Gas filaments of the cosmic web located around active galaxies in a protocluster

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Cosmological simulations predict that the Universe contains a network of intergalactic gas filaments, within which galaxies form and evolve. However, the faintness of any emission from these filaments has limited tests of this prediction. We report the detection of rest-frame ultraviolet Lyman-α radiation from multiple filaments extending more than one megaparsec between galaxies within the SSA22 protocluster at a redshift of 3.1. Intense star formation and supermassive black-hole activity is occurring within the galaxies embedded in these structures, which are the likely sources of the elevated ionizing radiation powering the observed Lyman-α emission. Our observations map the gas in filamentary structures of the type thought to fuel the growth of galaxies and black holes in massive protoclusters.

Imaging the cosmic web in emission would provide two-dimensional (2D) information. Filaments are predicted to emit the hydrogen Lyman-alpha (Lyα) line by means of the fluorescence induced by the ultraviolet background (UVB) radiation. The intrinsically low intensity of the UVB means the expected surface brightness of a filament is \(2.5 \times 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}\) at \(z = 3\) (9), so direct detection of UVB-induced fluorescent emission from IGM filaments has remained elusive (20). To circumvent this limitation, one can examine regions where local ionizing sources, such as star-forming galaxies and/or active galactic nuclei (AGNs), boost the local radiation field and hence elevate the Lyα emission to detectable levels (11). Extended, (up to hundreds of kiloparsecs) Lyα nebulae have been observed around quasars, with morphologies and kinematics suggestive of cosmic web filaments connecting to the quasar host galaxies (12–19). Similarly, using Lyα-emitting galaxies (LAEs) or extended emission arising from the circumgalactic medium (CGM) as tracers, statistical evidence for filaments has been reported (16–18). These studies do not directly connect the cosmic web to the population of galaxies and SMBHs on cosmological scales.

We searched for extended filamentary structures using the Multi Unit Spectroscopic Explorer (MUSE) on the European Southern Observatory’s Very Large Telescope (VLT). Our observations targeted the galaxy protocluster SSA22 at \(z = 3.09\) (19), which was already known to host 3D filamentary structures as traced by LAEs on a scale of 30 comoving megaparsec (comoving distances remain constant over time if the two objects are moving with the expansion of the Universe) (20). At the intersection of these large-scale structures lies the protocluster core, where several intensely star-forming galaxies are known to lie within a 2′ by 3′ region around the core, which was previously mapped at 1.1 mm with the Atacama Large Millimeter/submillimeter Array (ALMA) [the ALMA Deep Field in SSA22 (ADP2)] (21). To trace extended Lyα emission in this region, we mapped the ADP2 field with a six-pointing MUSE mosaic covering 116′′ by 169′′, equivalent to 0.9 by 1.3 physical Mpc at \(z = 3.09\) [Fig. 1 (22)].

We searched the MUSE data cube for extended Lyα emission in conjunction with a narrow-band image covering the expected wavelength of redshifted Lyα emission taken with Suprime-Cam on the Subaru telescope (22). We identified extended Lyα emission with surface brightness \(\Sigma_{\text{Lyα}} \sim 3 \times 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}\) across the observed field, visible in the optimally extracted Lyα map [Fig. 2 (22)]. This map shows bright areas associated with the CGM of galaxies, along with several patches of emission at low surface brightness that connect to, but are not immediately associated with, individual galaxies in this region. Most of this low-surface-brightness Lyα emission forms two main filaments running in a north-south direction, each with a total extent of >1 physical megaparsec in projection. The scale of this emission far exceeds the expected size of the dark-matter halo of even the most massive individual galaxies at this epoch (the halo radius is \(\sim 100 \text{ kiloparsec}\) for a \(10^{12.5} \text{ M_☉}\) halo at \(z = 3\), where \(M_☉\) is the mass of the Sun), so the Lyα signal likely traces a structure connecting several galaxies. This network of filaments likely extends beyond the region that we mapped, because the Lyα emission is detected up to the edge of the MUSE field of view.

