virial theorem (Peebles 1980) \(\langle T^{1/2}\rangle = \frac{\sigma_8^{0.5}}{0.54}\left(\frac{r_g}{100 \text{ kpc}}\right)^{0.2} \times 0.128 \text{ keV}\) where \(r_g\) is a short scale cutoff of the gas autocorrelation function. From the cluster abundance (Pen 1998b), we use \(\sigma_8 = 0.53\Omega^{0.55}\), and use the approximation \(\langle T\rangle_X = 0.13 \text{ keV}\).

The observed extragalactic XRB at 1/4 keV has an upper limit of 15 keV/cm\(^2\) s keV str (Cui et al. 1996). From shadowing studies, they found an extragalactic background of 45 keV/cm\(^2\) s keV str, of which at least 30 keV/cm\(^2\) s keV str has been resolved into point sources (Hasinger et al. 1993). Using \(\tau_0/h = 1\) and taking into account a factor of 2 suppression of the flux due to the energy dependent Gaunt factor (Rybicki and Lightman 1979), we obtain the main constraint
\[
\xi(0) < 60.
\] (3)

A less certain prediction is the clumping factor \(\xi(0)\). For a scale invariant spectrum in a flat universe, this is expected to be constant in time. According to Press-Schechter theory, most of the mass is in collapsed and virialized objects of approximately the non-linear mass scale. The average overdensity of collapsed objects is at least 178, and generally higher if the objects are not homogeneous or have collapsed at higher redshift. We expect at least a factor of two higher clumping, since virialized objects are certainly not uniform density objects. Estimates using stable clustering (Jain 1997) and numerical pure N-body simulations indicate that at least for the dark matter component, \(\xi(0) \gtrsim 10^4\). With these values, we far exceed the observed diffuse soft XRB constraints. If the distribution of gas traces light down to scale \(r_g\), and then forms a constant density core, we find \(\xi(0) = (r_g/5.5h^{-1}\text{Mpc})^{-1.8}\). Using (3) we find \(r_g > 800h^{-1}\text{ kpc}\), i.e. gas does not cluster on scales shorter than a Mpc, even though all other forms of matter do.

We can compare these estimates with direct numerical simulations (Cen et al. 1995). Scaling their Figures 3 and 4 to the cosmological XRB by multiplying the vertical abscissa by \(5 \times 10^{38}\) to obtain units of keV/cm\(^2\) s str keV, we find that they predict emission just below the observed upper bounds. Emission is weighted by the smallest scale clumping, which simulations at finite resolution always underestimate. We can see the effect in their Figure 8. Their COBE normalized simulation should predict \(\rho^2\) weighted temperatures of \(\sim 0.3\) keV, while the simulated temperatures are significantly higher. Increasing the resolution would primarily enhance the emission of smaller mass and lower temperature.
objects, which are smaller and more subject to numerical limitations. It would also raise
the clumping factor and X-ray emission. More recent simulations may move the results in
the expected direction (Cen and Ostriker 1998).

Using the cosmological Moving Mesh Hydro Code (Pen 1998a), we have performed
direct simulations to measure $\xi(0)$. We use a scale-free CDM models with $128^3$ grid cells
and an equal number of dark matter particles. The correlation function is $\xi \propto (r/r_0)^{-1.8}$
with $r_0 = 4 \, h^{-1}\text{Mpc}$ in a $16 \, h^{-1}\text{Mpc}$ box. In order to extend the dynamic range, the initial
conditions were determined by factoring the correlation function (Pen 1997). The grid was
allowed to compress a factor of 10, giving a minimal grid spacing of $13 \, h^{-1}\text{kpc}$, with an
effective resolution which is several times that value. We used $\Omega_b = 0.1$. In Figure 1 we plot
the gas correlation function $\xi(r)$ at different redshifts scaled to their relative amplitudes
using scale invariance. The simulation moves from the lower right to the upper left as
the non-linear mass scale grows, and the effective resolution increases. We see that the
clumping factor is limited by the initial resolution at all times. The clumping factor $\xi(0)$
monotonically increases with time, reaching a value of $\sim 900$ at $z = 0$ when the non-linear
mass scale reaches $32$ grid cells. Our limited resolution allows us to only place a lower
bound on $\xi(0) > 900$. One would expect low density models to have higher clumping factors
since objects formed earlier.

