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Spatial correlation between submillimetre and Lyman-α galaxies in the SSA 22 protocluster

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Lyman-α emitters are thought to be young, low-mass galaxies with ages of ~10^8 yr (refs 1, 2). An overdensity of them in one region of the sky (the SSA 22 field) traces out a filamentary structure in the early Universe at a redshift of $z \approx 3.1$ (equivalent to 15 per cent of the age of the Universe) and is believed to mark a forming protocluster[3,4]. Galaxies that are bright at (sub)millimetre wavelengths are undergoing violent episodes of star formation[5–8], and there is evidence that they are preferentially associated with high-redshift radio galaxies[9], so the question of whether they are also associated with the most significant large-scale structure growing at high redshift (as outlined by Lyman-α emitters) naturally arises. Here we report an imaging survey of 1,100-μm emission in the SSA 22 region. We find an enhancement of submillimetre galaxies near the core of the protocluster, and a large-scale correlation between the submillimetre galaxies and the low-mass Lyman-α emitters, suggesting synchronous formation of the two very different types of star-forming galaxy within the same structure at high redshift. These results are in general agreement with our understanding of the formation of cosmic structure.

Many different populations of young star-forming galaxies in the early Universe are known, but the relations among them and to the cosmic large-scale structure are still not well understood. The members of one of these populations are characterized by their strong Lyman-α (Lyα) emission (luminosity, $L_{\mathrm{Ly}\alpha} \gtrsim 10^{42}$ erg s^{-1}), arising from ionized gas; their deficiency in ultraviolet continuum emission, which is interpreted as having a relatively small stellar component[1] ($M_{\mathrm{star}} \lesssim 10^9 M_\odot$, where $M_\odot$ is the solar mass); and their small size[2] ($\lesssim$1 kpc in diameter). The Lyα emitters towards SSA 22 trace a large-scale (~10 arcmin) filamentary structure that extends over several tens of megaparsecs (co-moving scale) and which may be the largest protocluster yet detected at high redshift[4].

Massive galaxies forming through accretion and mergers of small galaxies in such high-density environments are expected to be dust-obscured starbursts, which are too faint to detect at optical wavelengths but are observed as submillimetre-bright galaxies (SMGs). It is known from previous studies that SMGs have molecular gas reservoirs of $10^{10}M_\odot$–$10^{11}M_\odot$ (ref. 10) for their star-formation activities, suggesting that they are progenitors of massive elliptical galaxies seen in the cores of present-day clusters[8,11]. Individual ~5-arcmin^2-wide, deep submillimetre surveys in the direction of powerful, high-redshift radio galaxies, which are also believed to trace protoclusters[12], have presented tentative evidence for an enhancement in the number density of submillimetre sources around them[9]. Although these observations were limited in sensitivity and spatial coverage, they support the idea that SMGs are related to large-scale structure. To better understand the connection between the formation of massive galaxies and large-scale structure, we mapped the large-scale distribution of (sub)millimetre-bright, dusty starburst galaxies in the SSA 22 protocluster.

We carried out a wide-area (390-arcmin^2) survey of the SSA 22 field at 1,100 μm using the AzTEC camera[13] mounted on the Atacama Submillimeter Telescope Experiment (ASTE)[14], Chile (see also Supplementary Fig. 1). Our AzTEC map (Fig. 1a), which is more than 20 times larger than any of the existing maps at submillimetre wavelengths in this field (see, for example, refs 15–17), is wide enough to cover the region of the entire protocluster. We have detected 30 SMGs with signal-to-noise ratios $s/n \geq 3.5$ (a full source list is given in Supplementary Table 1). Their intrinsic flux densities are in the range 1.9–8.4 mJy (1 Jy = 10^{-23} erg s^{-1} cm^{-2} Hz^{-1}), corresponding to far-infrared luminosities of $L_{\mathrm{FIR}} > 4 \times 10^{12} L_\odot$ (where $L_\odot$ is the solar luminosity) if we assume an emissivity index of $\beta = 1.5$, a dust temperature of $T_{\mathrm{dust}} = 40$ K and that the sources are located at $z = 2$–6. The inferred star-formation rates of the 1,100-μm sources are ~$10^3 M_\odot$ yr^{-1}, assuming that star formation is the dominant mechanism that heats the dust.

