Warm–hot intergalactic medium in the Sculptor supercluster

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ABSTRACT
We have analysed the soft X-ray emission in a wide area of the Sculptor supercluster by using overlapping ROSAT Position Sensitive Proportional Counter pointings. After subtraction of the point sources, we have found evidence for extended, diffuse soft X-ray emission. We have investigated the nature of such extended emission through the cross-correlation with the density of galaxies as inferred from the Münster Redshift Survey. In particular, we have analysed the correlation as a function of the temperature of the X-ray emitting gas. We have found a significant correlation of the galaxy distribution only with the softest X-ray emission (0.1–0.3 keV) and only for gas temperatures \( kT < 0.5 \) keV. We have excluded the fact that this soft X-ray diffuse emission, and its correlation with the galaxy distribution, is significantly contributed by unresolved active galactic nuclei, groups of galaxies or individual galaxies. The most likely explanation is that the soft, diffuse X-ray emission is tracing warm–hot intergalactic medium, with temperatures below 0.5 keV, associated with the large-scale structures in the Sculptor supercluster.

Key words: large-scale structure of Universe – X-rays: diffuse background.

1 INTRODUCTION
Cosmological simulations predict the formation at low redshifts (\( z < 1 \)) of a diffuse gas phase with temperatures of the order of \( T \sim 10^5–10^7 \) K and typical densities 10–30 times the mean baryonic density (although 30 per cent of this gas can exceed overdensities greater than 60, and even greater than 100 in the proximity of clusters of galaxies). This gas phase should be distributed in large-scale filamentary structures connecting virialized structures (Cen & Ostriker 1999; Davé et al. 2001). Such warm–hot intergalactic medium (WHIM) has been identified as the main contributor to the missing matter in the baryonic census, i.e. \( \approx 36 \pm 11 \) per cent of the baryons (Fukugita & Peebles 2004).1 The formation of these warm gaseous filaments is a result of the infall of baryonic matter onto the previously formed dark matter cosmic web. The gravitational potential of the dark matter heats the gas through shocks and triggers the formation of galaxies. The WHIM can be observed in the soft X-rays (below \( \sim 2 \) keV; Croft et al. 2001) as low surface brightness structures. The detection of its radiation is very difficult because of many Galactic foregrounds – such as the Local Hot Bubble (LHB) and the Galactic halo – and extragalactic background due to active galactic nuclei (AGNs), groups of galaxies and clusters. Simulations and X-ray background studies have shown that the WHIM continuum emissivity below 2 keV is roughly of the same order of magnitude as the Galactic foregrounds. More specifically, \( F_{0.5–2\text{keV}}(\text{WHIM}) \approx 7 \text{ keV s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ keV}^{-1} \) (Croft et al. 2001; Kuntz, Snowden & Mushotzky 2001) and \( F_{0.2–0.3\text{keV}}(\text{WHIM}) \approx 15 \text{ keV s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ keV}^{-1} \) (Croft, private communication). Within this context, Pierre, Bryan & Gustad (2000) have shown, from simulated observations, that XMM can observe strong filaments up to \( z \sim 0.5 \) in the 0.4–4 keV energy band.

Cen et al. (1995) pointed out that this gas phase should also emit characteristic spectral lines mainly due to oxygen, neon and iron ions. The level of emissivity of these spectral features is below the sensitivity and spectral resolution limits of the current X-ray instruments. However, cosmological simulations show that these lines will be detectable with the future generation of X-ray satellites (Yoshikawa et al. 2003; Fang et al. 2004).

Various detections of (continuum) WHIM emission have been claimed, obtained by observing soft X-ray structures in galaxy overdense regions (Scharf et al. 2000; Bagchi et al. 2002; Zappacosta et al. 2002), or by detecting a soft X-ray excess in clusters of galaxies (Finoguenov, Briel & Henry 2003; Kaasra et al. 2003), or in their proximity (Tittley & Henriksen 2001; Soltan, Freyberg & Hasinger 2002), or through shadowing effects (Bregman & Irwin 2002). These

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observations have been possible by means of X-ray satellites very sensitive to low energies (<1–2 keV), such as ROSAT and XMM.