We must thus conclude that the gas could not have followed the gravitational evolution
of the dark matter, as one would have expected in the scenario of purely gravitationally
driven collapse. Two potential solutions come to mind. Baryons could have cooled into
compact objects which do not contribute to the XRB. But this poses problems for clusters
of galaxies, where vast quantities of gas have been observed (White et al. 1993). In a
hierarchical model of structure formation, clusters form from the merger of smaller objects.
But if the smaller objects had their baryons locked up into compact objects, it would be
very difficult to release the gas again to form the Intra-cluster medium (ICM).

The second solution would be to heat the gas sufficiently, such that it does not fall
into the gravitational potential well of the dark matter halos. The required energies can
be estimated from the two-point correlation function. We calculate the energy required
to convolve the gas with a spherical tophat to satisfy (3). For a gas distribution $\rho_g$ in a
dark matter potential $\phi$, we have $E = \int \rho_g \phi$, which for our power law correlation formally
diverges due to long wavelength contributions. We consider a specific model in which a
smoothed density distribution is given as a convolution over the original gas field. The
change in energy is finite, in fact $\Delta E = \int \Delta \rho_g \phi$ and the average specific energy change is
$\Delta \mathcal{E} = \Omega_0 \rho_c 4\pi G r_0^3 \int W(r/r_0)\xi(r/r_0)d^3(r/r_0)$. We let $W$ be a spherical tophat of radius $r_g$.
Using $\sigma_8$ from above, we obtain $\Delta \mathcal{E} = 0.8 \times 3(5 - n)^{-1}(3 - n)^{-1}(2 - n)^{-1}(r_g/r_0)^{2-n}$ keV,
where \( n \sim 1.8 \). The constraint for the smoothed gas field simply translates to \( \sigma_g^2 \lesssim 60 \), which can again be expressed in terms of the correlation function \( r_g > 823 \sigma_{v_g}^{10/9} h^{-1} \text{kpc} \). In this model, approximately 2 keV of heating would be required to satisfy the constraints from the XRB. This assumes that smoothing was applied to all points in space, which probably overestimates the energy requirement. We obtain a lower energy bound by just truncating the correlation function, so that \( \xi(r) = (r_g/r_0)^{-1.8} \) for \( r < r_g \). This requires 0.25 keV, but must be taken as a lower limit since it violates locality. We will now proceed to build a more realistic model which allows us to quantify the heat injection required to evade the bound from equation (3).

3. Halo Model

We will consider a model for the distribution of gas within each halo. We assume the gravitational potential to be dominated by dark matter with a singular isothermal sphere mass distribution. The mass-rotation relation for the dark matter is taken from the isothermal Press-Schechter model (Eke, Cole and Frenk 1997)

\[
M = \frac{v_c^3}{4\pi G} \left( \frac{3}{4\pi\Delta \rho_c} \right)^{1/2} .
\]

\( v_c \) is the circular rotation speed of the object. The virial radius \( r_\Delta \) of an object is defined as the fiducial point where the mean interior density is \( \Delta \sim 178 \Omega^{-1/2} \) times the mean cosmological density. It corresponds to half the turnaround radius of a top hat model. For an isothermal sphere \( r_\Delta = v_c \sqrt{\frac{3}{4\pi G \rho_c \Delta}} \). The gas is assumed to have two phases: an outer region \( r > r_1 \) where gas traces mass isothermally with a gas fraction \( f_g \), and an inner region where the gas has been heated to constant entropy. Such a distribution is the generic outcome of central non-gravitational heating where entropy is injected in the center, which is then convectively transported outward. Observationally (Danos and Pen 1998, Cooray 1998), the best fit for the gas fraction is \( f_g = 0.06 h^{-3/2} \). For the outer region, the gas density profile is given by an isothermal sphere \( \rho_g = f_g v_c^2/4\pi r^2 G \). In the inner region \( r < r_1 \), the gas density is then \( \rho_g = \frac{v_c^2 f_g}{4\pi G} \left[ 1 + \frac{12}{25} \log\left( \frac{r_1}{r} \right) \right]^{3/2} \). We can define an equivalent core radius \( r_c = 0.487 r_1 \). For this choice, the free-free luminosity of the two phase object is identical to an isothermal \( \beta = 2/3 \) model with core radius \( r_c \) (Jones and Forman 1984). \( L_X = \epsilon_{ff} f_g^2 v_c^4 T^{1/2}/(16 r_c G^2) \). Due to the enhanced central entropy, the emission weighted temperature of our objects will be 10% higher than the isothermal temperature \( \langle T \rangle_X = 1.1 \times \mu m_p v_c^2/2k \). We can estimate the energy required to increase \( r_1 \). We calculate the difference in binding energy between a singular isothermal gas distribution in the dark matter well, to one with finite \( r_1 \). While the energy injection in our model is concentrated to the center, we define a mean energy \( \delta T \) to be the total injected energy divided by the total virial gas mass. We obtain \( r_\Delta = 1.582 \left( 1 - \sqrt{1 - 1.029 \frac{\delta T}{T}} \right) \). In the limit of \( \delta T/T \ll 1 \), we find \( r_\Delta = 0.814 \delta T/T \). The
clumping factor \( C \) of an individual object is \( C = \frac{\Delta}{3} \left( 1.553 \frac{\Delta}{r_1} - 1 \right) \) and in the limit that \( T_1 \ll T \), we have the linear relation \( C = 0.52T\Delta/\delta T \). We find the average clumping factor \( \langle C \rangle = \xi(0) = \int_0^\infty \frac{df}{dT}C(T)dT \) where the lower cutoff assumes that objects with energy injection larger than their virial temperature have ejected all their gas. The Press-Schechter distribution function is \( f(> M) = \sqrt{\frac{2}{\pi}} \int_0^\infty \sigma e^{-u^2/2}du \). We use the standard value \( \delta_c = 1.686 \). Using a power law mass fluctuation spectrum \( \sigma(M) = (M/M_8)^{-\alpha} \) (Pen 1998b), we find

