A dust-obscured massive maximum-starburst galaxy at a redshift of 6.34

Dominik A. Riechers1,2, C. M. Bradford1,3, D. L. Clements4, C. D. Dowell3, I. Pérez-Fournon5,6, R. J. Ivison7,8, C. Bridge1, A. Conley9, Hai Fu10, J. D. Vieira10, J. Wardlow10, J. Calanog10, A. Cooray1,10, P. Hurley11, R. Neri12, J. Kamenetzky13, J. E. Aguirre14, A. Conley9, Hai Fu10, J. D. Vieira10, J. Wardlow10, J. Calanog10, A. Cooray1,10, P. Hurley11, R. Neri12, J. Kamenetzky13, J. E. Aguirre14, I. Valtchanov15, M. Viero1, L. Wang11, M. Zemcov1,3 & J. Zmuidzinas1,3

Massive present-day early-type (elliptical and lenticular) galaxies probably gained the bulk of their stellar mass and heavy elements through intense, dust-enshrouded starbursts—that is, increased rates of star formation—in the most massive dark-matter haloes at early epochs. However, it remains unknown how soon after the Big Bang massive starburst progenitors exist. The measured redshift (z) distribution of dusty, massive starbursts has long been suspected to be biased low in z owing to selection effects1, as confirmed by recent findings of systems with redshifts as high as ~5 (refs 2–4). Here we report the identification of a massive starburst galaxy at z = 6.34 through a submillimetre colour-selection technique. We unambiguously determined the redshift from a suite of molecular and atomic fine-structure cooling lines. These measurements reveal a hundred billion solar masses of highly excited, chemically evolved interstellar medium in this galaxy, which constitutes at least 40 per cent of the baryonic mass. A ‘maximum starburst’ converts the gas into stars at a rate more than 2,000 times that of the Milky Way, a rate among the highest observed at any epoch. Despite the overall downturn in cosmic star formation towards the highest redshifts2, it seems that environments mature enough to form the most massive, intense starbursts existed at least as early as 800 million years after the Big Bang.

We have searched 21 deg2 of the Herschel/SPire data of the HerMES blank field survey7 at wavelengths 250–500 μm for ‘ultra-red’ sources with flux densities S250 μm < S500 μm < S350 μm and S500 μm > 3.5 times higher than those of the brightest high-redshift starbursts HFLS 3 hosts an intense starburst. The 870-μm flux of HFLS 3 is detected emission shortward of 1 m and 20 cm, with no detected emission shortward of 1 μm (see Supplementary Information section 1 for additional details), corresponding to a source density of ≤0.24 deg−2. For comparison, models of number counts in the Herschel/SPire bands suggest a space density of massive starburst galaxies at z > 6 with S250 μm > 30 mJy of 0.014 deg−2 (ref. 7).

To understand the nature of galaxies selected by this technique, we have obtained full frequency scans of the 3-mm and 1-mm bands towards HFLS 3 (also known as 1HERMES S350 J170647.8–6.3369, the brightest candidate discovered in our study. These observations, augmented by selected follow-up over a broader wavelength range, unambiguously determine the galaxy redshift to be z = 6.3369 ± 0.0009 based on a suite of 7 CO lines, 7 H2O lines, and OH, OH−, H2O−, NH3 [C] and [C] lines detected in emission and absorption (Fig. 1). At this redshift, the Universe was just 880 million years old (or one-sixteenth of its present age), and 1° on the sky corresponds to a physical scale of 5.6 kpc. Further observations from optical to radio wavelengths reveal strong continuum emission over virtually the entire wavelength range between 2.2 μm and 20 cm, with no detected emission shortward of 1 μm (see Supplementary Information section 2 and Supplementary Figs 1–11 for additional details).

HFLS 3 hosts an intense starburst. The 870-μm flux of HFLS 3 is 3.5 times higher than those of the brightest redshift starbursts in a 0.25-deg2 region containing the Hubble Ultra Deep Field (HUDF)7. From the continuum spectral energy distribution (Fig. 2), we find that the far-infrared (FIR) luminosity LIR and inferred star formation rate (SFR) of 2,900 Msun yr−1 of HFLS 3 (where Msun is the solar mass) are 15–20 times those of the prototypical local ultra-luminous starburst Arp 220, and >2,000 times those of the Milky Way (Table 1 and Supplementary Information section 3). The SFR of HFLS 3 alone corresponds to ~4.5 times the ultraviolet-based SFR of all z = 5.5–6.5 star-forming galaxies in the HUDF combined2, but the rarity and dust obscuration of ultra-red sources like HFLS 3 implies that they do not dominate the ultraviolet photon density needed to reionize the Universe48.