Theoretical works had predicted that the WHIM should be detectable through ultraviolet (UV) and X-ray absorption lines imprinted on the spectra of background quasi-stellar objects (QSOs; Hellsten, Gnedin & Miralda-Escudé 1998; Perna & Loeb 1998). The detectability of such absorption features does not depend on the brightness of the filaments but on their column density and on the brightness of the background QSO. So far, several detections have been reported through X-ray and far-ultraviolet (FUV) absorption lines probing the hot and cool phase of the WHIM (Nicastro et al. 2002; Tripp 2002; Mathur, Weinberg & Chen 2003).

Simulations show that the WHIM should be distributed in filamentary structures extending over several tens of Mpc and connecting clusters of galaxies. Therefore, superclusters (hosting several clusters) are optimal regions where WHIM is more likely to be detected. In this paper, we focus on the Sculptor supercluster (hereafter SSC; Schuecker & Ott 1991; Seitter 1992). This is one of the richest local superclusters, comprising more than 20 clusters of galaxies (Einasto et al. 1997) spread over a projected length of more than 140 Mpc at a redshift z ~ 0.105. It is located in the South Galactic Pole, a region where the Galactic hydrogen column density is low enough (N_H ≈ 1.5 ± 0.2 × 10^{20} cm^{-2}) to avoid significant effects of patchy absorption that could mimic a pattern of apparent X-ray structures (see Zappacosta et al. 2002, for more details). The SSC has already been observed by Spiekermann (1996) and Obayashi, Makishima & Tamura (2000), using ROSAT and ASCA data, with the purpose of detecting large-scale X-ray diffuse emission. They did not find indications for emission extended in large-scale structures. However, Spiekermann focused the analysis on the relatively energetic bands at 0.5–3 keV (without investigating the correlation with the galaxy distribution), whereas Obayashi et al. observed in an even harder band (0.8–10 keV) and by using pointings centred on clusters with the goal of detecting hot diffuse emission in their outskirts.

In this paper we present evidence for a correlation between the galaxy distribution and soft X-ray emission in the central region of the SSC. In particular, we show that galaxies and the softest X-ray emission (<0.3 keV) correlate in regions with gas temperatures kT < 0.5 keV. This finding is interpreted as WHIM emission associated with the large-scale structures in the SSC.

2 DATA DESCRIPTION

Our aim is to detect WHIM over the central region of the supercluster (8.3 × 6.4 deg^2, corresponding to 57 × 44 Mpc^2 at z = 0.105), which is populated by more than 15 Abell clusters. We considered 10 Position Sensitive Proportional Counter (PSPC) partially overlapping pointings taken from the ROSAT archive, which cover the core of the SSC (see Fig. 1). Unfortunately, the exposures of these pointings are not homogeneous, ranging from ~4 to ~24 ks. As a consequence, our quantitative analysis will be restricted only to the three deepest fields (i.e. those with exposures >18 ks, represented by thick circles in Fig. 1).

To map the galaxy density distribution in the SSC, we have used data from the Münster Redshift Project (MRSP; Seitter 1992; Spiekermann et al. 1994; Ungruhe, Seitter & Duerbeck 2003). The MRSP is a catalogue of galaxies obtained by scanning direct and

![Figure 1. The position of the 10 partially overlapping ROSAT PSPC pointings in the region of the SSC. For each pointing, the ROSAT observation ID and the exposure time are shown. The position of the South Galactic Pole (SGP) is also shown. The three deepest pointings (which will be used for the subsequent quantitative analysis) are identified with thick circles.](https://academic.oup.com/mnras/article-abstract/357/3/929/1078497/Warm-hot-intergalactic-medium-in-the-Sculptor/1078497-1078497-1)

2 Here and in the rest of the paper, we assume a cosmology with \( \Omega_m = 0.3, \Omega_\Lambda = 0.7 \) and \( H_0 = 70 \) km s^{-1} Mpc^{-1}.

3 Galactic extinction in this region affects \( r_F \) by at most 0.04 mag.
3 A GLANCE AT THE SCULPTOR REGION

Fig. 2 shows a comparison of the structures found with the wavelet algorithm in both the optical and the three ROSAT bands: more specifically (see also Table 1), 0.14–0.284 keV (R2; the 1/4 keV band), 0.44–1.21 keV (R45; the 3/4 keV band) and 0.73–2.04 keV (R67; the 1.5 keV band). The upper panels show the projected density of galaxies and the 1/4 keV flux for all the pointings. The lower panels show the X-ray flux in the three ROSAT bands focused on to the region of the three deepest PSPC pointings (see Fig. 1). Contours at significance levels from 2σ to 4σ (spaced by 1σ) are shown in the latter.

