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A BOUND ON X-RAY EMISSION FROM THE INTRASUPERCLUSTER MEDIUM

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ABSTRACT

The Bahcall-Soneira complete sample of superclusters was searched for X-ray emission in the *HEAO 1* A-2 data base. No statistically significant emission from diffuse intrasupercluster gas was detected; a 3 σ upper limit to the mean individual flux is 10^{-11} ergs cm^{-2} s^{-1}. Implications of this bound to measurements of the Zeldovich-Sunyaev effect toward clusters within a supercluster and to the supercluster contribution to the cosmic X-ray background are discussed.

Subject headings: cosmic background radiation — cosmology — galaxies: clustering — X-rays: sources

I. INTRODUCTION

In recent years there has been a growing interest in agglomerations—binaries, groups, clusters and clusters of clusters of galaxies. These systems, which constitute the upper end of the known clustering hierarchy, have come to be known as superclusters (hereafter SC). Their study (for a review, see Oort 1983) is in its infancy, but it is quite clear that SC could not have attained a degree of relaxation which is anywhere comparable to that of clusters. In this regard SC are fundamentally different from galaxies and clusters.

Clustering on the very largest scales is of basic importance in theories for the evolution of structure in the Universe (Blumenthal *et al.* 1984; Davis 1985; Persic and Salucci 1987). Such issues as the behavior of the mass-to-light ratio on SC scales, the baryonic content, and the velocity field in SC are of very much cosmological interest. We have very little observational information on the physical conditions of the SC environment, so it is useful to try to infer whatever we can from available data bases. Particularly relevant for inferring the SC baryonic content are, perhaps, X-ray data.

Previous measurements which could be viewed as indicative of intercluster X-ray emission are the measurements of A2147 (Cooke *et al.* 1977) in the Hercules SC, and of A401 (Maccagni *et al.* 1978; Ulmer *et al.* 1979) in the A399–A401 SC. The X-ray centroids of these clusters are offset from the optical cluster centers, as has also been found in the *HEAO 1* A-2 data (Pravdo *et al.* 1979). However, the latter authors were unable to distinguish whether the emission is diffuse intrasupercluster (ISC) or the superposed cluster emission. In their analysis of *Einstein* (*HEAO* 2) observations of the region between A399 and A401 Ulmer and Cruddace (1981) also concluded that the observed emission can be most simply explained as the superposed emission from the two clusters. It has also been claimed that the *Uhuru* data show evidence for emission from three other SC (Murray *et al.* 1978), but this is not supported by the A-2 data (Pravdo *et al.* 1979). Here we report the result of a more extended analysis of the *HEAO 1* A-2 data from a complete sample of SC in the Bahcall and Soneira (1984, hereafter BS) catalog.

II. X-RAY EMISSION FROM SUPERCLUSTERS

The A-2 experiment aboard *HEAO 1* completed two 6 month scans of the entire sky in the 2–60 keV energy range (Rothschild *et al.* 1979). We analyzed the data set for counts in the field of BS complete (out to a redshift $z \approx 0.08$) sample of SC. Counting rates for all 18 SC centroid positions were computed for both complete sky coverages according to a procedure described by Worrall, Marshall, and Boldt (1979). The field of view ($3° \times 1\overset{\circ}{.}5$) and detector combinations chosen for this analysis are as in Marshall *et al.* (1980).

In order to avoid contamination by known, bright X-ray sources with fluxes above 1.25 $R15$ counts per second,[3] all positions with 6° from such sources were discarded from the final analysis. This criterion also excludes those SC where a member cluster separated less than 6° from the centroid is itself a bright X-ray source (Piccinotti *et al.* 1982). As a result, 10 fields (BS 1, 3, 5, 6, 7, 8, 9, 10, 11, 13) were included in the final analysis. Best-estimate 2–10 keV fluxes were calculated for each field in the manner described by Worrall and Marshall (1984). Averaging the photon fluxes over the 10 SC, we obtain a mean energy flux (2–10 keV) per SC of $5.2 \pm 2.1 \times 10^{-12}$ ergs cm^{-2} s^{-1}, for a thermal bremsstrahlung spectrum characterized by $kT \approx 10$ keV. In order to check possible systematic effects, the same procedure was applied to 940 high galactic latitude ($|b| > 20°$), randomly selected fields void of known X-ray sources. The mean flux over this sample of "empty" fields, $1.4 \pm 0.2 \times 10^{-12}$ ergs cm^{-2} s^{-1}, was then subtracted from the SC mean as a systematic offset. The net mean SC flux is then $f = 3.8 \pm 2.1 \times 10^{-12}$ ergs cm^{-2} s^{-1}. By the Kolmogorov-Smirnov test, the hypothesis that the SC and the control fields are not drawn from the same sample is correct at the 98% confidence level.

