Dark Cosmology Centre

Niels Bohr Institutet

A dusty, normal galaxy in the epoch of reionization

Darach Watson*, Lise Christensen*, Kirsten Knudsen†, Johan Richard‡, Anna Gallazzi*,§, and Michał Michałowski**

*Dark Cosmology Centre, U. Copenhagen, †Chalmers University, ‡CRAL Lyon, §INAF-Osservatorio di Arcetri, **IfA, Edinburgh

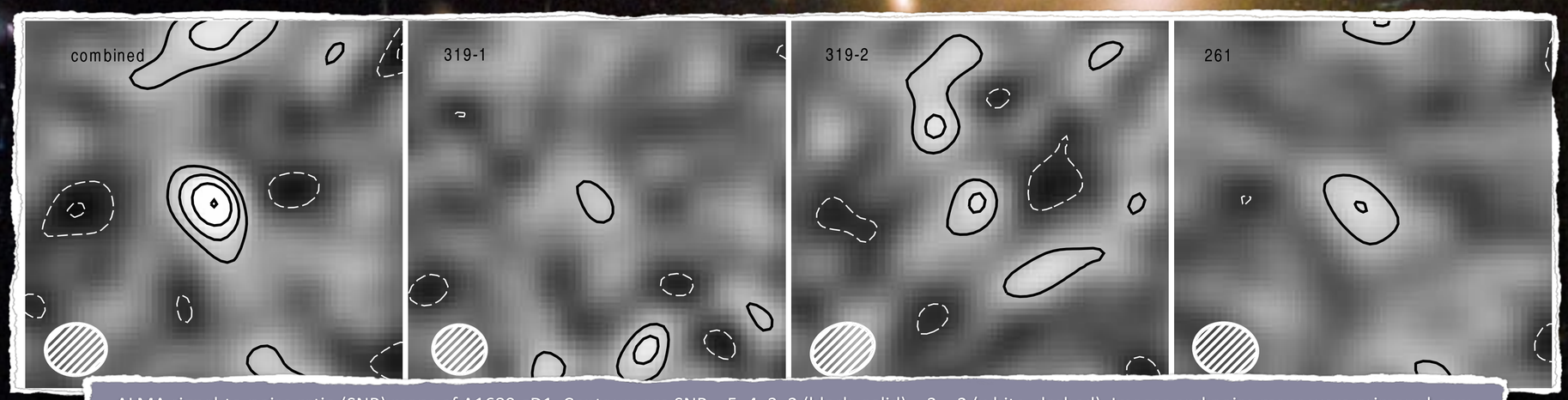
We have detected thermal dust emission from an archetypal early universe star-forming galaxy, A1689-zD1. We detect its stellar continuum in spectroscopy and determine its redshift to be z = 7.5±0.2 from a spectroscopic detection of the Lyα break. A1689-zD1 is a sub-L^* galaxy and more representative of the star-forming population during reionisation than other high redshift dusty galaxies found before, with a total star-formation rate of about 12 $M_\odot$ yr^{-1}. The galaxy is highly evolved: it has a large stellar mass, and is heavily enriched in dust, with a dust-to-gas ratio close to that of the Milky Way.

The gravitationally lensing galaxy cluster Abell 1689. The colour image is composed with Hubble filters: F105W (blue), F125W (green), F160W (red). The zoomed box (4″×4″) shows A1689-zD1. Contours indicate FIR dust emission detected by ALMA at 3, 4, and 5σ local RMS (yellow, positive; white, negative). The ALMA beam (1.36″×1.15″) is shown, bottom left. Images and noise maps were primary-beam corrected before making the signal-to-noise ratio (SNR) maps. Slit positions for the first set of X-shooter spectroscopy are overlaid in magenta (dashed boxes indicate the dither), while the parallactic angle was used in the remaining observations (pink dashed lines).

