DISCOVERY OF A LARGE-SCALE FILAMENT CONNECTED TO THE MASSIVE GALAXY CLUSTER MACS J0717.5+3745 AT $z = 0.55^{1,2,3}$

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ABSTRACT

We report the detection of a $4\, h^{-1}_{100}$ Mpc long large-scale filament leading into the massive galaxy cluster MACS J0717.5+3745. The extent of this object well beyond the cluster’s nominal virial radius ($\sim$2.3 Mpc) rules out prior interaction between its constituent galaxies and the cluster and makes it a prime candidate for a genuine filament as opposed to a merger remnant or a double cluster. The structure was discovered as a pronounced overdensity of galaxies selected to have $V-R$ colors close to the cluster red sequence. Extensive spectroscopic follow-up of over 300 of these galaxies in a region covering the filament and the cluster confirms that the entire structure is located at the cluster redshift of $z = 0.545$. Featuring galaxy surface densities of typically $15\, h^{-2}$ Mpc$^{-2}$ down to luminosities of $0.13 L^*$, the most diffuse parts of the filament are comparable in density to the clumps of red galaxies found around A851 in the only similar study carried out to date (Kodama et al.). Our direct detection of an extended large-scale filament funneling matter onto a massive distant cluster provides a superb target for in-depth studies of the evolution of galaxies in environments of greatly varying density and supports the predictions from theoretical models and numerical simulations of structure formation in a hierarchical picture.

Subject headings: galaxies: clusters: individual (MACS J0717+3745) — large-scale structure of universe

Online material: color figures

1. INTRODUCTION

In the now widely accepted hierarchical picture of structure formation, massive galaxy clusters form through a series of successive mergers of smaller clusters and infalling groups, as well as through continuous accretion of matter in their surroundings. Both numerical simulations (e.g., Colberg et al. 2000) and theoretical work (Bond et al. 1996; Yess & Shandarin 1996) predict that this growth process proceeds in a highly nonisotropic fashion with infall and mergers occurring along preferred directions, resulting in spatially highly correlated structures often referred to as the “cosmic web” (Bond et al. 1996).

While there is overwhelming qualitative evidence in support of this picture from large-scale galaxy redshift surveys (e.g., Geller & Huchra 1989; York et al. 2000; Colless et al. 2001), such surveys sample only a very small volume to a depth sufficient to probe the scales of several megaparsecs that characterize the actual infall region around clusters. Also, galaxies are expected to represent only a small fraction of the total baryonic mass contained in filaments, which—according to some estimates—could rival the mass content of clusters (Cen & Ostriker 1999). Observational evidence of diffuse gas and dark matter in these filamentary structures has, however, proven difficult to obtain, owing to the low densities involved. The direct detection of filaments in the vicinity of galaxy clusters thus remains an observational challenge that is central to our understanding of the cluster formation process.

In this Letter we present the optical discovery of a large-scale filament associated with a massive X-ray–selected galaxy cluster at $z = 0.55$. Throughout we assume a $\Lambda$ cold dark matter cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $h_0 = H_0/(100\, \text{km s}^{-1}\, \text{Mpc}^{-1}) = 0.7$.

2. EXPECTATIONS FROM NUMERICAL SIMULATIONS

Using simulations conducted by the Virgo consortium, Colberg et al. (1999) investigate the relation between the infall pattern around massive clusters and the large-scale filamentary structure surrounding them. As expected in a filamentary universe, they find the infall onto clusters to occur preferentially from distinct directions. Interestingly, there is a tight correlation between the infall directions at different times for a given cluster: although different filaments dominate the infall at different times (redshifts), the filaments themselves are stable over the full redshift range of the simulation. While filaments funneling matter onto the cluster contribute to the observed large-scale structure over a wide range of scales, all filaments are much more prominent in the vicinity of massive clusters, the infall region, than in between clusters. Colberg and coworkers’ study also confirms the relevance of filaments for the baryon budget of the universe: at radii between 4 and 6.5 Mpc more than 40% of the total mass is contained in filaments.

3. OBSERVATIONAL EVIDENCE OF FILAMENTS

Observational evidence of diffuse gas or galaxy overdensities in three-dimensional space (not to mention dark matter) in filaments is sparse. X-ray detections of filaments have been reported for superclusters and double clusters (Kull & Böhringer 1999; Tittley & Henriksen 2001; Rines et al. 2001), but the interpretation of these findings as evidence of filaments has been questioned on the grounds that the observed emission might be due to gas swept out of these cluster associations in earlier merger

\[ L_{\Lambda} = H_0/(100\, \text{km s}^{-1}\, \text{Mpc}^{-1}) \]

\[ Q_p = \frac{p}{Q_{p_{0.7}}} \]

\[ \frac{p_{100}}{h} = 0.7 \]

\[ M_{\Lambda} \]

\[ p_{p_{0.7}} \]