The above value for possible SC emission includes contributions from member clusters whose flux is below 1.25 $R15$ s^{-1} but may contribute at the centroid position due to the (finite) collimator's angular width. In order to check dependence of the result on explicit accounting of the member clusters' contributions, we reanalyzed the data for the fields where the constituent clusters are an angle $\theta > 3°$ (collimator's resolution) but

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[3] One $R15$ count per second corresponds to an energy flux over the 2–10 keV band equal to 2.5×10^{-11} ergs cm^{-2} s^{-1} for a typical Abell cluster and 2.2×10^{-11} ergs cm^{-2} s^{-1} for a typical AGN (Piccinotti *et al.* 1982).

$\theta < 6°$ (collimator's width) away from the centroid position. Contributions to the flux at the positions of SC members within this annulus were subtracted out. Doing so, however, has not significantly affected our deduced value for f.

Thus, diffuse emission from the BS superclusters has not been found in the A-2 data at a statistically significant level, and a 3 σ upper limit is

$$f < 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1} . \quad (1)$$

III. DISCUSSION

We have obtained an upper bound on the (presumably) diffuse X-ray emission from 10 BS superclusters. The richness of a SC obviously is a matter of definition; BS consider cluster density enhancements (over the background) as SC if the enhancement factor, A is ≥ 20. From Table 1 of BS, it is seen that for $A \geq 20$, eight of the 10 sampled SC each contain two rich, Abell clusters. The other two have four and five such members. Therefore, our comments below are preliminary.

The SC in the BS sample are small groups of rich clusters. The least extended of these have intercluster separations of about 20 Mpc. The mass-to-(blue)-light ratio of SC seems to be higher than that of clusters (Davis *et al.* 1980 and references therein). If the baryonic mass fraction in SC is about the same as in clusters (Blumenthal *et al.* 1984), then the mass fraction in hot gas in the intrasupercluster (ISC) space is comparable to its value in clusters. And if the ISC material has a more regular distribution than the (rich) member clusters, then a radial extent, $R \approx 10$ Mpc may serve as a typical scale for the more compact SC. Having few clusters each, the mass of a SC in the sample, M is $O(10^{16}\ M_\odot)$. With these values of M and R, the velocity field would have a characteristic dispersion of $O(10^3$ km s$^{-1})$ if the SC attained some degree of virialization. It is interesting that Bahcall, Soneira, and Burgett (1986) find some evidence for velocities in this range. The ISC gas temperature corresponding to this velocity is $O(10^8$ K), which is also within the expected temperature range for the gas in the member clusters. Even if velocities of clusters within SC were lower, the temperature of the ISC gas is still expected to be of $O(10^8$ K). This clearly follows if the gas originated in clusters, but perhaps also if it has an intergalactic origin. Nevertheless, in our estimates we take 10^8 K to be but an assumed, nominal value for T.

The mean redshift (weighted according to $1/z^2$) of the SC in the BS sample is 0.05, so that the mean 2–10 keV X-ray flux is

$$f \approx 8 \times 10^{-12}(h_{50})^2(M/10^{16}\ M_\odot)^2(R/10 \text{ Mpc})^{-3}(\eta/0.1)^2 \text{ ergs cm}^{-2} \text{ s}^{-1} , \quad (2)$$

