EVIDENCE FOR X-RAY EMISSION FROM A LARGE-SCALE FILAMENT OF GALAXIES?

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ABSTRACT

Cosmological simulations predict that a large fraction of the baryonic mass of the universe exists as $10^7 - 10^8$ K diffuse, X-ray-emitting gas, tracing low-density filament and sheetlike structures exterior to massive clusters of galaxies. If present, this gas helps reconcile the current shortfall in observed baryon counts relative to the predictions of the standard big bang model. We present here the discovery and analysis of a 5 σ significance half-degree filamentary structure, which is present in both the $I$-band galaxy surface density and the unresolved X-ray emission in a deep ROSAT PSPC field. The estimated diffuse X-ray emission component of this structure has a surface brightness of $\approx 1.6 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ arcmin$^{-2}$ (0.5–2 keV), comparable to the predictions for intercluster gas, and may represent a direct detection of this currently unconfirmed baryonic component.

Subject headings: cosmology: observations — large-scale structure of universe — X-rays: galaxies

1. INTRODUCTION

Low-density, large-scale, filamentary, and sheetlike structures are seen in the space distribution of galaxies and are expected in many models of structure formation (e.g., cold dark matter). Recent simulations (Cen & Ostriker 1993, 1999; Scaramella, Cen, & Ostriker 1993; Bryan et al. 1994) suggest that low-density gas exists in such structures and can be shocked to $10^7 - 10^8$ K without violating microwave background spectral distortion constraints (Wright et al. 1994; Cen & Ostriker 1993). Furthermore, in order for the observed baryon "budget" (Fukugita, Hogan, & Peebles 1998) to match the detailed predictions of big bang nucleosynthesis, we might expect at least ~50% of present-day baryons to be in the form of these warm and hot plasmas.

Attempts to detect X-ray emission from filaments that might connect clusters (Briel & Henry 1995) have yielded an upper limit to the emission of $4 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ arcmin$^{-2}$ (at a 2 σ significance). Studies of a likely supercluster sheet at $z \approx 0.25$ have yielded evidence for X-ray gas below 1 keV in a fairly localized, diffuse structure (Wang, Connolly, & Brunner 1997); however, the X-ray surface brightness is more than 10 times higher than that expected from model estimates of the integrated surface brightness originating from warm intercluster gas (Cen & Ostriker 1993, 1999; Bryan et al. 1994; Cen et al. 1995). These fall in the range of $1.5 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ arcmin$^{-2}$, where the major contribution comes from structure at $z \approx 0.2$. Kull & Böhringer (1999) detect evidence for extended emission between a cluster pair in the Shapley supercluster; however, the emission is ~2.5 times brighter than the Briel & Henry (1995) upper limit and may be due to a cluster merger/interaction rather than genuine intercluster gas.

In order to investigate spatial correlations between galaxies and X-ray-emitting intergalactic gas, we have undertaken a complete optical survey of the inner regions of 22 deep fields from the ROSAT PSPC archive (the ROSAT optical/X-ray [ROX] survey; M. Donahue et al. 1999, in preparation). Galaxy counts to a completeness limit of $I$-band $m_i = 23$ have been obtained for the central $30' \times 30'$ region of each field.

In addition to seeking distant galaxy clusters via coincidences of galaxy-space overdensities and X-ray emission, this data set is well suited to investigating the angular cross-correlation $w(\theta)$ of the unresolved X-ray background with the distribution of optical galaxies; $w(\theta)$ is a measure of the mean fractional excess X-ray intensity relative to the mean background at an angle $\theta$ from a given galaxy. Extensive information about the composition of the X-ray background and the clustering properties of X-ray luminous sources can then be obtained (see, e.g., Refregier, Helfand, & McMahon 1997 and Almaini et al. 1997). We evaluate $w(\theta)$ independently for each field using a finite-cell estimator (Refregier et al. 1997, eqs. [2] and [6]).