\[
\langle C \rangle = 3 \frac{\sqrt{2T}}{\pi \delta T} 0.518\alpha \delta_T \Delta \left( \frac{2\sigma_8}{\delta_c} \right)^{\frac{2}{3}} \int_{w_1}^\infty w \frac{1}{3}\frac{4}{2} e^{-w}dw
\]

(4)

where \( T_8 \sim 5\Omega_0^{2/3} \) (Pen 1998b) and \( w_1 = \delta_2^2(\delta T/T_8)^{3\alpha}/2\sigma_8^2 \). For most CDM-like spectra, \( \alpha \sim 1/3 \), which simplifies the (4) to \( \langle C \rangle = 100 \frac{\Omega_0}{H_0^{1/2}} \times \left[ 2\sqrt{w_1}e^{-w_1} + \sqrt{\pi} \text{erfc}(\sqrt{w_1}) \right] \) keV where now \( w_1 = 5\Omega\delta T/T \). The leading order expansion of the bracket in is \( \sqrt{\pi} - (4w_1^{3/2}/3) \). We can compare the predicted clumping to the constraint (2). By assumption, all gas has a temperature of \( \gtrsim \delta T \). For an \( \Omega = 1 \) scenario, we can satisfy the diffuse XRB constraint at 1 keV for \( \delta T \gtrsim 1 \) keV. We used an extragalactic diffuse flux limit of 8 keV/cm\(^2\) s str keV (Hasinger et al. 1993) at 1 keV.

4. Galactic X-ray background

While the cosmological constraint depends on parameters including geometry of the universe and the evolution of the clumping, our own Galaxy provides a completely independent constraint on the thermal state of the intergalactic medium. Simulations (Navarro et al. 1995) and observations indicate that the matter distribution is well approximated by an isothermal sphere extending from ca 1/10th of the virial radius out to the virial radius. In that range, gas and dark matter do appear to trace each other to within a factor of two, and are within a factor of two of the singular isothermal sphere. Approximating our solar system to be at the center of the gravitational galaxy halo, we find

\[
F = \epsilon T^{1/2}r_1 \left( \frac{v_c^2 f_g}{4\pi G r_1^2} \right)^2 \left[ \frac{1}{3} + \int_0^1 \left( 1 - \frac{12}{25} \log u \right)^{7/2}du \right] \frac{\text{erg}}{\text{cm}^2 \text{ s str}}.
\]

(5)