As shown in Fig. 3, A and B, the majority of the Lyα emission is detected over a finite-of-sight velocity range of \(-500\) to \(+1000 \text{ km s}^{-1}\) relative to \(z = 3.09\). This velocity range reflects not only the 3D distribution of matter on large scales, but also the gas kinematics within the protocluster core, which, coupled with radiative transfer effects, can produce velocity

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graduated of several hundreds of kilometers per second.

Observations of the SSA22 protocluster have detected 35 Lyα blobs (LABs), defined as extended Lyα nebulae with sizes between several tens and several hundreds of kiloparsec (23–25). Two of these LABs lie within our field of view, each with sizes of ~40 kiloparsec when measured at a Lyα surface brightness threshold of $\Sigma_{\text{Lyα}} = 2.2 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ (24). Figure 2 shows that these two LABs are parts of a larger network of megaparsec-scale filaments. Embedded in these filaments are also other patches of enhanced Lyα emission, some of which are associated with galaxies. We interpret the previously known LABs as bright knots within a wider network of gas filaments, and surmise that the fainter and more extended Lyα-emitting gas in these filaments has previously eluded detection because of its low surface brightness (18, 26).

To explore the link between these filaments and the associated galaxy population, we measured redshifts of galaxies in this field using a multiwavelength spectroscopic dataset. The deep, 1.1-mm ADF22 map enables us to identify submillimeter galaxies (SMGs), which are massive, intense starburst galaxies with large amounts of gas and dust in their interstellar mediums. The x-ray–luminous AGNs, which host growing SMBHs, were identified from observations using the Chandra space telescope (22, 27). Spectroscopic redshifts for these populations were determined using a combination of emission lines [CO $J = 3 \rightarrow 2$, Hβ, and (O iii) 4959 and 5008 A lines] from ALMA data and observations with the Multi-Object Spectrometer for Infra-Red Exploration (MOSFIRE) on the Keck I telescope (22). We confirmed that 16 SMGs and 8 x-ray–luminous AGNs are protocluster members, with redshifts 3.085 \leq z \leq 3.098 (table S2). All of the SMGs and x-ray–luminous AGNs were distributed within the same structure (see Figs. 2 and 3), closely tracking the Lyα filaments both spatially (in projection) and in velocity (fig. S10).

A similar pattern was also evident for normal star-forming galaxies and LAEs (fig. S7). We interpret this close alignment as evidence that the Lyα filaments are directly linked to the population of active galaxies and SMBHs. Gas filaments are thought to supply (under the effect of gravity) the fuel for active SMGs and x-ray–luminous AGNs.

The filaments have Lyα brightness above the level expected from fluorescence emission induced by the UVB (8, 11). Radiative transfer calculations predict a maximum surface brightness from optically thick gas of $\sim 2.5 \times 10^{-20}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ assuming a z ~3 UVB (9). Our observations contain emission at levels of $\Sigma_{\text{Lyα}} \geq 3 \times 10^{-20}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, which, in the optically thick limit, requires an intensity of the ionizing radiation field that is ~12 times brighter than that predicted by UVB models (22). This corresponds to a Lyα emitting photon flux $\psi > 4 \times 10^3$ cm$^{-2}$ s$^{-1}$. If we assume that the gas is fully ionized, then the observed surface brightness would imply even higher photon fluxes, densities of $\sim 6 \times 10^{-3}$ cm$^{-3}$ (22) for gas at $T \sim 10^4$ K (where $T$ is temperature), and a typical filament width of 100 kpc (Fig. 2).

Fluctuations in the observed surface brightness suggest a variable density across the structure, as commonly found for bright Lyα nebulae (12). Figure 2 also shows regions of much higher surface brightness, particularly overlapping with galaxies (see also fig. S7). The fainter emission regions display lower velocity dispersions (full width at half maximum (FWHM) ~150 km s$^{-1}$) than the bright knots (FWHM ~730 km s$^{-1}$), where the surface brightness of the latter is similar to the typical brightness of the LABs (figs. S4 and S9). This higher surface brightness may indicate the presence of localized sources of ionization, such as star formation or AGN activity, as commonly seen in LABs (28).