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events. Briel & Henry (1995) find an upper limit on the X-ray surface brightness of filaments between clusters of $4 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ arcmin$^{-2}$ (0.5–2.0 keV) from ROSAT All-Sky Survey data. This value is about an order of magnitude lower than the X-ray surface brightness detected by, e.g., Kull & Böhringer. More recent work by Kodama et al. (2001) and Durret et al. (2003) is promising in the sense that filamentary structures are detected in the vicinity of isolated galaxy clusters. Unfortunately, the hypothesized filaments all lie well within the virial radius of the cluster and may thus again be merger residuals rather than genuine filaments. The most promising possible detection (3 $\sigma$) of a filament thus remains the half-degree long X-ray feature discussed by Scharf et al. (2000), which, at $1.6 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ arcmin$^{-2}$ (0.5–2.0 keV), has a X-ray surface brightness consistent with predictions. Scharf and coworkers tentatively identify their discovery as a filament extending over at least 8 Mpc (for an assumed redshift of $z > 0.3$). Without discernible connection to a massive cluster of galaxies within the study region, this filament is, however, again unlikely to be the kind of structure predicted to funnel matter onto massive clusters at the densest vertices of the cosmic web.

4. MACS J0717.5+3745

The massive galaxy cluster MACS J0717.5+3745 [$\alpha = 07^h17^m31.5^s$, $\delta = +37^\circ45^\prime25^\prime$ (J2000.0)] was independently discovered as the host of a diffuse radio source by Edge et al. (2003) and as a bright X-ray source in the course of the MASSive Cluster Survey (MACS; Ebeling et al. 2001). Extensive follow-up observations of MACS J0717.5+3745, one of the most massive clusters known at $z > 0.5$ and a severely disturbed system, have been conducted by the MACS team at energies ranging from hard X-rays to submillimeter wavelengths. The detection of the Sunyaev-Zel’dovich effect in the direction of MACS J0717.5+3745 is reported by LaRoque et al. (2003); a detailed investigation of the system’s X-ray properties and a weak-lensing study of the dark matter distribution around MACS J0717.5+3745 are in preparation.

Deep imaging observations of MACS J0717.5+3745 in the V, R, I, and $z'$ passbands were performed with the SuprimeCam wide-field camera (Miyazaki et al. 2002) on the Subaru 8.3 m telescope on Mauna Kea in December 2000 and 2001. SuprimeCam provides a large field of view of $34^\prime \times 27^\prime$ and a 0.2 pixel$^{-1}$ scale. The integration times in V, R, I, and $z'$ were $6 \times 4, 6 \times 8, 7 \times 6$, and $9 \times 3$ minutes, and the seeing (as measured from the final co-added frames) was 0′60, 0′88, 0′74, and 0′60, respectively.

Multiobject spectroscopy (MOS) observations of galaxies in the MACS J0717.5+3745 field were performed on the Keck 10 m telescope using the Low Resolution Imaging Spectrograph (Oke et al. 1995) in 2000 November, 2002 January, and 2002 November. Additional MOS follow-up observations were obtained using the DEep Imaging Multi-Object Spectrograph spectrograph on Keck II in 2003 December and the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2003) on Gemini North in 2004 March. Full details of the observational setup will be provided by E. Barrett et al. (2004, in preparation). Redshifts were determined via a multitemplate cross-correlation method typically emphasizing the calcium H and K lines (H. Ebeling et al. 2004, in preparation, will contain details).

5. RESULTS

Figure 1 shows a color-magnitude diagram for all galaxies within 2 Mpc of the nominal cluster center (slightly less than the nominal virial radius of 2.3 Mpc) as obtained from our Subaru data. The cluster red sequence is clearly visible. Galaxies within the gray band (corresponding to $I < 22.5$ and $V−R$ values within ±0.2 mag of the red sequence) were given highest priority for follow-up spectroscopy; bluer galaxies were included where permitted by the mask design constraints.

Figure 2 shows a $20 \times 20$ arcmin$^2$ subregion of the $VRz'$ SuprimeCam image. Overlay are the contours of the surface density of galaxies with $I < 22.5$ and $V−R$ colors consistent with the cluster red sequence (highlighted by the shaded region in Fig. 1). Adaptive-kernel smoothing has been applied such that the significance of all features within the bold red contour is at least 3 $\sigma$. The full extent of the galaxy overdensity (including the cluster) is 6.3 Mpc, of which about 4.3 Mpc can be attributed to the filament. This apparently coherent structure thus extends well beyond the virial radius (~2.3 Mpc) of the cluster at its northwestern endpoint, making it the first convincing candidate for the type of filament found to channel matter onto massive clusters in the numerical simulations of, e.g., Colberg and coworkers. The galaxy surface densities within the filament are found to range from 10 to 20 galaxies Mpc$^{-2}$ with our $I$-band magnitude limit of 22.5 corresponding to a limiting $V$-band luminosity$^4$ of $0.10L^*$ at $z = 0.545$.