To support the outer gas in pressure equilibrium, the central gas will have a temperature higher than the virial halo temperature. The emission weighted temperature seen at the center differs from the virial temperature, becomes instead \( T_X = 2.25 \times \mu m_p v_c^2/2k \), more than twice the isothermal value. For a rotation speed of 220 km/s, we expect \( T_X = 0.34 \) keV, independent of the core radius \( r_1 \) as long it is greater than the heliocentric distance: \( r_1 \gg R_0 \).
The 1/4 keV galactic background is known to be dominated by the local hot ISM bubble, which is difficult to disentangle from a halo distribution. Instead, we will use the 1 keV background constraint, for which \( F = \frac{0.003}{(h^3 r_1^3)} \) keV/cm\(^2\) s str keV. \( r_1 \) is measured in Mpc. Current reports lie near 20 keV/cm\(^2\) s str keV (Miyaji et al. 1998), of which Hasinger et al. (1993) constrain the homogeneous component to less than 20%. This value is lower than the previously used value since the cosmological XRB could be clumped. The lower limit for the heated core radius is \( r_1 > 150 h^{-1} \) kpc. The virial radius of our galaxy is \( r_\Delta = 127 h^{-1} \) kpc, which is smaller than the required core radius. This corresponds to a scenario where all the IGM gas must have been completely expelled from our galaxy. Unbinding the gas from the galactic potential well requires a minimum heat injection of 150 eV per nucleon. We now have two independent lines of evidence that very significant non-gravitational heating of the IGM must have occurred. Supernovae might be one potential energy source which we will discuss further in section 5.

In the calculation of our energy injection estimates, we have taken the binding energy difference between a model where the gas traces the mass to one where it satisfies the XRB constraint. It would seem plausible that this is a lower bound to the actual energy injection required. In addition to the potential energy change, a similar amount of energy may be expended to raise the entropy of the gas. Placing the heating process too early causes some of the injected energy to be lost to cosmic expansion, thus requiring even larger energy inputs. We should also note that in a cosmological context, energy is not strictly conserved, and it is in principle possible to extract energy from the dark matter through its time dependent potential. Simulations seem to suggest that gas traces the total mass up to overdensities of at least 10\(^3\) (Navarro et al. 1995), suggesting that in fact this energy exchange process does not play a dominant role. We assumed that objects formed recently. An earlier formation time would increase the clumping factor, and raise the predicted X-ray emission.

5. Potential Tests

We now consider several predictions of the violent heating model. We have assumed an equal specific energy injection in all objects independent of mass. This model predicts the core radius \( r_c \propto T^{-1} \), which can be compared to the cluster luminosity-temperature relation. From the equations in section 3, \( L_{44} = 2.1 h^{-2} \Omega^{-1/4} \left( \frac{T}{5 \text{ keV}} \right)^3 \left( \frac{\text{keV}}{\delta T} \right) \times 10^{44} \text{erg/s} \) which can be compared to the Henry and Arnaud (1991) data. Their relation is consistent with the slope \( L \propto T^3 \), and agrees for values of \( \delta T \sim 1 \) keV. Metzler and Evrard (1994) had studied numerical simulations with similar parameters and arrived at consistent conclusions. In
this simplest model where the heating is uncorrelated with the mass of the object, we find that the required heating to explain the cluster core radii can simultaneously explain the soft XRB.

If the current spatial stellar distribution is a tracer of the heat source distribution, we obtain an upper limit on the heating time scale to be the cooling time of the gas. The observed metallicities in clusters is about 1/3 solar, suggesting that approximately 1% of the gas had undergone nuclear burning, releasing a few MeV of kinetic energy for each burnt nucleon. We have a mean energy injection about 10 keV for the gas, of which 10% must remain after radiative and adiabatic losses. We require that the heating time not be more than 10 times longer than the cooling time in order for the injected heat to be retained. The local luminosity density in the disk is \( \sim 0.07 L_\odot/pc^3 \) (Binney and Tremaine 1987). Our galaxy has a virial mass of \( 2.6 \times 10^{12} M_\odot \), and using the cosmological gas fraction \( f_g \) from above, we expect a total gas mass of \( 1.6 \times 10^{11} h^{-3/2} M_\odot \). At a total luminosity of \( 1.4 \times 10^{10} L_\odot \), we have a mean gas to light ratio of \( 11 h^{-3/2} M_\odot/L_\odot \). We expect a cooling time of \( t_{\text{cool}} \sim 2.8 \times 10^5 \left( \frac{M_\odot}{L_\odot} \right) \) years assuming a temperature \( T = 1 \) keV. Allowing 90% of the injected energy to dissipate radiatively, we need to inject the energy in \( \delta t = 10 t_{\text{cool}} \). We infer that the heating must have occurred over \( \sim 10^7 \) years.

Each supernova injects about ten \( M_\odot \) of metals, so we expect \( \sim 10^8 \) supernovae in the cooling time. We draw two conclusions: 1. there must have been a short burst of very active star formation and supernova explosions, during which about 10 supernovae detonated per year. 2. the galaxy would have been at least ten times brighter during this period since only stars of \( M/L < 1 \) will burn out. The epoch of this explosive heating is not constrained, and different galaxies may burst at different times. We do predict that a small fraction \( (\sim 10^{-3}) \) of all galaxies at high redshift \( (z > 1) \) undergo enormous supernova bursts. Dust obscuration can weaken these luminosities.

