A 100-kiloparsec wind feeding the circumgalactic medium of a massive compact galaxy

The galaxy SDSS J211824.06+001729.4 that we study here, which we call Makani (Hawaiian for ‘wind’), is an example of a merger of two galaxies hosting a galactic wind thought to be powered by extreme star-formation surface density\(^1\). At redshift \(z = 0.459\), Makani is a compact but massive galaxy, with \(\log(M/M_\odot) = 11.1(\pm 0.2)\), where \(M_\odot\) and \(M\) are the stellar and solar masses, respectively (Extended Data Fig. 4). Our Hubble Space Telescope imaging analysis reveals a highly peaked stellar core (radius 400 pc) framed by two tidal tails of 10–15 kpc so that half of the galaxy’s light extends to about 2.5 kpc (ref. \(^{16}\); Fig. 1). Its stellar populations include old (more than a billion years, Gyr), medium-aged (0.4 Gyr), and young (less than 7 million years, Myr) components (Extended Data Fig. 5), with a current star-formation rate of 100–200 \(M_\odot\) yr\(^{-1}\). It may contain a dust-obscured accreting supermassive black hole, or active galactic nucleus (AGN), on the basis of its X-ray luminosity of \(\log(L_{2–10\text{ keV}}) = 42.5^{+0.4}_{-0.6}\) erg s\(^{-1}\) (ref. \(^{16}\)), its mid-infrared slope, and the presence of highly ionized gas such as [Ne VI] at wavelength \(\lambda = 3.426\) Å (log\(L = 40.6^{+0.1}_{-0.0}\) erg s\(^{-1}\)). However, any AGN is not currently energetically dominant\(^{12,13}\) or radio-loud (G. C. Petter et al., manuscript in preparation) and the data could be explained by star formation and shocks. Extremely high-density star formation, like that found in Makani, is capable of powering fast winds, independent of an AGN\(^{13}\).

To study the spatial extent of its outflow, we observed Makani with the Keck Cosmic Web Imager (KCWI)\(^2\). The emission from the [O II] lines at \(\lambda = 3,726\) Å and 3,729 Å in these data reveals a nebula with approximate mirror symmetry around the north–south and east–west axes, extending to radii of 50 kpc north and south of the galaxy nucleus, and 40 kpc east and west of it (Fig. 1). Its morphology resembles that of a limb-brightened, bipolar bubble, similar to those seen in other galactic winds\(^{12,17}\) but on a much larger scale. This nebula is remarkable in the context of other [O II] emitters. Its area of 4,900 kpc\(^2\) (136 arcsec\(^2\) above a 5 brightness limit per spaxel (spectral pixel) of \(5 \times 10^{-18}\) erg s\(^{-1}\) cm\(^{-2}\)) makes it the largest [O II] nebula detected around a single galaxy in the field\(^{18,19}\) or in galaxy groups\(^{20,21}\). Its [O II] luminosity of \(3.3 \times 10^{42}\) erg s\(^{-1}\) is several times the break in the galaxy luminosity function, \(L_\odot\), at \(z = 0.45\) (ref. \(^{22}\)). Its rest-frame equivalent width (40 Å), half-light radius (17 kpc), and maximum radial extent (50 kpc) put it at the top end of [O II] emitters at \(z \leq 0.6\) and radio-galaxy nebulae\(^{18,23}\), perhaps indicative of the unusual nature of this nebula as a giant galactic wind.

On the basis of its light distribution alone, the hourglass shape of the nebula strongly suggests a bipolar galactic wind emerging from its host galaxy. The spatially resolved gas kinematics confirm this impression and separate the wind cleanly into an outer region with low-velocity gas only and an inner region containing both low- and high-velocity gas (Fig. 2). The outer region with lower velocities spans radii of 20–50 kpc, while the high-velocity gas is concentrated within a radius of about 10 kpc. We call these two wind components, and the associated star-bursts that are thought to have produced them, episodes I (0.4 Gyr ago) and II (7 Myr ago). We sort spaxels by the average maximum blueshifted velocity of \(\langle v_{\text{max}} \rangle = -700\) km s\(^{-1}\), although sorting by velocity dispersion \(\sigma\) produces similar results. Episode I then has gas with maximum