**Fig. 1.** Multiwavelength images of ADF22 illustrating the overdensity of galaxies and AGNs in a narrow redshift range at $z = 3.09$. Each panel is centered at ($\alpha$, $\delta$) = (22h17m34.0s, +00d17m00s), where $\alpha$ is right ascension and $\delta$ is declination, and 2’ by 3’ in size, with the inner dashed area showing the MUSE coverage, 116’ by 169’ (0.9 by 1.3 Mpc at $z = 3.1$). North is up and east is left. (A) Pseudocolor map created from the MUSE cube (synthesized $V$-, $R$-, and $I$-bands are used for the blue, green, and red channels, respectively). (B) The 1.1-mm ALMA continuum map of ADF22 (22). Identified sources at $z = 3.09$ are marked with white circles (SMGs) and squares (AGNs); positions and redshifts are listed in table S2. (C) Pseudocolor map of the Chandra x-ray data: 2 to 8 keV (hard band), 0.5 to 8 keV (full band), and 0.5 to 2 keV (soft band) are used for the blue, green, and red channels, respectively.

**Fig. 2.** Lyα emission map optimally extracted from the MUSE observations and covering the same field as that in Fig. 1. Lyα emissions largely consist of two groups of filamentary structures for >1 physical megaparsec. One high-surface-brightness filament is visible running north to south on the west side of the field, whereas a fainter (and hence more fragmented) structure runs north to south up the east side of the field. Contours with solid, dashed, and dotted lines show Lyα surface brightness levels of $\Sigma_{\text{Lyα}} = 0.3$, 1.0, and $2.0 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, respectively (these correspond to 2, 7, and 13 $\sigma$ above the representative noise level). Navy blue contours indicate the extent of the two LABs in this field (23). Positions of SMGs and x-ray–luminous AGNs at $z = 3.09$ are also shown. The large, filled black circle shows data removed around a foreground, low-redshift galaxy.
Given the large number of active galaxies in this region, the elevated photon flux required to power the filaments could be provided by the galaxy population identified within our field. To test this hypothesis, we determined the number of ionizing photons provided by x-ray–selected AGNs and SMGs (22). Under the simple assumption that the ionizing sources typically lie 250 kpc from filaments, the required photon flux corresponds to a photon number emission rate of $Q_{\text{ion}} \sim 10^{57}$ s$^{-1}$ to power the whole filament. The eight x-ray AGNs in the structure have $L_x \sim 10^{44}$ erg s$^{-1}$ corresponding to a total rate of $Q_{\text{ion}} \sim 10^{57}$ s$^{-1}$, whereas the 16 SMGs that are protocluster members form stars at a rate of 160 to 1700 $M_\odot$ year$^{-1}$ and hence produce a total of $Q_{\text{ion}} \sim 10^{57}$ s$^{-1}$. This is sufficient ionizing photon flux to power the filament emission, even under the assumption that only 1% of the photons escape their host galaxies. This simple estimate, although an approximation of the more complex radiative transfer in this region, supports our interpretation that the gas residing in these filamentary structures is ionized by the photons produced by star-forming galaxies and AGNs in the massive protocluster core.

The volume densities of SMGs and x-ray AGNs in this field are about three orders of magnitude higher than the volume average at this epoch (22). Such an overdensity of active populations is very rare (29), and there is little observational evidence regarding how this intense activity is fueled and sustained. Cosmological simulations suggest that rapid infall of gas from the cosmic web into protoclusters may lead to the formation of SMGs (30). Although gas inflows are not directly observable in our data, the location of SMGs and AGNs within the filaments supports the idea that large reservoirs of gas are funneled toward forming galaxies under the effect of gravity, triggering and sustaining their star formation and driving the growth and activity of their central SMBHs. Assuming a typical density of $6 \times 10^{-3}$ cm$^{-3}$ for filaments with (projected) thicknesses of ~100 kiloparsec, the region imaged by our observations contains $\sim 10^{12} M_\odot$ of gas (depending on the filling factor of the gas), which is potentially available to accrete onto galaxies in this region and so fuel their continuing star formation (22).