Table 1. ROSAT energy bands and conventional notations, where ‘Alt.’ is short for ‘Alternative’.

<table>
<thead>
<tr>
<th>Band</th>
<th>Range</th>
<th>Alt. notation</th>
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<tr>
<td>R2</td>
<td>0.14–0.284 keV</td>
<td>1/4 keV&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>R45</td>
<td>0.44–1.21 keV</td>
<td>3/4 keV</td>
</tr>
<tr>
<td>R67</td>
<td>0.73–2.04 keV</td>
<td>1.5 keV</td>
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<sup>a</sup>The notation 1/4 keV is often referred to as the R12 ROSAT broad energy band. In this paper, we use this notation restricted to the R2 energy band.

Both galaxies and gas show large-scale structures including clusters of galaxies and filamentary structures connecting them. There is also a lot of X-ray diffuse emission not clearly related to visible structures in the galaxy map, which could be a result of foreground by our Galaxy (e.g. LHB and Galactic halo) or of a blend of unresolved emission by AGNs (mainly in low-exposure pointings). A contribution could also come from foreground (or background) superstructures. Note that Spieckermann (1996) and Obayashi et al. (2000) focused their searches on the harder X-ray emission (i.e. >0.5 keV) in the region of the ROSAT pointing 800069p (see Fig. 1), which is considered the core of the SSC (it contains five Abell clusters). This region shows diffuse emission only for the soft 1/4 keV band (i.e. at energies below 0.3 keV).

4 SPECTRAL ANALYSIS

Filamentary X-ray structures connecting clusters are not necessarily a result of warm–hot gas. They could also arise from AGN unresolved emission, as both WHIM and galaxies trace gravitational potential wells of dark matter filaments (Scharf et al. 2000; Zappacosta et al. 2002).
In order to assess the true nature of these filamentary patterns, we need to perform an accurate comparison with the distribution of galaxies along with the analysis of the spectral shape of the X-ray emission. We have to limit our analysis to the three deepest fields (700275p, 700133p-1 and 700528p) where we are confident that a larger fraction of the AGN contribution to the X-ray background has been resolved.

Fig. 3 shows the spectral shapes measured for these pointings sorted by decreasing exposure times. Fig. 3(a) shows the count rate, while in Fig. 3(b) the spectra are normalized by the area in each field. Fluxes are not corrected for the Galactic N_H absorption (this correction would increase the flux in the 1/4 keV band by a factor of ~3). Dotted lines show the sum of point-like sources detected by SExtractor, while the solid lines show the total flux in each field (shaded regions indicate the dispersions of the slopes within each field). The difference between them is the diffuse residual emission and it is shown with the dashed line. We note that the residual soft, diffuse fluxes have values of ~380 x 10^{-6} count s^{-1} arcmin^{-2}, well above those found for the LHB emission through shadowing measurements in the region of the South Galactic Pole (Snowden et al. 2000), which lie in the range 100–300 x 10^{-6} count s^{-1} arcmin^{-2}. After subtraction of the LHB and after correction for Galactic absorption, the residual diffuse, extended emission has a value of ~540 x 10^{-6} ± 300 x 10^{-6} count s^{-1} arcmin^{-2}. This residual emission may include both Galactic halo and extragalactic emission as a result of unresolved AGNs, clusters/groups of galaxies or true WHIM emission. We identify and disentangle these various contributions both through an analysis of the spectral shape and through the correlation with the galaxy distribution.

As discussed above, a residual component due to unresolved AGNs, or unidentified clusters/groups, could still be present even in images with longer exposures. The three ROSAT energy bands can be used to make a colour–colour diagram, with the goal of separating colours typical of a warm gas from unresolved AGNs and clusters. In particular, the WHIM is expected to have a softer emission with respect to clusters and AGNs.