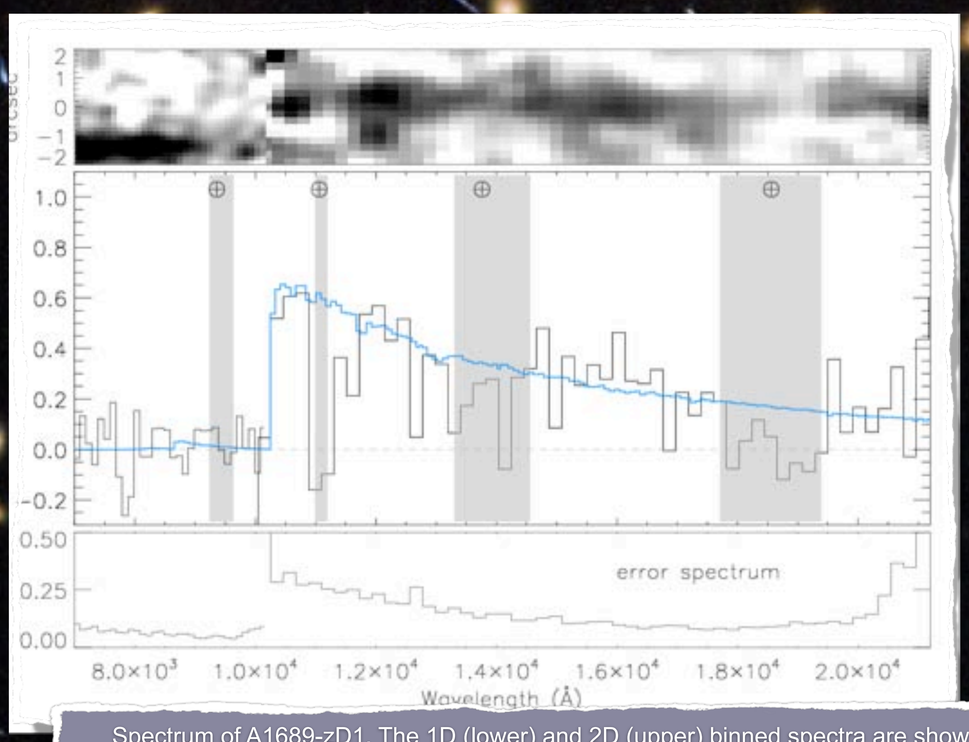
Candidates for the modest galaxies that formed most of the stars in the early universe, at redshifts z > 7, have been found in large numbers with extremely deep restframe-UV imaging. But it has proved difficult for existing spectrographs to characterise them in the UV. The detailed properties of these galaxies could be measured from dust and cool gas emission at far-infrared wavelengths if the galaxies have become sufficiently enriched in dust and metals. So far, however, the most distant UV-selected galaxy detected in dust emission was only at z = 3.2, and recent results had cast doubt on whether dust and molecules could be found in typical galaxies at this early epoch.

A1689-zD1 was observed by ALMA at 226GHz and is detected at 5.0σ with an observed flux of 0.61 ± 0.12 mJy in the combined image

Far-infrared emission requires the production of metals, whether in the solid phase as dust, or as ionised gas; to be detected, such galaxies must have enriched their interstellar media with metals and dust. While the metals are primarily produced and distributed via supernova explosions and so metal enrichment happens concurrently with massive star formation, the site of dust production is less certain. However, the mechanism must be very rapid[13] and these observations of A1689-zD1 place the strongest direct constraints so far on the rapidity of dust enrichment, occurring within only 500 Myr of the beginning of star-formation in the universe.



ALMA signal-to-noise ratio (SNR) maps of A1689-zD1. Contours are SNR = 5, 4, 3, 2 (black, solid), –3, –2 (white, dashed). Images and noise maps were primary-beam corrected before making SNR maps. Beam sizes are shown, bottom left in each panel. Panels are 8″×8″. The panels show, left to right, the combined data, the two tunings of observation 2011.0.00319.S and observation 2012.1.00261.S. A1689-zD1 is detected, left to right, at 5.0σ, 2.4σ, 3.1σ, and 3.0σ. Natural weighting was used and the visibilities were tapered with a 1″ circular Gaussian kernel, resulting in beams of 1.36″×1.15″, 1.19″×1.09″, 1.43″×1.12″, 1.43″×1.17″ left to right.