The most prominent new finding is that the distribution of the brighter (≥2.7 mJy) half of the 1,100-μm sources (15 of the 30, hereafter termed 'bright' SMGs; Table 1), which suffer little from incompleteness and false detections (Supplementary Figs 2 and 3), appears to be correlated with the high-density region of Lyα emitters[4], as seen in Fig. 1b. A concentration of bright SMGs ~5 arcmin northwest of the field centre is evident. Seven of the 15 bright SMGs (47%) are concentrated within a 50-arcmin^2 region in the direction that has a large-scale filamentary structure of Lyα emitters ~50 Mpc in depth (see fig. 1 of ref. 18). The number density over this region is 2–3 times higher than those found in blank-field surveys at 1,100 μm (ref. 19). Furthermore, the three most significant sources ($8.4^{+0.8}_{-1.0}$, $4.4^{+0.9}_{-0.8}$, $4.1^{+1.0}_{-0.8}$ mJy) are all located close (<4.5 arcmin) to the peak of the Lyα emitter overdensity. Photometric redshift estimates for the SMGs based on their radio and 24–1,100-μm flux ratios (Supplementary Fig. 4) indicate that they are probably at high redshift ($z > 1$). The redshift estimates also suggest that some fraction of the bright SMGs, including the three most significant sources towards SSA 22, can be located at $z = 3.1$ and may mark the local peak of the underlying mass distribution in the protocluster.

A two-point angular cross-correlation function is often used in determining the fractional increase in the probability of finding a

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source of one population within a unit solid angle as a function of angular distance from a source of another population, relative to a random distribution. We use an angular cross-correlation function to quantify the degree of cohabitation between the Lyα emitters and the bright SMGs. Figure 2 shows the cross-correlation function, which reveals strong correlation signals at angular distances less than 5 arcmin for the bright sample, suggesting close association of the Lyα emitters with the bright SMGs that are most probably embedded in the more massive dark haloes. Monte Carlo simulations (Supplementary Information) also show a correspondence between the two distributions, at a 97.3% significance level, further supporting the positional association of Lyα emitters with bright SMGs.

The gravitational lensing magnification of background galaxies by foreground large-scale structure would immediately preclude the