6. Conclusion

We have shown that the current constraints from the XRB significantly constrain the current thermal state of the intergalactic medium. The absence of significant emission from our galactic halo places a lower bound of 0.15 keV energy injection. A stronger constraint arises from the absence of diffuse intergalactic emission, for which the emission in enhanced by the clumping factor of the gas. We found that a mean energy injection of \( \delta T \gtrsim 1 \) keV is required. Photoheating is not a possible solution. Such a process would raise the temperature of the gas to \( \sim 0.002 \) keV. In the best possible case, this heating occurred at \( z \sim 0 \), and the objects instantaneously collapse today. The XRB constraints require that
the overdensity be less than 100, for which adiabatic compression can raise the energy
to at most 0.04 keV, far short of the required heat input. Our halo model also accounts
for the observed cluster luminosity-temperature relation if $\delta T \sim 1$ keV. The cosmological
diffuse XRB should be detectable soon at temperatures near 1 keV. This is consistent with
past simulations (Metzler and Evrard 1994, Suginohara and Ostriker 1998). If the heating
process traced the present day light distribution, we obtain upper limits on the heating
time scale, which predicts galaxies undergoing short violent supernova bursts at $z > 1$.

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REFERENCES

Barcons, X., Fabian, A.C., Rees, M.J. 1991, Nature, 350, 685.

Binney, J. and Tremaine, S. 1987, “Galactic Dynamics”, Princeton University Press.

Burles, S. and Tytler, D. 1998, ApJ, 499, 699.

Cen, R., Kang, H., Ostriker, J.P. and Ryu, D. 1995, ApJ, 451, 436.

Cen, R. and Ostriker, J.P. 1998, preprint, astro-ph/9806281

Cooray, A. 1998, A& A, 333, 71.

Cui, W., Sanders, W.T., McCammon, D., Snowden, S.L., Womble, D.S. 1996, ApJ, 468,
117.

Danos, R. and Pen, U. 1998, astro-ph/9803058.

Eke, V.R., Cole, S., Frenk, C.S. 1996, MNRAS 282, 263.

Fukugita, M., Hogan, C.J. and Peebles, P.J.E. 1998, astro-ph/9712020

Hasinger, G., Burg, R., Giacconi, R., Hartner, G., Schmidt, M., Trümper, J., and Zamorani,
G. 1993, A& A, 275, 1.

Henry, J.P. and Arnaud, K. 1991, ApJ, 372, 410.

Jain, B. 1997, MNRAS, 287, 687.
Jones, C. & Forman, W. 1984, ApJ, 276, 38.

Metzler, C.A. and Evrard, A.E. 1994, ApJ, 437, 564.

Miyaji, T., Ishisaki, Y., Ogasaka, Y., Ueda, Y., Feyberg, M.J., Hasinger, G. and Tanaka, Y. 1998, A& A, 334, L13.

Navarro, J.F., Frenk, C.S. and White, S.D.M. 1995, MNRAS, 275, 720.

Peebles, P.J.E. 1980, “The Large Scale Structure of the Universe”, Princeton University Press.

Pen, U. 1997, ApJ, 490, L127.

Pen, U. 1998a, ApJS, 115, 19.

Pen, U. 1998b, ApJ, 498, 60.

Raymond, J.C., Cox, D.P., Smith, B.W. 1976, ApJ, 204, 290.

Rybicki, G. & Lightman, A, 1979, Radiative Processes in Astrophysics, (John Wiley & Sons).

Suginohara T. and Ostriker, J.P. 1998, astro-ph/9803318.

White, S.D.M., Navarro, J.F., Evrard, A.E., & Frenk, C.S. 1993, Nature, 366, 429.
Fig. 1.— Numerical estimates of the correlation function clumping factor $\langle C \rangle = \xi(0)$ for gas in adiabatic scale free simulations. The solid lines show the correlation function in the simulation at redshifts $z = 180, 16, 4, 1, 0$ scaled to the appropriate non-linear mass scale. The dashed line is the scale free correlation for $n = -1.8$ and $r_0 = 4 \, h^{-1}\text{Mpc}$. We see that the simulations are still limited by resolution, and give a lower bound of $\langle C \rangle \gtrsim 900$. This rules out passively evolving IGM models, and requires significant active heating to evade soft XRB constraints.