Fig. 4 shows the [1/4 keV]/[3/4 keV] band ratio (R2/R45) versus the [3/4 keV]/[1.5 keV] band ratio (R45/R67) for different types of sources (the ratios are in counts and corrected for Galactic absorption). The dotted lines and full symbols indicate the behaviour of thermal emission (optically thin plasma, MEKAL model), corrected for Galactic absorption, at a redshift z = 0.1 and metallicities 0.1 and 0.3 Z_{⊙}, for several temperatures expressed in keV. The dashed lines and open symbols indicate the colours of AGNs with two different slopes (quite typical in the ROSAT band), both unabsorbed and with intrinsic absorptions of N_H = 1–5 x 10^{20} cm^{-2}. The three horizontal shaded regions correspond to the three temperature bins adopted in Fig. 5 (for each of these regions the error on the average colours is shown). Note that plasmas with low temperatures (kT < 0.5 keV) can be efficiently selected through high values of the [3/4 keV]/[1.5 keV] colour (larger than ~2).

Figure 3. Global spectral shapes (not corrected for Galactic absorption) for the three deepest fields: (a) count rate; (b) count rate normalized per unit area. The solid lines represent the whole flux detected, the dotted lines show the point-source component and the dashed lines show the residual flux obtained by the subtraction of the first two. Grey regions in (a) show the dispersions of the spectral shapes over each field.

Figure 4. Colour–colour diagram ([1/4 keV]/[3/4 keV] band ratio versus [3/4 keV]/[1.5 keV] band ratio) for various classes of sources. The dotted lines and solid symbols indicate thermal emission (MEKAL model), corrected for Galactic absorption, at a redshift z = 0.1 and metallicities 0.1 and 0.3 Z_{⊙}, for several temperatures expressed in keV. The dashed lines and open symbols indicate the colours of AGNs with two different slopes (quite typical in the ROSAT band), both unabsorbed and with intrinsic absorptions of N_H = 1–5 x 10^{20} cm^{-2}. The three horizontal shaded regions correspond to the three temperature bins adopted in Fig. 5 (for each of these regions the error on the average colours is shown). Note that plasmas with low temperatures (kT < 0.5 keV) can be efficiently selected through high values of the [3/4 keV]/[1.5 keV] colour (larger than ~2).
intrinsic absorptions of $N_H = 1-5 \times 10^{20} \text{ cm}^{-2}$. The most interesting feature inferred from the colour–colour diagram in Fig. 4 is that the R45/R67 ratio ([3/4 keV]/[1.5 keV]) is an excellent tracer of the gas temperature. In particular, gas cooler than $\sim 0.5$ keV (typical of WHIM) is characterized by R45/R67 > 2, while gas warmer than 0.5 keV (typical of groups and clusters) or AGNs have R45/R67 < 2. Therefore, we have used the ratio R45/R67 to discriminate WHIM regions from areas dominated by unresolved AGNs and clusters.

The X-ray emission in the three fields of the SSC investigated by us spans a wide range of colours. In particular, R45/R67 ranges from $\sim 0.5$ (typical of AGNs and clusters) to values larger than 2 (typical of WHIM).

5 CORRELATION ANALYSIS

The X-ray colours alone (and in particular the inferred low temperatures) do not necessarily allow the identification of the diffuse X-ray emission with WHIM, because foreground components such as the LHB and Galactic halo are also characterized by soft emission and low temperatures. However, any correlation between soft X-ray emission and distribution of galaxies would support the idea that the diffuse X-ray emission is extragalactic and associated with large-scale structures. In this section we discuss the correlation between the X-ray emission and the density of galaxies as a function of the X-ray colour.

The most widely used criteria to correlate two data sets are the Pearson correlation coefficient $r$ and the Spearman’s rank correlation coefficient $r_s$ (also known as the Spearman’s rho). Both assume values ranging from +1 (perfectly correlated) to −1 (completely anticorrelated). A null value means that the two quantities are not related at all. The first correlation coefficient is based on the assumption that the data follow a Gaussian distribution, while the second makes no assumptions, measuring the correlation on ranked data (i.e. the data are converted to ranks and then correlated). The Spearman’s rho is a better indicator that two variables are correlated when they are tied by a non-linear monotonic correlation.

In our case, cosmological models do not predict how galaxies and gas are linked. More specifically, it is not clear whether there is a linear correlation between the density of galaxies and gas emission, or whether some physical mechanism links the formation of galaxies and the gas phase in a non-linear way. Therefore, the Spearman’s rho is probably better suited in this case. However, we will also show the Pearson correlation results for comparison.