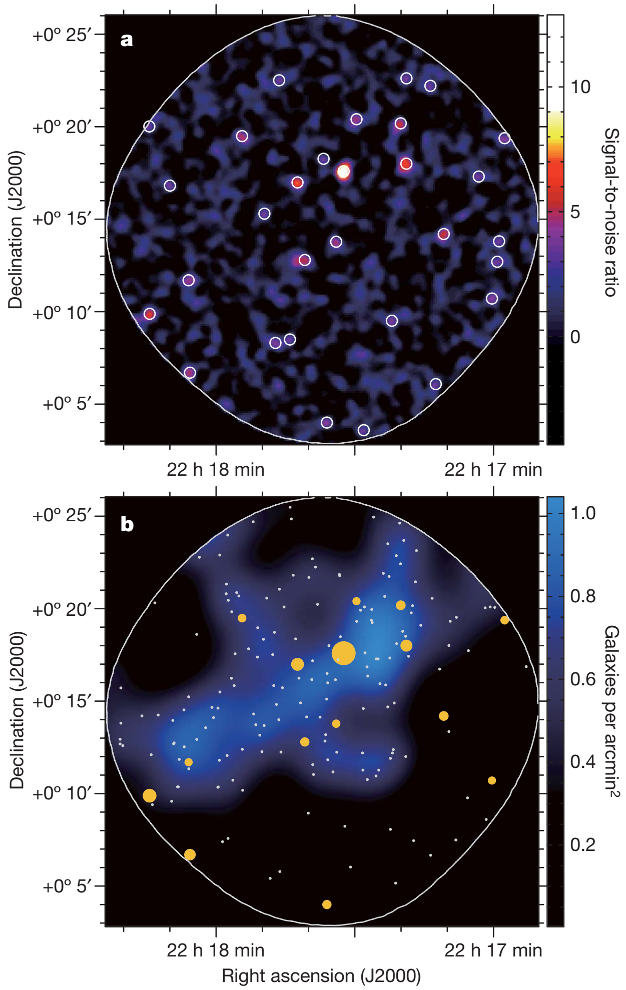

Figure 1 | The positions of 1,100-μm sources and Lyα emitters towards the SSA 22 protocluster region. a, The colour scale shows the map of signal-to-noise ratio at 1,100 μm. The map shows 30 sources with signal-to-noise ratios ≥3.5 (circles). Observations of SSA 22 (field centre at RA = 22 h 17 min 36 s, dec. = +0° 15′ 00′′ (J2000)) were obtained using the AzTEC camera[13], operating at 1,100 μm, mounted on the ASTE 10-m submillimetre telescope[14] during the July–September 2007 observing season. The data consist of a total of 42 h of integration time on source under excellent conditions (zenith atmospheric opacity at 220 GHz, $\tau_{220\,\mathrm{GHz}} = 0.01$–$0.10$). This resulted in a root-mean-square noise level of 0.68–0.99 mJy per beam over 390 arcmin^2. The point spread function of AzTEC on ASTE has a full-width at half-maximum of 28 ± 1 arcsec. **b,** The locations of the bright submillimetre galaxies with $S_{1,100\,\mu\mathrm{m}} \geq 2.7$ mJy (orange filled circles) and the Lyα emitters at $z = 3.1$ (white dots). The sizes of the orange circles are proportional to their 1,100 μm fluxes. The number density field of the Lyα emitters is shown in the colour scale, highlighting the density enhancement of the Lyα emitters, which is thought to trace out the underlying large-scale structure at $z = 3.1$.

Table 1 | The bright SMG sample found in SSA 22

Source name	Coordinate (J2000)		Flux density (mJy)		s/n
	RA (h:min:s)	Dec.	S_{observed}*	S_{deboost}†	
SSA22-AzTEC1	22:17:32.42	+0° 17′ 35.5′′	8.7 ± 0.7	$8.4^{+0.8}_{-1.0}$	12.8
SSA22-AzTEC2	22:17:42.38	+0° 16′ 59.3′′	4.9 ± 0.7	$4.4^{+0.9}_{-0.8}$	7.2
SSA22-AzTEC3	22:17:18.85	+0° 18′ 0.0′′	4.7 ± 0.7	$4.1^{+1.0}_{-0.8}$	6.8
SSA22-AzTEC4	22:18:14.37	+0° 9′ 53.1′′	5.6 ± 0.9	$4.7^{+1.2}_{-1.0}$	6.2
SSA22-AzTEC5	22:17:10.77	+0° 14′ 11.8′′	4.0 ± 0.7	$3.3^{+1.0}_{-0.8}$	5.6
SSA22-AzTEC6	22:17:20.07	+0° 20′ 11.0′′	4.0 ± 0.7	$3.3^{+1.0}_{-0.8}$	5.6
SSA22-AzTEC7	22:17:40.82	+0° 12′ 47.6′′	3.6 ± 0.7	$3.1^{+0.8}_{-0.9}$	5.2
SSA22-AzTEC8	22:18:5.65	+0° 6′ 42.0′′	4.9 ± 1.0	$3.9^{+1.2}_{-1.2}$	5.0
SSA22-AzTEC9	22:17:54.40	+0° 19′ 29.5′′	3.6 ± 0.7	$2.9^{+0.9}_{-0.9}$	5.0
SSA22-AzTEC10	22:17:34.03	+0° 13′ 46.8′′	3.4 ± 0.7	$2.8^{+0.9}_{-0.9}$	4.8
SSA22-AzTEC11	22:17:29.64	+0° 20′ 24.4′′	3.3 ± 0.7	$2.7^{+0.9}_{-0.9}$	4.7
SSA22-AzTEC12	22:17:36.04	+0° 4′ 0.2′′	4.0 ± 0.9	$3.1^{+1.1}_{-1.1}$	4.5
SSA22-AzTEC13	22:18:5.95	+0° 11′ 41.9′′	3.3 ± 0.7	$2.7^{+0.9}_{-1.0}$	4.5
SSA22-AzTEC14	22:17:0.34	+0° 10′ 42.6′′	3.7 ± 0.9	$2.7^{+1.2}_{-1.2}$	4.2
SSA22-AzTEC15	22:16:57.60	+0° 19′ 22.8′′	4.1 ± 1.0	$2.9^{+1.4}_{-1.3}$	4.2

A full list of the 30 submillimetre galaxies is given in Supplementary Table 1. The astrometric accuracy of the catalogue is ~10 arcsec.
* Observed flux density before flux bias correction, plus the 1σ error.
† Deboosted flux density (flux density corrected for the flux bias due to confusion noise using the method described elsewhere[28]), plus the 68% confidence interval.

physical connection between the galaxies and the foreground structure. Some authors[20,21] have reported correlations between bright (sub)millimetre sources and optically selected low-redshift galaxies (mostly at $z < 1$) in other regions of the sky. In general, SMGs are often found at high redshift (median, $z = 2.2$; ref. 22), and the maximal gravitational lensing magnification for a background galaxy at $z \gtrsim 2$ occurs when the foreground lensing structure is at $z \approx 0.5$. Therefore, they concluded that the correlation signal is most probably the result of amplification of background SMGs due to gravitational weak lensing by the foreground low-redshift galaxies. By contrast, the origin of the correlation signals in SSA 22 is most likely intrinsic to the large-scale structure in which both populations, SMGs and Lyα emitters, are embedded. Because the redshift estimates for the SMGs place them at distances coeval with the Lyα emitters, it is unlikely that the correlation seen in SSA 22 is due to amplification of a much higher-redshift ($z \gg 3.1$) SMG population lensed by the structure traced by the Lyα emitters, which are all located at $z = 3.1$ (not $z \approx 0.5$).