Spectrum of A1689-zD1. The 1D (lower) and 2D (upper) binned spectra are shown, with the 68% confidence uncertainty on the 1D spectrum in the bottom panel. The redshift z = 7.5 is determined from the Lyα break at 1035 nm. Sky absorption (grey bands) and the best-fit SED (blue line) are shown. The Lyα break is close to the spectrograph's NIR/VIS arm split, however, the break is clearly detected in the NIR arm alone. A nearby galaxy ($z \sim 2$) visible in the bottom part of the 2D spectrum is detected in both the VIS and NIR arms.

The galaxy continuum is detected and can be seen in the binned spectrum (left). The Lyα cutoff is at 1035±24 nm and defines the redshift, z = 7.5±0.2. No lines are detected: EW<4Å for both Lyα and CIII] 1909Å. Our search space is largely free of sky emission lines; they cover only 16% of the range for Lyα, less for CIII]. Fits to the galaxy's spectral energy distribution yield a lensing-corrected stellar mass of $\log(M_*/M_\odot) = 9.23$, with a light-weighted stellar age, t, of $\log(t/\mathrm{yr}) = 7.91$. The lensing-corrected UV luminosity is ~1.8×10^{10} $L_\odot$, resulting in a $\mathrm{SFR_{UV}}$ of 2.7±0.3 $M_\odot$ yr^{-1} uncorrected for dust extinction.

Table 1 | Comparison of A1689-zD1 to other high redshift star-forming galaxies.

Galaxy name	Redshift, z	Stellar mass, M_* (10^{10} $M_\odot$)	$\mathrm{SFR_{UV}}$ ($M_\odot$ yr^{-1})	$\mathrm{SFR_{IR}}$ ($M_\odot$ yr^{-1})	$\mathrm{SFR_{IR}}$ ($M_\odot$ yr^{-1})	Dust mass, M_D (10^7 $M_\odot$)
HFLS3 (ref. 21)	6.34	$50^{+10.0}_{-30}$	1.3 ± 0.4*	–	1300 ±200†	30 ±10†
HCM6A (ref. 22)	6.56	–	9 ± 2	2	<28 (ref. 26)	<10 (ref. 26)
Himiko (ref. 8)	6.60	15 ± 2	30 ± 2	35 ± 1	<8	<4.72 (ref. 26)
A1703-zD1 (ref. 23)	6.8	0.7–1.5	7.3 ± 0.3	–	<16 (ref. 26)	<5.7 (ref. 26)
IOK-1 (ref. 24)	6.96	<40	23.9 ± 1.4 (ref. 27)	10 ± 2	<10 (ref. 28)	<6.4 (ref. 28)
z8-GND-5296 (ref. 2)	7.51	$1^{+0.2}_{-0.1}$	330^{+710}_{-10}	–	<127 (ref. 26)	<50 (ref. 26)
HG090423 (ref. 25)	8.2	<0.05 (ref. 29)	<0.38 (ref. 30)	–	<5(ref. 29)	<2‡
A1689-zD1	**7.5**	$\mathbf{1.7^{+0.7}_{-0.5}}$	**2.7 ± 0.3**	**<0.7**	$\mathbf{9^{+4}_{-2}}$	$\mathbf{4^{+4}_{-2}}$

The SFRs are derived from extinction-uncorrected ultraviolet emission, Lyα emission and far-infrared emission, respectively.
*Derived from the *Hubble* F160W photometry and corrected for lensing.
†95% lower bound only.
‡Assuming the same dust parameters assumed for A1689-zD1.

Link to the paper
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Background: Abell1689_galaxy cluster