Our observations have uncovered a large-scale filamentary structure in the emission from the core of the SSA22 protocluster. Evidence of similar structures in other protoclusters from imaging observations (15, 25) suggests that this may be a general feature of protoclusters in the early Universe. The network of filaments in SSA22 is found to connect individual galaxies across a large volume, allowing it to power star formation and black-hole growth in active galaxy populations at $z \sim 3$.

REFERENCES AND NOTES

1. J. R. Bond, J. Kolman, D. Pogosyan, Nature 360, 603–606 (1996).
2. V. Springel et al., Nature 435, 629–636 (2005).
3. A. Dekel, B. Holwerda, M. Gentile, ApJ 707, L175–L180 (2010).
4. M. Fumagalli et al., Mon. Not. R. Astron. Soc. 413, 1976–1988 (2011).
5. D. Martínez et al., Mon. Not. R. Astron. Soc. 468, 376–3787 (2019).
6. M. Rauch, Ann. Rev. Astron. Astrophys. 36, 267–316 (1998).
7. K. G. Lee, M. White, Astrophys. J. 631, 181 (2016).
8. J. A. Kollmeier et al., Astrophys. J. 708, 1048–1075 (2010).
9. F. Haardt, P. Madonna, Astrophys. J. 746, 125–134 (2012).
10. S. G. Gallego et al., Mon. Not. R. Astron. Soc. 475, 3854–3869 (2018).
11. S. Cantalupo, M. Cusin, S. J. Lilly, F. Miniati, Astrophys. J. 628, 61–75 (2005).
12. S. Cantalupo, F. Annigoni-Batella, J. X. Prochaska, J. F. Hennawi, P. Madonna, Nature 506, 63–66 (2014).
13. D. C. Martin et al., Nature 524, 192–195 (2015).
14. E. Borisova et al., Astrophys. J. 831, 39–57 (2016).
15. S. Kikuta, Y. Matsuda, R. Cen, C. C. Steidel, M. Yagi, T. Hayashino, M. Imanishi, Y. Komiyama, R. Momose, T. Saito, Ly$\alpha$ view around a z=2.8 hyperluminous QSO at a node of the cosmic web. arXiv:1904.07747 [astro-ph.GA] (16 April 2019).
16. M. Fumagalli et al., Mon. Not. R. Astron. Soc. 462, 1978–1988 (2016).
17. L. Woszczek et al., Nature 562, 229–232 (2018).
18. D. K. Erb, M. Bogosavljević, C. C. Steidel, Astrophys. J. 740, L31–L36 (2011).
19. C. Steidel et al., Astrophys. J. 492, 428–438 (1998).
20. Y. Matsuda et al., Astrophys. J. 634, L125–L128 (2005).
21. H. Umehata et al., Astrophys. J. 815, L18–L13 (2015).
22. See supplementary materials.
23. C. C. Steidel et al., Astrophys. J. 532, 170–182 (2000).
24. Y. Matsuda et al., Astron. J. 128, 569–584 (2004).
25. D. Christopher Martin et al., Astrophys. J. 786, 107–125 (2014).
26. M. Fumagalli et al., Mon. Not. R. Astron. Soc. 471, 3686–3698 (2017).
27. B. D. Lehnert et al., Astrophys. J. 691, 687–695 (2009).
28. J. E. Geach et al., Astrophys. J. 700, 1–9 (2009).
29. C. M. Casey, Astrophys. J. 824, 96–51 (2016).
30. D. Narayanan et al., Nature 525, 496–499 (2015).

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SUPPLEMENTARY MATERIALS
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Glowing filaments of the cosmic web

Most gas in the Universe lies in the intergalactic medium, where it forms into sheets and filaments of the cosmic web. Clusters of galaxies form at the intersection of these filaments, fed by gas pulled along them by gravity. Although this picture is well established by cosmological simulations, it has been difficult to demonstrate observationally. Umehata et al. mapped emission from the intergalactic medium in an area around galaxies that are starting to form a cluster (see the Perspective by Hamden). They found that the gas is arranged into filaments, whose position and velocity correlate with star-forming galaxies, supporting the theoretical picture.

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