DISCOVERY OF A LARGE-SCALE GALAXY FILAMENT NEAR A CANDIDATE INTERGALACTIC X-RAY ABSORPTION SYSTEM

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ABSTRACT

We present an analysis of the large-scale galaxy distribution around two possible warm-hot intergalactic medium (WHIM) absorption systems reported along the Markarian 421 sight line. Using the Sloan Digital Sky Survey (SDSS), we find a prominent galaxy filament at the redshift of the \( z = 0.027 \) X-ray absorption line system. The filament exhibits a width of 3.2 Mpc and a length of at least 20 Mpc, comparable to the size of WHIM filaments seen in cosmological simulations. No individual galaxies fall within 350 projected kpc so it is unlikely that the absorption is associated with gas in a galaxy halo or outflow. Another, lower-significance X-ray absorption system was reported in the same Chandra spectrum at \( z = 0.011 \), but the large-scale structure in its vicinity is far weaker and may be a spurious alignment. By searching for similar galaxy structures in 140 random smoothed SDSS fields, we estimate an \(~5\%–10\%\) probability of the \( z = 0.027 \) absorber-filament alignment occurring by chance. If these two systems are indeed physically associated, this would represent the first known coincidence between a large-scale galaxy structure and a blind X-ray WHIM detection.

Key words: cosmology: observations – intergalactic medium – large-scale structure of universe

1. INTRODUCTION

Despite theoretical expectations that the warm-hot (\( T > 10^7 \) K) component of the \( z < 1 \) intergalactic medium (IGM) contains 25\%–50\% of the baryons in the local universe (Davé et al. 2010), this material has thus far frustrated attempts at unambiguous detection and characterization. This is primarily due to its high temperatures (\( 10^5–10^7 \) K) and low densities (\( 10^{-6} \) to \( 10^{-4} \) cm\(^{-3}\)), rendering it all but undetectable through well-studied UV/optical absorption lines such as Ly\( \alpha \), Mg\( \text{II} \), and oftentimes even O\( \text{VI} \). Instead, the primary signature of this warm-hot intergalactic medium (WHIM) is expected to be highly ionized metal X-ray lines (both in absorption against the warm-hot intergalactic medium (WHIM) is expected to

Williams et al. (2005) performed detailed ionization and curve-of-growth analyses of the strong \( z = 0 \) X-ray absorption in the Mrk 421 spectrum; while these X-ray lines are inconsistent with known Galactic gaseous components, an origin in the large-scale WHIM surrounding the Galaxy and Local Group could not be conclusively inferred. Emission signals detected indirectly via the X-ray background autocorrelation function (Galeazzi et al. 2009) and directly in overdense regions (Zappacosta et al. 2005; Mannucci et al. 2007; Werner et al. 2008) have also been found, but the former method relies heavily on proper point-source subtraction and the latter may be probing extended, bound intracluster gas rather than the “representative” diffuse WHIM.

Perhaps the most convincing evidence thus far has been the detection of X-ray absorption lines associated with large-scale, nonvirialized galaxy structures like the Sculptor Wall (Buote et al. 2009; Fang et al. 2010) and the Pisces-Cetus Supercluster (Zappacosta et al. 2010). Such filamentary structures are expected to be associated with large reservoirs of diffuse WHIM gas (Davé et al. 2001), and thus X-ray absorption searches focusing on such systems have a higher probability of success than their blind counterparts. However, this method also has its drawbacks: notably, gas associated with these moderately high-density regions may still not be representative of typical WHIM properties, and individual galaxies with small (\( \leq 50 \) kpc) impact parameters can contaminate the WHIM absorption (J. Mulchaey et al. 2011, in preparation), thereby complicating the interpretation of a detection.

Nonetheless, the spatial coincidence of even weak X-ray absorption lines with other structures (whether galaxies, cluster outskirts, or large-scale nonvirialized filaments) is exciting, since little is known about the warm-hot gas in these environments. Here, we revisit the Chandra-detected absorption line systems reported by N05, searching for galaxy structures in public data that have been released since the detections. In Section 2, we describe the data and selection procedure, in Section 3 we discuss the galaxies and structures found near the absorbers, interpretations of the results can be found in

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Section 4, and we briefly summarize the conclusions in Section 5. Cosmological parameters \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_0 = 0.3 \), and \( \Omega_\Lambda = 0.7 \) are assumed throughout.