We do not expect to find a high correlation between galaxies and WHIM. In fact, the three ROSAT bands do not correlate strongly among themselves, with correlation coefficients in the range 0.2–0.3 (which means a low correlation).

Regions containing clusters would certainly give a higher value of $r_s$ because they have many galaxies and high hard X-ray fluxes in small areas. Cooler regions should have few galaxies spread over large areas with low soft X-ray flux, and therefore a low correlation signal is expected.

We have correlated the galaxy density map with the X-ray merged maps. Unfortunately, in this analysis we had to reject the 700528p field because it covers a region centred at the cross of four photographic plates of the Münster Survey, where the galaxy catalogue shows clear spatial inhomogeneities. So we are left with the two deepest pointings with exposures greater than 19 ks (fields 700133p-1 and 700275p). Moreover, because we use the ratio R45/R67 to discriminate between ‘cold’ and ‘hot’ regions, we selected those regions with a good signal in R45. In particular, we avoided exceedingly noisy regions by selecting the areas with the R45 flux higher than $M_X - 2\sigma_X$, where $M_X$ is the median value and $\sigma_X$ is the standard deviation over the field (anyway, this criterion selects most of the field, and more specifically $\sim 95$ per cent).

Fig. 5 shows the behaviour of the correlation coefficient (Spearman rho and Pearson coefficients in upper and lower panels) as a function of the $3/4$ keV/1.5 keV ratio. The vertical dotted lines indicate the plasma temperatures, as labelled at the top of each panel. The horizontal dotted lines indicate the specific values of the $3/4$ keV/1.5 keV ratio. Arrows show the shift of the dotted lines in the case of a metallicity of 0.3 $Z_\odot$, corresponding to specific values of the $3/4$ keV/1.5 keV ratio. Panels (a) and (b) show the behaviour of the Spearman correlation coefficient, while panels (c) and (d) are for the Pearson correlation coefficient.

panels, respectively) as a function of the colour [3/4 keV/1.5 keV] (R45/R67) for the three ROSAT energy bands. The temperatures corresponding to this ratio (assuming a metallicity of 0.3 Z⊙) are shown in the upper part of the graph and indicated in each plot by vertical dotted lines. The arrows show the position of the dotted lines in the case of a metallicity of 0.1 Z⊙. We have measured the correlation for three temperature ranges to probe the ‘hot’ (kT > 0.9 keV), ‘medium’ (0.5–0.9 keV) and ‘cold’ (kT < 0.5 keV) gas. For each range we show the median value of the R45/R67 ratio. Vertical error bars show the 1σ confidence on the value of the correlation coefficient.

The results from the two correlation coefficients do not differ significantly. The most important result is the finding of a weak, but significant correlation between the density of galaxy and the very soft 1/4 keV flux, only for regions with gas temperature below 0.5 keV (i.e. ‘cold’ regions). The correlation coefficient is 0.16–0.17 and significant at 3σ–3.5σ (depending on the correlation coefficient adopted). The correlations with the other ROSAT bands (and other temperatures) do not show any significant signal, except for a marginal (2.5σ) correlation in the ‘hot’ bin of the 1.5 keV band (which will be discussed briefly at the end of this section).

A correlation between galaxy distribution and very soft X-ray emission, limited to the ‘cold’ (kT < 0.5 keV) regions, is just what is expected from WHIM emission that is tracing large-scale structures. However, there are a few other possibilities that could, in principle, explain the correlation in the soft band, as discussed in the following.

One alternative possibility is that the soft, cold emission is directly emitted by the individual galaxies of the SSC, or by a subpopulation of them, which are particularly active (starbursts). In this case, the X-ray emission would be a result of the warm–hot interstellar medium of the galaxies and their superwinds. In our field there are at most 0.5 galaxy arcmin−2. We have made two very conservative assumptions: (i) all these galaxies are starburst (and not dominated by a mixture of – less active – spirals and ellipticals); (ii) the residual diffuse X-ray emission (due to Galactic halo and extragalactic components) has the minimum value of 300 × 10−6 count s−1 arcmin−2 obtained by subtracting from the measured X-ray flux the maximum value of the LHB (see Section 4). We have assumed for a starburst a typical luminosity of 1041 erg s−1 in the 0.2–2 keV energy band (see figs 3 and 4 in Norman et al. 2004) and a spectrum made of a thermal component (kT = 0.7 and Z = Z⊙) plus an absorbed power law (N_H = 1022 cm−2 and Γ = 0.8) representing the X-ray binary contribution (see Norman et al. 2004). We have estimated that the galaxies should contribute a flux of ~1059 erg s−1 arcmin−2 in the R2 ROSAT band. The latter value is a factor of ~20 lower than the average diffuse R2 flux of ~1062 erg s−1 arcmin−2 that we measure in the ROSAT maps. This means that the X-ray emission from normal and starburst galaxies cannot contribute significantly to the correlation in the ‘cold’ regions of the supercluster.