To test the hypothesis that the apparently coherent structure evident in Figure 2 is indeed a large-scale filament connected to MACS J0717.5+3745, we need to establish whether the color selection illustrated in Figure 1 and applied in Figure 2 selects primarily galaxies at the cluster redshift. Figure 3 shows that the spatial distribution of all galaxies with spectroscopic redshifts as of 2004 March samples the full extent of the galaxy overdensity of Figure 2. Figure 4 demonstrates (1) that the redshift distribution of galaxies within the cluster proper is indistinguishable from the one in the filament, and (2) that our $V−R$ color criterion is efficient at selecting galaxies at $z \sim 0.55$, i.e., the cluster redshift. We conclude that the entire filament as shown in Figure 2 is located at $z = 0.55$ and thus at

$^4$ We assume a value of $M^* = -20.23$ (Brown et al. 2001) for field galaxies in the local universe, moderate passive evolution in $M^*$ of ~0.4 mag out to $z = 0.545$, and a typical color of $V−I = 2$ for an elliptical galaxy at $z = 0.545$. 

![Figure 1](https://example.com/figure1.png)
Fig. 2.—$V-R$ color image of a 20 $\times$ 20 arcmin$^2$ region around MACS J0717.5+3745 as obtained with SuprimeCam. The overlaid contours show the adaptively smoothed surface density distribution of galaxies with $I < 22.5$ and $V-R$ colors following the cluster red sequence (cf. the shaded region in Fig. 1). Contours are spaced logarithmically, with the lowest contour corresponding to 10 galaxies Mpc$^{-2}$ (50% above the background value) and the levels of adjacent contours differing by 20%. Contours are shown dotted outside the region within which the adaptive-smoothing criterion (significance greater than 3 $\sigma$) is met (bold red contour). The contour marking the shallow peak of the southeastern end of the filament marks a local peak galaxy surface density of 20.7 galaxies Mpc$^{-2}$. Since the bottom edge of the shown region is also the edge of the overall Subaru SuprimeCam image, it is conceivable that the filament in fact extends yet farther south than suggested by the galaxy surface density contours shown here.

the same redshift as the massive galaxy cluster at its northwestern endpoint.

6. CONCLUSIONS

MACS J0717.5+3745 is one of the most massive clusters known at $z > 0.5$, with a pronounced double-peaked galaxy distribution indicative of an ongoing merger event and a radio relic near the core suggesting additional recent merger activity (Edge et al. 2003). Our discovery of a large-scale filament leading into the cluster extends the evidence for significant dynamical activity to scales of at least 5 Mpc from the cluster core, well beyond the virial radius of 2.3 Mpc. Although numerical simulations by Balogh et al. (2000) suggest that some fraction of the galaxies observed as far out as twice the virial radius from the center of a massive cluster may have been scattered there by previous interactions with the cluster core, their distribution should be approximately isotropic and strongly declining with radius. Neither is the case for this filament, which therefore should consist predominantly of matter approaching the cluster for the first time.

The cluster merger axis points to the northwest in excellent alignment with the overall orientation of the filament, suggesting that the current merger activity is due to a group from the filament falling into the cluster core. The prominence of the filament out to at least 4 Mpc implies that infall of matter in the same direction will persist for roughly the next 4 Gyr assuming an infall rate of $\sim 1000$ km s$^{-1}$ ($\sim 1$ Mpc Gyr$^{-1}$).

Extending to (and possibly beyond) a distance of 4–5 Mpc from the cluster core, the filament is detected as a pronounced overdensity of galaxies with $V-R$ colors within $\pm 0.20$ mag of the cluster red sequence. At measured densities of typically 4 (15, 30) Mpc$^{-2}$ for red galaxies with $L > 0.3 (0.1, 0.02)L_V$ at $z = 0.545$, the most diffuse part of the contiguous filament leading into MACS J0717.5+3745 is as dense as the clumps of (mainly) red galaxies around A851 ($z = 0.41$) discovered by Kodama et al. (2001). The prevalence of early-type galaxies in our filament is also in qualitative agreement with recent
Fig. 3.—Locations of all galaxies with spectroscopic redshifts as of 2004 March; filled symbols mark galaxies with redshifts between 0.52 and 0.57, i.e., the 3σ range around the systemic redshift of MACS J0717.5+3745 (see also Fig. 4). The area shown is the same as depicted in Fig. 2. The shaded regions and box outlines mark the fields targeted with the individual MOS masks. The dotted line marks a circle of 1 Mpc radius around the nominal cluster center. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 4.—Top: Histogram of all 302 redshifts obtained by us so far in the regions highlighted in Fig. 3. The shaded histogram represents the redshift distribution of galaxies within 1 Mpc of the cluster core (Fig. 3, dashed circle). Bottom: Galaxy redshift vs. offset in V−R color from the cluster red sequence for all galaxies observed so far. Our color criterion efficiently selects galaxies at and around z = 0.55. [See the electronic edition of the Journal for a color version of this figure.]

processes and environmental effects governing the transition from field to cluster galaxies. Additional observations are planned to map the dark matter distribution along the filament via weak lensing and to measure galaxy morphologies and colors in this region.

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