2. DATA AND GALAXY SAMPLES

Markarian (Mrk) 421 is an X-ray bright \( z = 0.03 \) blazar located at \( \alpha = 11^h04^m27^s3, \delta = +38^\circ12^\prime32^\prime \). By combining two deep Chandra Low-Energy Transmission Grating spectra of this object taken during extreme X-ray outbursts, N05 reported the detection of two significant absorption line systems: one at \( z = 0.011 \pm 0.001 \) (detected in two absorption lines with \( >2\sigma \) significance) and another at \( z = 0.027 \pm 0.001 \) (detected in four lines, three of which are stronger than \( 2\sigma \)). Hereafter we refer to these absorbers as “A1” and “A2,” respectively. The quoted redshift errors are primarily due to wavelength-dependent uncertainties in the Chandra-LETG dispersion relation. Taking all detected lines together, N05 report a “conservative” significance (i.e., taking into account possible spurious line detections over a wide wavelength range in their multi-component fits) of 3.5\( \sigma \) for A1 and 4.9\( \sigma \) for A2.

Since the publication of these putative WHIM detections, the Sloan Digital Sky Survey (SDSS; York et al. 2000) has publicly released a comprehensive catalog of galaxy redshifts spanning the northern Galactic cap (including the Mrk 421 region). This survey is at least 90% complete to \( r = 17.77 \) (Strauss et al. 2002), corresponding to about 0.04 \( L_\star \) at \( z = 0.03 \) (where \( L_\star \) is the characteristic luminosity in the Schechter function; Blanton et al. 2001). Here, the incompleteness is primarily due to the 55\( ^\circ \) minimum fiber spacing in the spectroscopic survey; in regions where the survey tiles overlap the incompleteness is expected to be higher, so 90% should be considered a conservative lower limit. In the SDSS photometric catalog, only one \( r < 17.77 \) galaxy lies within 55\( ^\circ \) of Mrk 421, a known companion to the quasar host at \( z = 0.03 \). Thus, it is unlikely that any projected companions near Mrk 421 are missed due to the minimum fiber spacing.

In order to provide samples of galaxies and galaxy structures both near and unrelated to the absorbers, we retrieved data on all galaxies (unconstrained by sky position) from the SDSS Data Release 7 (Abazajian et al. 2009) “BESTDR7” database within \( \pm 450 \text{ km s}^{-1} \) around the X-ray detections: 0.0095 < \( z < 0.0125 \) and 0.0255 < \( z < 0.0285 \). These intervals are sufficient to broadly encompass all of the detected lines’ best-fit wavelengths in each absorption system, thus conservatively allowing for uncertainties in the absorbers’ redshifts (as well as possible systematic offsets between the galaxies and filament gas) while effectively excluding foreground and background interlopers. Aside from the redshift constraints, we further required objects to be flagged as galaxies by the SDSS pipeline (specClass == 2) and have high-redshift confidence (zConf > 0.95).

3. GALAXIES AND LARGE-SCALE STRUCTURES NEAR THE ABSORBERS

The line-of-sight galaxy redshift distribution in a narrow cylinder (with a radius of 5 Mpc) centered on Mrk 421 is shown in Figure 1; the mean absorber redshifts are marked with arrows. In both cases, the absorbers coincide with significant spikes in the galaxy distribution: a rather broad one approximately between \( z = 0.009–0.012 \) and a narrow one at \( z = 0.027 \) (superposed on a larger overdensity ranging from at least

\[ z = 0.025–0.033 \]. Interestingly, the space between the two absorbers is largely devoid of galaxies.

While the absorbers evidently lie within 5 projected Mpc of galaxy structures in redshift space, the actual nature of these overdensities is not obvious from the histogram. Figures 2 and 3 therefore show the galaxy distributions within two narrow redshift slices (depth \( \Delta z = \pm 0.0015 \)) in boxes 20 Mpc on a side. Objects blueshifted relative to the absorbers are plotted as solid circles, and redshifted galaxies are shown as crosses. Large-scale galaxy structures are again apparent in both slices: near A1 there appears to be a broad (albeit somewhat diffuse) filament or sheet of galaxies to the north and east of the absorber, while A2 lies on the edge of a strong, well-defined galaxy filament. In both cases, the absorbers appear to lie in “boundary” regions, near relatively large voids or underdense regions.