Another possibility is that cold groups of galaxies could contribute in some way to the correlation in the soft, cold regions. Indeed, a fraction of small groups may have temperatures as low as 0.4 keV (Muldrew et al. 2003). However, as discussed in detail in Appendix A, the contribution to the coldest gas temperatures as a result of cold groups (i.e. those with kT < 0.5 keV) is, at most, 1 per cent of the studied region. Therefore, ‘cold’ groups cannot account for the soft X-ray emission or for the correlation found in Fig. 4. Warmer systems, such as ‘hot’ groups (kT > 0.5 keV) and clusters cannot explain the correlation; indeed, these systems would give a significant correlation also in the higher temperature bins and also in the harder bands.

Finally, another possibility is that the correlation in the soft band, and at cold temperatures, is contributed by clusters/groups in formation and not yet virialized. These systems would have a temperature lower than standard clusters/groups. However, the distinction between forming, non-virialized clusters/groups and WHIM is subtle, and probably just semantic. Indeed, the definition of WHIM (from a physical point of view) is that of a medium associated with forming, non-virialized structures (Cen & Ostriker 1999). Therefore, even a contribution from cold, forming clusters/groups should be included in the WHIM budget.

Summarizing, the scenario that better explains the correlation between galaxies and cold gas emitting at 1/4 keV is that a fraction of the diffuse soft X-ray emission is a result of WHIM associated with the galaxy distribution in the SSC.

In order to further investigate the latter scenario, we have also tried to estimate the density of the emitting gas. Such an estimate is very uncertain, because we do not have much information on the geometry of the emitting gas (the WHIM emission is disentangled only through a statistical analysis over a wide field). Moreover, we do not know exactly what fraction of the 1/4 keV emission is actually emitted by the WHIM: indeed, although we measure a flux for the 1/4 keV diffuse emission, the weak correlation with the galaxy distribution may indicate a real, physically weak association between galaxies and WHIM, but may also point at a significant dilution from other unrelated X-ray components (foreground and background emission; see Section 1). We have estimated the density of the gas emitting the soft X-ray radiation by making extreme, opposite assumptions on the geometry of the gas (i.e. either distributed only in the putative filaments of Fig. 2, or distributed over the whole field where the cross-correlation was performed) and on its contribution to the 1/4 keV emission (i.e. either contributing to the whole LHB-subtracted R2 emission, or contributing only to the 20 per cent responsible for the correlation with galaxies). The inferred gas densities range from 4 × 1044 cm−3 (δ ∼ 15), well in the range of the WHIM specifications, up to 1045 cm−3 (δ ∼ 400), which may be expected for WHIM in the proximity of clusters (Section 1).

Finally, we briefly discuss the nature of the marginal correlation between galaxy distribution and X-ray emission in the hard, R67 band (and some of R45), limited to ‘hot’ temperatures (Fig. 5). This can be easily explained in terms of contribution from a population of unresolved, weakly obscured AGNs. Indeed, a small absorbing column density of N_H ∼ 5–1021 cm−2 is enough to absorb most of the 1/4 keV flux, while leaving the harder bands nearly unaffected. Moreover, AGNs have R45/R67 colours nearly identical to ‘hot’ plasma (see Fig. 4). Unresolved, obscured AGNs certainly contribute significantly to the X-ray background and span a wide range of absorbing N_H (Mainieri et al. 2002). Small amounts of X-ray absorption are also detected in several type 1 AGNs (Maiolino 2001; Maiolino et al. 2001), which are the dominant population found by ROSAT (Lehmann et al. 2001) and Chandra (Barger et al. 2003; Szokoly et al. 2004). Therefore, it is expected that a fraction (10–20 per cent) of unresolved AGNs, which contribute to the diffuse signal detected by us, are also slightly absorbed. These slightly obscured, unresolved AGNs (probably also belonging to the SSC) are probably responsible for the correlation in the hard band, and not in R2, for ‘hot’ X-ray colours.