Seven fields in the ROX survey exhibit positive plateaus in $w(\theta)$ at angular scales $\gtrsim 2'$; this result is distinctly different from the expectations of discrete X-ray sources (Refregier et al. 1997; C. Scharf et al. 1999, in preparation). In one of these fields (labeled CL 1603, with equatorial coordinates R.A. = $16^h04^m28^s$, decl. = $+43^d13^m12^s$ (J2000)) and a ROSAT exposure time of 29 ks), we have observed a highly extended optical/X-ray structure. While correlated optical and X-ray structure is seen in other fields, none exhibit the apparently contiguous extent of this ~30' feature.

2. DATA ANALYSIS

We have corrected all ROSAT data for telescope vignetting and jitter using standard exposure maps (Snowden et al. 1992), and the maximum correction within the fields is ~15%. The 0.5–2 keV counts are used (we have attempted to perform a similar analysis using the 0.1–0.5 keV band, but the higher background noise restricts us to measuring uninteresting upper limits), thereby reducing the background contribution from the Galaxy, minimizing the size of the point-spread function, and maximizing the sensitivity to thermal bremsstrahlung emission from warm and hot gas.

Before computing $w(\theta)$ for each survey field or performing the analyses presented here, we remove all identifiable discrete X-ray sources and spurious optical features. We clip, or mask, the X-ray data using a wavelet-based source detection algorithm (Rosati et al. 1995) that finds all sources (extended or pointlike)
down to a signal-to-noise ratio of ~4. The mean surface brightness is then determined in circular annuli about each source, and the X-ray source photons are masked to a radius defined by a surface brightness limit reflecting the background level. The mean value of this limit is $7 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ arcmin$^{-2}$ (0.5–2 keV) over all 22 fields. For the CL 1603 field, it is $1.9 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ arcmin$^{-2}$. Our final measurements are not sensitive to the precise specification of this limit. Bright stars and scattered light in our optical fields are removed by clipping out tainted rectangular areas. The optical and X-ray masks are then combined, and the total mask is applied to both optical and X-ray data sets. There are no obvious correlations between the spatial masking and the apparent filamentary X-ray structure seen in the CL 1603 field, as illustrated in Figure 1.

In order to assess the significance and flux of the morphologically complex structure seen in field CL 1603, we define its boundary using an aperture encircling those regions with a galaxy density greater than 6 galaxies arcmin$^{-2}$ at $I < 22.5$, as shown in Figure 2. The structure’s flux was measured only within the part of this aperture that falls between the dashed lines, and the background X-ray level was estimated using all data exterior to the dashed lines.

The background-subtracted flux of this structure is then $3.1 \times 10^{-3}$ counts s$^{-1}$ (90 counts total), corresponding to $3.6 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ (0.5–2 keV) in an area of 176 arcmin$^2$. Thus the mean excess surface brightness is $2 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ arcmin$^{-2}$. Given the background of $1.6 \times 10^{-4}$ counts s$^{-1}$ arcmin$^{-2}$ (825 counts total in 176 arcmin$^2$), the apparent filament has a signal-to-noise ratio of ~3.

### 3. STATISTICAL SIGNIFICANCE OF FAINT STRUCTURE

An alternative way to assess this structure’s significance is to compare the CL 1603 field with the others in the ROX survey, by computing the excess X-ray flux within similar optically defined apertures. This technique takes into account fluctuations due to all sources, including the “cosmic” variance from field to field and correlations of optical galaxy counts with pointlike X-ray sources too faint to be resolved. We define a flux contrast for each field $\Delta X/X$, which is the fractional excess of X-ray counts relative to the expected background within regions containing greater than 6 galaxies arcmin$^{-2}$. This threshold corresponds to a galaxy density somewhat lower than the mean galaxy density at $I < 22.5$ of 7.28 galaxies arcmin$^{-2}$, as determined from the DEEP sky survey (Postman et al. 1998). Our results are relatively insensitive to this choice, but limits outside of the range 5–8 galaxies arcmin$^{-2}$ encompass too little background/source area to compute a sensible contrast in the fields. The mean flux contrast per field is estimated together with its dispersion, which we assume to be normally distributed for this simple analysis.