To better quantify the structures near the absorbers, we reject by eye galaxies that do not appear to be “members” of the structure nearest each absorber (shown as gray points; this method is discussed further in Section 4.1), and perform simple linear fits to the positions of the remaining galaxies. These fits are plotted as dashed lines in Figures 2 and 3, and the number of galaxies as a function of perpendicular distance from these best-fit lines are shown in the inset plots. The filament near A2 exhibits a strong, nearly Gaussian shape around this line with FWHM = 3.2 Mpc (though non-Gaussian wings extending to \( \pm 4 \text{ Mpc} \) may also be present). On the other hand, the \( z = 0.011 \) structure is not as well defined, with galaxies more widely distributed over a span of \( \sim 8 \text{ Mpc} \) in the perpendicular direction. There is a denser, well-defined clump or filament of galaxies to the southeast (gray points in Figure 2) that may be part of a nearly north–south filament, but at a perpendicular distance of 6.4 Mpc (if extrapolated to the north; gray line in the figure) its association with the absorber is even less likely. Taking the dashed best-fit lines as the nearest filaments’ “centers,” A1 and A2 lie at perpendicular distances of 4.7 and 2.7 Mpc from the centers of their respective galaxy structures.
Although large-scale galaxy filaments are expected to trace substantial reservoirs of WHIM gas, such X-ray absorbers are also likely to be present in individual galaxy halos and low-mass groups (e.g., Williams et al. 2005). A1 is relatively isolated: one galaxy lies a projected 588 kpc to the southwest, but this is well outside the typical extent of warm-hot galaxy halos (up to 100 kpc; e.g., Anderson & Bregman 2010). On the other hand, two moderately bright (≈0.4 and 0.8 $L_\star$) spiral galaxies lie somewhat closer to A2: 364 and 397 projected kpc to the east and southeast, respectively. While it is still unlikely that gas associated with these individual galaxies’ halos extends to this distance, due to the proximity of these galaxies to each other (343 kpc projected separation and exactly the same redshift), it is possible that they reside in a bound system comparable to the Local Group. Such a system may contain diffuse bound warm-hot gas (analogous to intracluster media) extending to several hundred kpc, which could be responsible for the observed X-ray absorption. However, the redshifts of the galaxies ($z = 0.0285 \pm 0.001$) are at the upper edge of our selection window and $+450$ km s$^{-1}$ higher than the nominal absorber velocity; the median redshift of the galaxies in the larger filament is thus a marginally better match to that of the absorber.

4. DISCUSSION

4.1. Semantic Uncertainties

Due to their rather subjective definitions, the nature of these large-scale structures (e.g., filaments, sheets, and/or clumps), and which galaxies should be included as members of the structures, are difficult to quantify (for one novel method, see Bond et al. 2010). Because they span $\sim 20$ Mpc or more, simply counting galaxies in a cylinder of this size around an absorber provides no information on the spatial configuration of the nearby large-scale structure, or whether a well-defined filament (if one is within the field) actually intercepts the absorber’s position. Similarly, traditional measures of local galaxy density ($n$th nearest neighbor, for example) are in a sense “too local” to provide information on WHIM-scale structures.

We therefore employ a semiqualitative technique of picking out the nearest linear filamentary structures by eye, excluding galaxies which lie significantly outside these structures, and defining the filament’s “center” through a linear fit to the sky positions of the galaxies in that redshift slice. This combines the particular strengths of human pattern recognition (successfully employed by other studies, e.g., Galaxy Zoo; Lintott et al. 2008) while still allowing quantitative measures of the filaments’ physical properties (dimensions, redshift distribution, number of constituent galaxies, and distance from the absorber to the center). In principle these observations can then be compared directly to simulations as long as comparable analysis techniques are used for the mock galaxy catalogs.

