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Galaxy growth in a massive halo in the first billion years of cosmic history

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According to the current understanding of cosmic structure formation, the precursors of the most massive structures in the Universe began to form shortly after the Big Bang, in regions corresponding to the largest fluctuations in the cosmic density field[1–3]. Observing these structures during their period of active growth and assembly—the first few hundred million years of the Universe—is challenging because it requires surveys that are sensitive enough to detect the distant galaxies that act as signposts for these structures and wide enough to capture the rarest objects. As a result, very few such objects have been detected so far[4,5]. Here we report observations of a far-infrared-luminous object at redshift 6.900 (less than 800 million years after the Big Bang) that was discovered in a wide-field survey[6]. High-resolution imaging shows it to be a pair of extremely massive star-forming galaxies. The larger is forming stars at a rate of 2,900 solar masses per year, contains 270 billion solar masses of gas and 2.5 billion solar masses of dust, and is more massive than any other known object at a redshift of more than 6. Its rapid star formation is probably triggered by its companion galaxy at a projected separation of 8 kiloparsecs. This merging companion hosts 35 billion solar masses of stars and has a star-formation rate of 540 solar masses per year, but has an order of magnitude less gas and dust than its neighbour and physical conditions akin to those observed in lower-metallicity galaxies in the nearby Universe[7]. These objects suggest the presence of a dark-matter halo with a mass of more than 100 billion solar masses, making it among the rarest dark-matter haloes that should exist in the Universe at this epoch.

SPT0311−58 (SPT-S J031132−5823.4) was originally identified in the 2,500-deg^2 South Pole Telescope (SPT) survey[8,9] as a luminous source (flux densities of 7.5 mJy and 19.0 mJy at wavelengths of 2.0 mm and 1.4 mm, respectively) with a steeply increasing spectrum, indicative of thermal dust emission. Observations with the Atacama Large Millimeter/submillimeter Array (ALMA) provide the redshift of the source. The $J=6$–5 and $J=7$–6 rotational transitions of the carbon monoxide molecule and the $^3P_2$–$^3P_1$ fine-structure transition of atomic carbon were found redshifted to 87–103 GHz in a wide spectral scan[6]. The frequencies and spacings of these lines unambiguously place the galaxy at a redshift of $z=6.900(2)$, which corresponds to a cosmic age of 780 Myr (using cosmological parameters[10] of Hubble constant $H_0=67.7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, matter density $\Omega_\mathrm{m}=0.309$ and vacuum energy density $\Omega_\Lambda=0.691$). An elongated faint object is seen at optical and near-infrared wavelengths, consistent with a nearly edge-on spiral galaxy at $z=1.4\pm0.4$ that acts as a gravitational lens for the background source (see Methods section ‘Modelling the SED’; here and elsewhere the error range quoted corresponds to a 1σ uncertainty). Together, these observations indicate that SPT0311−58 is the most distant known member of the population of massive, infrared-bright but optically dim, dusty galaxies that were identified from ground- and space-based wide-field surveys[11].

The far-infrared emission from SPT0311−58 provides an opportunity to study its structure with little confusion from the foreground galaxy. We conducted ALMA observations at about 0.3″ resolution at three different frequencies (see Methods): 240 GHz, 350 GHz and 420 GHz, corresponding to rest-frame wavelengths of 160 μm, 110 μm and 90 μm. The observations at 240 GHz include the 158-μm fine-structure line of ionized carbon ([C II]) and those at 420 GHz the 88-μm fine-structure line of doubly ionized oxygen ([O III]). The 160-μm continuum and the [C II] and [O III] line emission maps of the source are shown in Fig. 1. Two emissive structures are visible in the map, denoted SPT0311−58 E and SPT0311−58 W, which are separated by less than 2″ on the sky before correction for gravitational deflection. Although the morphology of SPT0311−58 E and SPT0311−58 W is reminiscent of a lensing arc (SPT0311−58 W) and counter-image (SPT0311−58 E), the [C II] line clarifies the physical situation: SPT0311−58 E is separated from the brighter source SPT0311−58 W by 700 km s^{-1} and is therefore a distinct galaxy.

Lens modelling of the 160-μm, 110-μm and 90-μm continuum emission from SPT0311−58 was performed using a pixelated reconstruction technique[12] (Fig. 1c, Extended Data Fig. 5, Methods section ‘Gravitational lens modelling’). Its structure and lensing geometry is consistent between the observations, and indicates that the two galaxies are separated by a projected (proper) distance of 8 kpc in the

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