First, we test the “null” hypothesis that the CL 1603 structure is a random coincidence by evaluating the mean $\Delta X/X$ over all nonmatched optical/X-ray combinations of the 22 fields. This null hypothesis for the CL 1603 field is rejected at the ~4 $\sigma$ level (Table 1). X-ray emission in the universe is known to be positively correlated with the large-scale distribution of galaxies (Refregier et al. 1997; Almaini et al. 1997), but we do not yet know the relative contributions of discrete X-ray sources (clustered like galaxies) and diffuse, extended sources (gas in groups, clusters, and larger-scale structures). Following the previous work by Refregier et al. (1997), we assume that the 15 ROX survey fields without excess plateaus in $w(\theta)$ are more representative of cases in which the positively correlated X-ray emission is entirely the result of discrete sources that are themselves galaxies, or at least clustered like the observed galaxies. We should therefore expect a systematic (positive) difference between $\langle \Delta X/X \rangle$ for the seven “excess” fields and that for the 15
field, we find $\Delta X/\bar{X}$ to be excessive there at the 2–3 $\sigma$ level. However, these fields could themselves contain diffuse filamentary emission. If instead we establish a statistical baseline using the 15 fields with no large-scale excess, the significance of the CL 1603 structure rises to 4–5 $\sigma$. Taking the results for the 15 field mean (averaging rows 5 and 6 of Table 1) as the best estimate of the nondiffuse flux contrast and subtracting it from the flux contrast measured for CL 1603, we estimate that $\sim 77\%$ of the flux excess in this field may be due to unresolved diffuse emission. Applying this fraction to our previous, direct estimate of the structure’s surface brightness, we estimate that the diffuse X-ray component has a surface brightness of $\sim 1.6 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ (0.5–2 keV).

### 3.1. Cluster and Group Flux Contributions

Some of the X-ray emission in the CL 1603 field could potentially be coming from faint, unmasked X-ray clusters. In order to gauge their effect, we have applied an optical cluster finding algorithm (Postman et al. 1996) to the CL 1603 field (Fig. 2 shows the detections). None of the candidates are associated with resolved, extended X-ray sources with fluxes $\geq 1 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$, although 2, 3, and 4 are marginally coincident with sources identified as pointlike. However, they appear to be correlated with both the galaxy distribution and the enhancements in the unresolved X-ray emission. We have measured the flux in circular apertures defined by the extents of the optical candidates (Fig. 2) and have estimated the background using all data exterior to these regions. The signal-to-noise ratio for each candidate is $\leq 2$, and the 2 $\sigma$ fluxes are $\leq 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$. Consequently, no significant X-ray emission was detected from these individual objects. We note that excluding the flux within the apertures around objects 1, 2, and 3 reduces the total flux from the putative filament to $2.2 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$; however, the mean surface brightness is only reduced to $1.6 \times 10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ arcmin$^{-2}$. Within the Poisson uncertainties, this is therefore unchanged.

We do not know the distance to the structure in the CL 1603 field, but we make the following observations. At $18 < I < 21$, the galaxy density contrast is low compared with the overall ($I < 22.5$) density field, but it appears to trace the structure similarly. At $21 < I < 22$, the density contrast within the structure is significantly higher, and the central regions (near cluster candidates 2 and 3) are the highest peaks in the field. For $21 < I < 22$, the typical redshift would be $z = 0.5 \pm 0.1$ based on the spectrum emitted by a passively evolving elliptical galaxy (Postman et al. 1998). At $22 < I < 23$, the overall density fluctuation contrast is reduced, but again the central regions

### Table 1

**Summary of Mean Flux Contrast Measurements**

| Data Set          | $\langle \Delta X/\bar{X} \rangle$ | Dispersion ($\sigma$) | CL 1603 Relative Significance ($\sigma$) |
|-------------------|------------------------------------|-----------------------|-----------------------------------------|
| CL 1603           | 0.256                              | ...                   | ...                                     |
| Randomized        | 0.002                              | 0.066                 | 3.9                                     |
| 21 fields         | 0.081                              | 0.071                 | 2.5                                     |
| 20 fields (minus 4C 23.37) | 0.086                          | 0.069                 | 2.5                                     |
| 15 fields         | 0.058                              | 0.045                 | 4.4                                     |
| 14 fields (minus 4C 23.37) | 0.063                          | 0.040                 | 4.8                                     |