4.2. IGM, Galaxy, or Coincidence?

As noted previously, X-ray absorption systems like those reported by N05 can result from a variety of physical scenarios, including WHIM filaments, individual galaxy halos or outflows, and intragroup gas. Taken in its entirety, the evidence that the A2 absorption system is associated with a large-scale galaxy filament is compelling. The galaxies in the vicinity of A2 fall almost exclusively within a clear filamentary structure with length at least 20 Mpc and FWHM of 3.2 Mpc (Figure 3). The 95 galaxies in this structure have a median redshift of $z = 0.0269$,
exactly coincident with the absorber and are more or less isotropically distributed around this redshift (with 52 galaxies at $0.0255 < z < 0.0270$ and 43 at $0.270 < z < 0.0285$). This structure also defines a strong, narrow redshift spike (Figure 1), indicating that it is compact in both width and the $\Delta z$ direction. Although some of the absorption could in principle arise in the intragroup medium of a galaxy pair ~380 projected kpc away, its redshift ($z = 0.0285$) is not as good a match to the absorption system, so its physical distance could be as much as several Mpc.

On the other hand, the lower-redshift absorber A1 is not as clearly associated with a large-scale structure. While a possible filamentary structure or sheet appears in Figure 2, its projected distance is larger (4.7 Mpc) and the surface density is lower than the filament near A2; according to Figure 1 fewer galaxies fall near the absorber in redshift space as well. Nor are the galaxy redshifts in this structure in as good agreement with the absorber redshift as A2 and its filament: 14 galaxies lie above $z = 0.0110$ and 48 lie below, with a median $z = 0.0105$ (though this is still formally within the absorber’s redshift uncertainty). No individual galaxy or group lies within 0.5 Mpc of the absorber. Given the relative weakness of the A1 detection (seen in two $>3\sigma$ X-ray absorption lines, as opposed to the four significant lines tracing A2), it is possible that this detection is spurious (see also Kaastra et al. 2006), in which case the lack of a nearby galaxy or large-scale structure would not be surprising. However, if the A1 absorber is real, it may represent a true “void” absorption system or, alternatively, probe gas associated with the rather distant, diffuse sheet of galaxies to the north.

Given the ubiquity of filamentary and planar structures on ~20 Mpc scales (Bond et al. 2010), the significance of these absorber large-scale structure associations depend strongly on how common such structures are around any given point—for example, if a diffuse sheet of galaxies like that toward A1 is typical in most 20 × 20 Mpc fields, the presence of such a sheet near A1 becomes less physically meaningful. Conversely, if such sheets are rare, A1 and the sheet are almost certainly associated. To test this empirically, we drew 140 random samples of galaxies from a larger portion of the SDSS ($\alpha = 09h–16h$, $\delta = 10^\circ–40^\circ$; $z = 0.026–0.030$) in boxes with dimensions identical to Figures 2 and 3, smoothed the galaxy distributions with a $\sigma = 1.25$ Mpc Gaussian filter to better bring out extended structure, and searched by eye for similar filamentary structures near the box centers.

Seven such “random” samples are shown in Figure 4 along-side smoothed versions of Figures 2 and 3 (labeled as “A1” and “A2”) for comparison. Again the caveat about the difficulty of quantifying such structures applies; however, as many as 30%–40% of the random samples exhibit relatively diffuse galaxy distributions like that near A1. By contrast, strong filaments like the one coincident with A2 are rare: only in ~5%–10% of these 140 random samples do structures comparable to the filament in Figure 3 ($N_{\text{gal}} \gtrsim 100$, length ~20 Mpc, width ~5 Mpc) fall within a few Mpc of the box center. This test further reinforces the conclusion that A2 is real and associated with a nearby galaxy filament; on the other hand, the presence of a relatively common galaxy sheet near A1 may be a coincidence.

5. SUMMARY

Using the SDSS spectroscopic survey, we have investigated the presence and nature of large-scale galaxy structures in the vicinity of two possible WHIM absorbers reported by Nicastro et al. (2005a) in the Chandra spectrum of Mrk 421. Our conclusions are as follows.

1. The X-ray absorber at $z = 0.027$ coincides with a strong filamentary structure of galaxies. Given that such structures are expected to follow warm-hot intergalactic gas, this absorption system may therefore trace the intergalactic medium associated with this filament.

2. A weaker filament or sheet of galaxies may be associated with the weaker $z = 0.011$ absorption system. However, given the lower significance of this X-ray detection, the larger distance to the galaxy structure (4.7 Mpc), and the greater likelihood (~30%–40%) of a chance superposition, this absorber-filament alignment may be spurious.

3. Both of these absorbers lie more than 350 kpc from the nearest SDSS-detected galaxy; thus, if the X-ray detections are real, they likely trace gas associated with large-scale structures rather than individual galaxies.

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