where η is the baryonic mass fraction and $h_{50} = H_0/(50 \text{ km s}^{-1} \text{ Mpc}^{-1})$ for the Hubble constant (H_0). Before this estimate (eq. [2]) for the mean flux is compared with the upper limit given by equation (1), it should be noted that any degree of central concentration in a spherical distribution of gas would yield a higher flux. Merely as an illustration, consider a uniform temperature ISC gas with spatial profile $n = n_0(1 + \zeta^2)^{-1}$, where ζ is the distance from the center in terms of the core radius, a; viz: $\zeta = R/a$. For $R = 10$ Mpc and $a = 1$, 2, and 4 Mpc, the flux is higher than that from uniformly distributed gas by a factor of 3.1, 1.9 and 1.3, respectively. Supposing the gas is not very centrally concentrated, the upper limit (1) implies that

$$(h_{50})^2(M/10^{16}\ M_\odot)^2(R/10 \text{ Mpc})^{-3}(\eta/0.1)^2 < 1 . \quad (3)$$

It is interesting to estimate the magnitude of the Zeldovich-Sunyaev (ZS) effect due to ISC gas, and also to determine to what extent the measurements of the effect along a line of sight to a member cluster are affected by ISC gas. The effect—distortion of the cosmic microwave background (CMB) spectrum due to Thomson scattering of the photons by hot IC electrons (Zeldovich and Sunyaev 1969; Sunyaev and Zeldovich 1972; Gould and Rephaeli 1978)—is differentially measured. By beam chopping, the CMB intensity along a reference line of sight away from the center of a gas-rich cluster is subtracted from the intensity along a line of sight through the center. ISC gas introduces an additional distortion which may appreciably contaminate the reference beam. All the spatial dependence of the effect is in the Thomsonization parameter,

$$y = \int (kT_e/mc^2) n_e \sigma_T \, dl , \quad (4)$$

where T_e and n_e are the electron temperature and density, and σ_T is the Thomson cross section; the other symbols have their usual meaning. The integral is along a line of sight through the SC. As long as the ISC gas has a uniform distribution over distances within the beam-throw angle, it will have no net effect on the measured cluster signal. In general, however, this may not be the case.

The SC Thomsonization parameter can be easily estimated for a uniform distribution of the ISC gas at a temperature T, viz.,

$$y \approx 7 \times 10^{-6}(M/10^{16}\ M_\odot)(R/10 \text{ Mpc})^{-2}(\eta/0.1)(T/10^8 \text{ K}) . \quad (5)$$

Hence, for the Rayleigh-Jeans portion of the spectrum, the relative CMB temperature change is $\Delta T/T \approx 2y \approx 10^{-5}$ if the quantities in equation (5) assume the values to which they are scaled. By comparison, the value of y for the Coma cluster is $y \approx 10^{-4}$ (Rephaeli 1987). Thus, the ZS effect is weaker in SC than in a gas-rich cluster, unless M is larger and R smaller than their respective scaled values. As this is a possibility, the additional distortion caused by ISC gas may be detectable in the richer and more compact SC. In such SC, the measurement of the ZS effect toward a member cluster may be contaminated by the ISC gas. In particular, this will be the case if the cluster position in the SC is such that the reference lines of sight are mainly in direction of the SC center, while the line of sight through the center of the cluster is away from that direction.

Finally, the statistical completeness of the BS sample allows us to calculate an upper bound on the contribution of SC to the cosmic X-ray background. For a flat 2–10 keV spectrum (which roughly applies to a thermal bremsstrahlung source with $kT \gg 10$ keV) and no SC luminosity or number evolution, we find that the 3 σ upper limit to the contribution of SC to the surface brightness of the background is

$$\delta I_{SC} \leq 2 \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} . \quad (6)$$

This value has been obtained from our limit in equation (1) by applying expressions (5.53), (5.55), and (5.56) presented by Boldt (1987). The surface brightness of the residual background which results after subtraction of the estimated contributions of active galactic nuclei and clusters of galaxies (Leiter and Boldt 1982) in the 2–10 keV band is

$$1 \approx 0.4 \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} . \quad (7)$$

Based on our estimate in equation (6), it would seem that the

SC population represented by the BS sample contributes at most 1% to the (residual) X-ray background. Clearly, if SC formed very recently, at $z < 1$, then the 1% figure is an overestimate. On the other hand, if SC are older structures still partaking in the Hubble expansion, and undergoing luminosity evolution, then the above evaluation could be an underestimate of the SC contribution to the X-ray background.

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