*For, respectively, the field CL 1603, 462 nonrepeating randomized optical/X-ray data pairings of all 22 fields, all 21 ROX fields excluding CL 1603, all 15 fields not exhibiting large-scale excess in $w(\theta)$, and both data sets not including the field 4C 23.37, which is the only field to exhibit a negative value of $\Delta X/\bar{X}$. The greater than 6 galaxies arcmin$^{-2}$ optical apertures range in size between 10% and 75% of the total field areas.*
and the region close to candidate 1 show the largest enhancements. Estimated cluster-candidate redshifts from the cluster-finding algorithm (Postman et al. 1996) are as follows: (1) \( z = 0.6 \), (2) \( z = 0.5 \), (3) \( z = 0.3 \), and (4) \( z = 0.3 \). Given the expected success rate of \( \sim 70\% \) for correctly identifying real clusters with this method (Postman et al. 1996), it seems reasonable that the structure most likely lies at \( z \gtrsim 0.3 \) and has a physical extent \( \gtrsim 12 h_{50}^{-1} \) Mpc (for \( h_{50} = H_0/50 \) km s\(^{-1}\) Mpc\(^{-1}\) and \( q_0 = 0 \)). Our X-ray wavelet detection limits for extended sources (\( \sim 1 \times 10^{41} \) ergs s\(^{-1}\) cm\(^{-2}\)) implies that the optical cluster candidates could have \( L_X \lesssim (1-4) \times 10^{41} h_{50}^2 \) ergs s\(^{-1}\) (\( q_0 = 0 \)). This further suggests that the observed galaxy enhancement, while possibly containing very X-ray–poor systems, is a genuinely low-density, extended structure.

The original targets of the ROSAT observation, two previously identified high-redshift (\( z \sim 0.9 \)) cluster candidates (Gunn, Hoessel, & Oke 1986; Castander et al. 1994; Oke, Postman, & Lubin 1998), are labeled in Figure 2. The southern cluster is an unresolved X-ray source (Castander et al. 1994) but was not detected optically (<3 \( \sigma \)). The northern cluster is obscured optically by a nearby bright star and was also not detected in X-rays. Neither exhibits any strong correlation with the structure.

4. DISCUSSION

We have detected an apparent filamentary-like structure at \( \sim 3 \) \( \sigma \) significance in X-ray flux and \( \sim 3-5 \) \( \sigma \) significance as a joint X-ray/optical overdensity. If real, the structure is likely to be at \( z \gtrsim 0.3 \) and \( \gtrsim 12 h_{50}^{-1} \) Mpc in size. Although optical cluster candidates are detected in the region, if any are indeed X-ray luminous, then they must be faint, supporting the notion of an extended, low-density system. Our estimate of diffuse large-scale emission (\( 1.6 \times 10^{-16} \) ergs s\(^{-1}\) cm\(^{-2}\) arcmin\(^{-2}\)) is rather lower than previous constraints on large-scale filamentary X-ray emission (§ 1).

Because estimates of the diffuse X-ray background intensity (Pen 1999) are several times higher than that due to a single filament (Cen & Ostriker 1993, 1999), we estimate that several such filamentary structures could typically be superposed along any given line of sight, confusing their detection. Given the low measured background surface brightness in the CL 1603 data (§ 2), we therefore suspect that this field may in fact be filament poor, allowing a single structure to dominate.

The interpretation of this structure as being predominantly diffuse gas is clearly not yet secure, albeit theoretically plausible. Obtaining photometric and spectroscopic redshift information in this field (and surrounding fields) will be of enormous help in testing the reality of the observed structures. The CL 1603 field is clearly an excellent target for future X-ray missions such as the X-ray Multimirror Mission (XMM), where a factor of more than 10 increase in sensitivity over ROSAT should allow structures such as these to be studied in detail.

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