1California Institute of Technology, 1200 East California Boulevard, MC 249-17, Pasadena, California 91125, USA. 2Cornell University, 220 Space Sciences Building, Ithaca, New York 14853, USA. 3Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, California 91109, USA. 4Astrophysics Group, Imperial College London, Blackett Laboratory, Prince Consort Road, London SW7 2AZ, UK. 5Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain. 6Departamento de Astrofísica, Universidad de La Laguna, E-38205 La Laguna, Tenerife, Spain. 7UK Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK. 8Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK. 9Center for Astrophysics and Space Astronomy 389-UCB, University of Colorado, Boulder, Colorado 80309, USA. 10Department of Physics and Astronomy, University of California, Irvine, California 92697, USA. 11Astronomy Centre, Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, UK. 12Institut de Radioscopie Millimétrique, 300 Rue de la Physique, Domaine Universitaire, F-38406 Saint Martin d’Hères, France. 13Department of Astrophysical and Planetary Sciences, CASA 389-UCB, University of Colorado, Boulder, Colorado 80309, USA. 14Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA. 15Herschel Centre, European Space Astronomy Centre, Villanueva de la Cañada, 28691 Madrid, Spain. 16Observational Cosmology Laboratory, Goddard Space Flight Center, Greenbelt, Maryland 20771, USA. 17Laboratoire AIM-Paris-Saclay, CEA/DAM/Irfu – CNRS – Université Paris Diderot, CEA Saclay, Point Courrier 313, F-91191 GIF-sur-Yvette, France. 18Institut d’Astrophysique Spatiale (IAS), Bâtiment 121, Université Paris-Sud 11 and CNRS, UMR 8617, F-91405 Orsay, France. 19Institut d’Astrophysique de Paris, UMR 7095, CNRS, Université P. et M. Curie–Paris 6, 4, place Jussieu, F-75005 Paris, France. 20France. 21Military Institute for Nuclear Energy, Minsk, Minsk, Belarus. 22Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, British Columbia V6T 121, Canada. 23ESO, Karl-Schwarzschild-Strasse 2, D-85748 Garching bei München, Germany. 24Institute for Astrophysics, University of Minnesota, 116 Church Street Southeast, Minneapolis, Minnesota 55455, USA. 25Institute for Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 229-8510, Japan. 26Infrared Processing and Analysis Center, MS 100-22, California Institute of Technology, Pasadena, California 91125, USA. 27Mulard Space Science Laboratory, University College London, Holmbury St Mary, Surrey, RH5 6NT, UK. 28Department of Physics and Astronomy, Johns Hopkins University, Baltimore, Maryland 21218, USA.

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Figure 1 | Redshift identification through molecular and atomic spectroscopy of HFLS 3. a. Black trace, wide-band spectroscopy in the observed-frame 19–0.95 mm (histogram; rest-frame 2,600–130 μm) wavelength range with CARMA (3 mm; ‘blind’ frequency scan of the full band), the PdBI (2 mm), the JVLA (19–6 mm) and CSO/Z-spec (1 mm; instantaneous coverage). (CARMA, Combined Array for Research in Millimeter-wave Astronomy; PdBI, Plateau de Bure Interferometer; JVLA, Jansky Very Large Array; and CSO, Caltech Submillimeter Observatory.) This uniquely determines the redshift of HFLS 3 to be $z = 6.3369$ based on the detection of a series of H$_2$O, CO, OH, OH$^+$, NH$_3$, [C I] and [C II] emission and absorption lines. b–o. Detailed profiles of detected lines (histograms; rest frequencies are indicated by corresponding letters in a). i-mm lines (m–o) are deeper, interferometric confirmation observations for NH$_3$, OH (both PdBI) and [C II] (CARMA) not shown in a. The line profiles are typically asymmetric relative to single Gaussian fits, indicating the presence of two principal velocity components at redshifts of 6.3335 and 6.3427. The implied CO, [C I] and [C II] line luminosities are respectively $(5.08 \pm 0.45) \times 10^{10} L_{\text{sun}}$ $(3.0 \pm 1.9) \times 10^{11} L_{\text{sun}}$ and $(1.55 \pm 0.32) \times 10^{10} L_{\text{sun}}$. Strong rest-frame submillimetre to FIR continuum emission is detected over virtually the entire wavelength range. For comparison, the Herschel/SPIRE spectrum of the nearby ultra-luminous infrared galaxy Arp 220 is overplotted in grey (a). Lines labelled in italic are tentative detections or upper limits (see Supplementary Table 2). Most of the bright spectral features detected in Arp 220 are also detected in HFLS 3 (in spectral regions not blocked by the terrestrial atmosphere). See Supplementary Information sections 2–4 for more details.