6 CONCLUSIONS

We have investigated the emission from WHIM associated with large-scale structures in the central region of the SSC (z ≈ 0.1). We have analysed 10 overlapping ROSAT PSPC fields, covering the
central 8.3 × 6.4 deg^2 of the supercluster. After removal of the point sources, the ROSAT maps show indication of diffuse, filamentary structures, in some cases connecting known clusters of the SSC. The diffuse emission spans a wide range of X-ray spectral shapes: from relatively hard emission expected for clusters and unresolved AGNs, to very soft emission expected for WHIM.

To investigate the nature of the diffuse X-ray emission, we have cross-correlated the X-ray flux with the density of galaxies obtained from the Münster Redshift Catalogue (whose galaxies mostly belong to the SSC in this region). The correlation has been analysed as a function of the gas temperature (or X-ray spectral shape). The most important result is the finding of a significant correlation between the diffuse soft (0.1 – 0.3 keV) X-ray flux and the density of galaxies at the coolest gas temperatures (kT < 0.5 keV). Such a correlation is interpreted as emission by WHIM associated with the galaxy distribution.

We have also investigated the possible contribution to the diffuse soft X-ray emission, and to the correlation with galaxies, as a result of individual galaxies and cold clusters. We have found that in both cases the contribution is negligible.

We have also detected a weak, marginal correlation between the harder X-ray flux (1.5 keV, R67 band) and the density of galaxies at apparently higher gas temperatures (kT ∼ 1 keV). The latter correlation is ascribed to slightly obscured, unresolved AGNs.

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APPENDIX A: CONTRIBUTION FROM COLD GROUPS OF GALAXIES
Groups of galaxies are poorly studied objects because of their elusive nature, both in X-ray and optical. One of the largest samples studied so far (Mulchaey et al. 2003) contains 109 low-redshift galaxy groups. It is a collection of several catalogues of groups selected both in X-ray and optical. In this catalogue, temperatures have been derived only for a subsample of 61 objects that also show extended diffuse emission. The temperatures derived for these clumps range from 1.5 keV down to 0.4 keV. The latter overlaps the range of WHIM temperatures. As a consequence, ‘cold’ groups could mimic the WHIM behaviour, both in terms of X-ray spectral shape and correlation with galaxies. Therefore, it is important to quantify the density of ‘cold’ clusters and to estimate their contribution to the soft X-ray emission. The coldest groups (kT < 0.5 keV) are also the smallest (R_X < 120 kpc) and the least luminous (L_X < 10^{41.2} erg s^{-1}). To calculate the fraction of area expected to be covered by groups, we have used the catalogue of groups detected by the European Southern Observatory (ESO) Slice Project (ESP; Ramella et al. 1999) in a field close to the SSC region (~10 deg away). The survey has been carried out in two strips. We consider only the area near to the SSC (strip A; 22 × 1 deg^2). In this region, 190 groups were found up to redshift z = 0.2, ~71 at redshifts below the z_{SSC}, and only 18 below z = 0.05. We can assume the extreme scenario that all groups are colder than 0.5 keV and that all of them have a size R_X ~ 120 kpc (which is the maximum size found among cold groups). With these assumptions, we can calculate what is the

maximum fraction of our field occupied by cold groups in the following redshift ranges: $0 - 0.05$, $0.05 - z_{SSC}$, $z_{SSC} - 0.2$. To make things simpler, we calculate the angular sizes of groups in these bins using the mean redshift value, except for the last one where we assume that all groups have redshift $z_{SSC}$. We exclude from the sample all the identified groups with three galaxy members, because almost all these groups do not show diffuse emission that can contribute to the correlations (Mulchaey et al. 2003). With these extreme, conservative assumptions, we obtain that at most 1 per cent of the pixels in our image could be significantly contaminated by cold group emission. This means that cold groups cannot contribute to the correlation found in regions with $kT < 0.5$ keV.

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