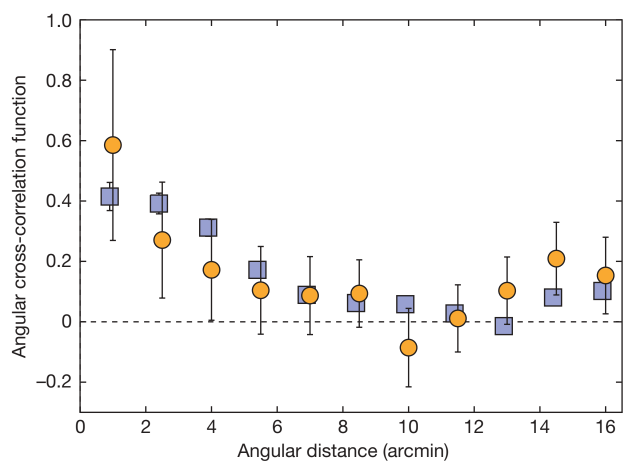

Figure 2 | Angular cross-correlation between submillimetre galaxies and Lyα emitters. The two-point angular cross-correlation function shown here is computed for the 166 Lyα emitters and the 15 brightest ($S_{1,100\,\mu\mathrm{m}} \geq 2.7$ mJy) submillimetre galaxies (orange circles). For reference, we also show the two-point angular autocorrelation function for the SSA 22 Ly-α emitters (blue squares). Small-number statistics prevent us from constraining the auto-correlation function well for the submillimetre galaxies. The correlation functions are computed using the estimator of ref. 29. The error bars are estimated from the root mean square of 1,000 bootstrap samples. See Supplementary Information for details.

We do not detect the dust emission from individual Lyα emitters at the sensitivity of our 1,100-μm observations. This is a strong indication that SMGs and Lyα emitters are different populations, even though the Lyα emitters are spatially correlated with the SMGs. Of the 166 Lyα emitters within our 1,100-μm coverage, none are within the 2σ error circle ($\sim$26-arcsec diameter for $3.5 < s/n < 4.5$ and $\lesssim 20$ arcsec for $s/n > 4.5$) of an SMG; on average, we expect 2–3 SMGs to have a chance to be associated with a Lyα emitter in AzTEC's 28-arcsec beam if 30 SMGs and 166 Lyα emitters are randomly scattered in the 390-arcmin^2 region of our survey. To estimate the dust mass of a typical Lyα emitter in SSA 22, we stack the 1,100-μm images on the positions of the 166 Lyα emitters. We see no dust emission above 107 μJy (2σ) at 1,100 μm, and derive limits on far-infrared luminosity of $L_{\rm FIR} < 1.9 \times 10^{11} L_\odot$ and $L_{\rm FIR} < 1.7 \times 10^{12} L_\odot$ for $\beta = 1.5$ and, respectively, $T_{\rm dust} = 40$ K and $T_{\rm dust} = 70$ K. These luminosities correspond to respective dust masses of $M_{\rm dust} < 1.4 \times 10^7 M_\odot$ and $M_{\rm dust} < 5.8 \times 10^6 M_\odot$, assuming a dust emissivity of $\kappa_{850\,\mu\rm m} = 0.15\,{\rm m}^2\,{\rm kg}^{-1}$ (ref. 23). This limit is 3–40 times lower than the dust masses previously derived[24,25] for Lyα emitters at $z = 6.5$. Of course, the result from a simple stacking analysis cannot strongly constrain the dust properties of the Lyα emitter population. Nevertheless, this limit is 1–2 orders of magnitude lower than the average dust mass found in the population of SMGs, supporting the argument that Lyα emitters are on average less dust obscured[1] than SMGs.

These results provide evidence in favour of the synchronous formation of two very different types of high-redshift star-forming galaxy, SMGs and Lyα emitters, within the same cosmic structure. Although the formation process of SMGs is not yet fully understood, the observational evidence shown here suggests that they may form preferentially in regions of high mass concentration, which is consistent with predictions from the standard model of hierarchical structure formation[26,27]: we are presumably observing a galaxy-formation site where large-scale accumulation of baryonic matter is occurring within the large dark matter halo. Millimetre/submillimetre interferometric identifications followed by accurate measurements of the SMG redshifts will allow us to investigate this further.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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