HFLS 3 is a massive, gas-rich galaxy. From the spectral energy distribution and the intensity of the CO and [C II] emission, we find a dust mass of $M_d = 1.3 \times 10^9 M_{\text{sun}}$ and total molecular and atomic gas masses of respectively $M_{\text{gas}} = 1.0 \times 10^{11} M_{\text{sun}}$ and $M_{\text{HI}} = 2.0 \times 10^{10} M_{\text{sun}}$. These masses are $15–20$ times those of Arp 220, and correspond to a gas-to-dust ratio of $\sim 80$ and a gas depletion timescale of $M_{\text{gas}}/\text{SFR} \approx 36$ Myr. These values are comparable to lower-redshift submillimetre-selected starbursts. From the [C I] luminosity, we find an atomic carbon mass of $4.5 \times 10^8 M_{\text{sun}}$. At the current SFR of HFLS 3, this level of carbon enrichment could have been achieved through supernovae on a timescale of $\sim 10^7$ yr (ref. 13). The profiles of the molecular and atomic emission lines typically show two velocity components (Fig. 1 and Supplementary Figs 5 and 7). The gas is distributed over a region of 1.7 kpc radius with a high velocity gradient and dispersion (Fig. 3). This suggests a dispersion-dominated galaxy with a dynamical mass of $M_{\text{dyn}} = 2.7 \times 10^{11} M_{\text{sun}}$. The gas mass fraction in galaxies is a measure of the relative depletion and replenishment of molecular gas, and is expected to be a function of halo mass and redshift from simulations. In HFLS 3, we find a high gas mass fraction of $f_{\text{gas}} = M_{\text{gas}}/M_{\text{dyn}} \approx 40\%$, comparable to what is found in submillimetre-selected starbursts and massive star-forming galaxies at $z \approx 2$ (refs 15, 16), but $\sim 3$ times higher than in nearby ultra-luminous infrared galaxies (ULIRGs) like Arp 220, and $>30$ times higher than in the Milky Way. From population synthesis modelling, we find a stellar mass of $M_*= 3.7 \times 10^{10} M_{\text{sun}}$, comparable to that of Arp 220 and about half that of the Milky Way. This suggests that at most $\sim 40\%$ of $M_{\text{dyn}}$ within the radius of the gas reservoir is due to dark matter. With up to $\sim 10^{11} M_{\text{sun}}$ of dark matter within 3.4 kpc, HFLS 3 is likely to reside in a dark-matter halo massive enough to grow a present-day galaxy cluster. The efficiency of star formation is given by $\varepsilon = t_{\text{dyn}} \times \text{SFR}/M_{\text{gas}}$ where $t_{\text{dyn}} = (r^2/2GM)^{1/2}$ is the dynamical (or free-fall) time, $r$ is the source radius,
Other high-redshift massive starburst galaxies (including the Eyelash) typically are at line intensities exceeding those of the CO lines. The intensities and ratios of the detected H$_2$O lines cannot be reproduced by radiative transfer models assuming collisional excitation, but are consistent with being radiatively pumped by FIR photons, at levels comparable to those observed in Arp 220 (Supplementary Figs 15 and 16). The CO and H$_2$O excitation is inconsistent with what is observed in quasar host galaxies like Mrk 231 and APM 08279+5255 at $z = 3.9$, which lends support to the conclusion that the gas is excited by a mix of collisions and infrared photons associated with a massive, intense starburst, rather than hard radiation associated with a luminous AGN. The physical properties of atomic and molecular gas in HFLS 3 are fully consistent with those of nearby ULIRGs, and the physical conditions of the gas in HFLS 3 are typical for high radiation environments in extreme starbursts and active galactic nucleus (AGN) host galaxies. The CO radiative transfer model suggests that the dust is located at $z > 6$ for typical models of the spectral energy distribution (except those with low dust temperatures), whereas red sources typically are at $z < 5.5$. See Supplementary Information section 1 for more details.

For details see Supplementary Information section 3.

* Literature values for Arp 220 and the Milky Way are adopted from refs 20 and 27–30. The total molecular gas mass of the Milky Way is uncertain by at least a factor of 2. Quoted dust masses and stellar masses are typically uncertain by factors of 2–3 owing to systematics.

** T$_{\text{dust}}$ is the dust temperature.

† Molecular gas mass, assuming $M_{\text{H}_2} = M_{\text{IR}}/1.0$ (see Supplementary Information section 3.1).

‡ Dynamical mass (see Supplementary Information section 3.4).

§ Gas mass fraction, assuming $f_{\text{gas}} = M_{\text{gas}}/M_{\text{IR}}$ (see Supplementary Information section 3.6).

‖ SFR, derived assuming SFR ($M_{\text{star}}$yr$^{-1}$) = 1.0 x 10$^{-10}$L$_{\text{IR}}$ (in $L_{\odot}$) (see Supplementary Information section 3.1).

* Stellar mass, derived from population synthesis fitting (see Supplementary Information section 3.4).

** Stellar mass, derived from spectral energy distribution fitting (see Supplementary Information section 3.1).

$\rho$ gas # the gas density.

For details see Supplementary Information section 3.

* Literature values for Arp 220 and the Milky Way are adopted from refs 20 and 27–30. The total molecular gas mass of the Milky Way is uncertain by at least a factor of 2. Quoted dust masses and stellar masses are typically uncertain by factors of 2–3 owing to systematics. The dynamical mass for the Milky Way is quoted within the inner 20 kpc to be comparable to the other systems, not probing the outer regions dominated by dark matter. The dust temperature in the Milky Way varies by at least ±5 K around the quoted value, which is used as a representative value. Both Arp 220 and the Milky Way are known to contain small fractions of significantly warmer dust. All errors are 1σ r.m.s. uncertainties.

† Molecular gas mass, assuming $M_{\text{H}_2} = M_{\text{IR}}/1.0$ (see Supplementary Information section 3.1).

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§ Gas mass fraction, assuming $f_{\text{gas}} = M_{\text{gas}}/M_{\text{IR}}$ (see Supplementary Information section 3.6).

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conditions in the ISM of HFLS 3 thus are comparable to those in the nuclei of the most extreme nearby starbursts, consistent with the finding that it follows the radio–FIR correlation for star-forming galaxies.

HFLS 3 is rapidly assembling its stellar bulge through star formation at surface densities close to the theoretically predicted limit for maximum starbursts\(^1\). At a rest-frame wavelength of 158 \(\mu\)m, the FIR emission is distributed over a relatively compact area with 2.6 kpc \(\times\) 2.4 kpc physical diameter along its major and minor axes respectively (Fig. 3; as determined by elliptical Gaussian fitting). This suggests an extreme SFR surface density of \(\Sigma_{\text{SFR}} \approx 600 \text{ M}_\odot \text{yr}^{-1} \text{ kpc}^{-2}\) over a 1.3-kpc-radius region, and is consistent with near-Eddington-limited star formation if the starburst disk is supported by radiation pressure\(^2\). This suggests the presence of a kiloparsec-scale hyperstarburst similar to that found in the \(z = 6.42\) quasar J1148+5251 (ref. 25). Such high \(\Sigma_{\text{SFR}}\) are also observed in the nuclei of local ULIRGs such as Arp 220, albeit on scales two orders of magnitude smaller. A starburst at such high \(\Sigma_{\text{SFR}}\) may produce strong winds. Indeed, the relative strength and broad, asymmetric profile of the OH \(1^1\Sigma^+_J(3/2–1/2)\) doublet detected in HFLS 3 may indicate a molecular outflow, reminiscent of the OH outflow in Arp 220\(^1\).

The identification of HFLS 3 alone is still consistent with the model-predicted space density of massive starburst galaxies at \(z > 6\) with \(S_{100\mu m} > 30\) mJy of 0.014 \(\text{deg}^{-2}\) (ref. 7). This corresponds to only \(10^{-7}\)–\(10^{-4}\) times the space density of Lyman-break galaxies at the same redshift, but is comparable to the space density of the most luminous quasars hosting supermassive black holes (that is, a different population of massive galaxies) at such early cosmic times\(^8\). The host galaxies around these very distant supermassive black holes are commonly FIR-luminous, but less intensely star-forming, with typically a few times lower \(L_{\text{IR}}\) than ultra-red sources\(^9\). This highlights the difference between selecting massive \(z > 6\) galaxies at the peak of their star formation activity through \(L_{\text{IR}}\), and at the peak of their black-hole activity through luminous AGN. The substantial population of ultra-red sources discovered with Herschel will be an ideal probe of early galaxy evolution and heavy element enrichment within the first billion years of cosmic time. These galaxies are unlikely to dominate the star formation history of the Universe at \(z > 6\) (ref. 5), but they trace the highest peaks in SFR at early epochs. A detailed study of this galaxy population will reveal the mass and redshift distribution, number density and likely environments of such objects, which if confirmed in larger numbers may present a stern challenge to current models of early cosmic structure formation.

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Supplementary Information is available in the online version of the paper.

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