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Ninety per cent of baryons are located outside galaxies, either in the circumgalactic or intergalactic medium\(^{12}\). Theory points to galactic winds as the primary source of the enriched and massive circumgalactic medium\(^{1–10}\). Winds from compact starbursts have been observed to flow to distances somewhat greater than ten kiloparsecs\(^7–10\), but the circumgalactic medium typically extends beyond a hundred kiloparsecs\(^3,4\). Here we report optical integral field observations of the massive but compact galaxy SDSS J211824.06+001729.4. The oxygen [O II] lines at wavelengths of 3726 and 3729 ångstroms reveal an ionized outflow spanning 80 by 100 square kiloparsecs, depositing metal-enriched gas at 10,000 kelvin through an hourglass-shaped nebula that resembles an evacuated and limb-brightened bipolar bubble. We also observe neutral gas phases at temperatures of less than 10,000 kelvin reaching distances of 20 kiloparsecs and velocities of around 1,500 kilometres per second. This multi-phase outflow is probably driven by bursts of star formation, consistent with theory\(^11,12\).
Makani, observed by emission from the \[\text{O} \, \text{ii}\] line at \(\lambda = 3,726 \, \text{Å}\) and \(3,729 \, \text{Å}\).

**Fig. 1** The giant galactic wind surrounding the massive, compact galaxy Makani, observed by emission from the \[\text{O} \, \text{ii}\] line at \(\lambda = 3,726 \, \text{Å}\) and \(3,729 \, \text{Å}\). The colour scale and white contours show observed-frame surface brightness, and the axes are labelled in kiloparsecs from the galaxy nucleus. Contours are 2–16% of peak flux, spaced by factors of 2. A rest-frame \(V\) band image of the galaxy (Hubble Space Telescope/WFC3 F814W filter) is superimposed on the centre of the \[\text{O} \, \text{ii}\] image taken with KCWI at the Keck II telescope. The small circle at the centre illustrates the radius of the compact core (400 pc). North is up and east is to the left.

The black contours are as in Fig. 1, and the white Hubble Space Telescope contour represents 1% of the peak stellar continuum flux, accentuating the extended diffuse stellar emission from tidal forces in the merger. In b, the purple colour denotes velocity dispersion and the yellow and red contours outline regions of specified \(\sigma = \sigma_{\text{max}}\) to delineate episodes I and II. The spatial separation of the episodes is also reflected in the \(\sigma\) map. The black contours in b outline the inner concentration of ionized gas at velocities \(-500 \text{ to } -1,500 \, \text{km s}^{-1}\) (Fig. 3d). We securely detect high-velocity \[\text{O} \, \text{ii}\] emission beyond this inner region through Voronoi binning.

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blueshifted velocities between \(-100\) and \(-700 \, \text{km s}^{-1}\) while episode II has a high-velocity tail of gas to \(v_{\text{max}} = -2,100 \, \text{km s}^{-1}\). Timescale arguments further support the existence of two starburst-driven wind episodes. In the 0.4 Gyr since the episode I starburst, a constant-velocity wind must have travelled at \(120 \, \text{km s}^{-1}\) to reach the edge of the nebula (50 kpc); representative velocities at the nebula outskirts are in fact \(100\)–\(200 \, \text{km s}^{-1}\). In the 7 Myr since the most recent starburst episode began, the speed required to reach the edge of the bulk of the episode II wind (10 kpc) is \(1,400 \, \text{km s}^{-1}\), which is also a typical maximum velocity in the inner nebula. The lack of high-velocity redshifted gas in episode II may be due to dust in the outflow blocking the far side of the wind, while the lack of high-velocity gas in the episode I wind is probably due to the dispersal of high-velocity gas to radii exceeding 50 kpc over 0.4 Gyr or the deceleration of the outflow as predicted by models\(^{11}\). Episode I gas also forms the telltale hourglass shape and has higher typical velocity dispersions (200 km s\(^{-1}\)) than expected for tidal features or gravitational motions at large radii\(^{24}\).

We find two other gas phases that we associate with the episode II (recent, inner) outflow. Using the Atacama Large Millimeter Array (ALMA), we detect molecular gas traced by CO(2–1) emission that is outflowing in a compact form, both blueshifted at \(-500\) to \(-1,500 \, \text{km s}^{-1}\) and redshifted at \(500\)–\(1,500 \, \text{km s}^{-1}\), from the nucleus 10 kpc northward (Fig. 3d). This gas is clearly part of episode II, given its high velocity and compact scale. Lower-velocity molecular gas, at \(|v| < 500 \, \text{km s}^{-1}\) and radius \(r < 20 \, \text{kpc}\) (Fig. 3c), is also likely to be part of the outflow because it is much more extended than the stellar disk and correlates spatially with extended, outflowing ionized gas. It may be gas from episode II that has decelerated after reaching scales of the order of 10 kpc. Using resonant line emission from Mg II at \(\lambda = 2,796 \, \text{Å}\) and \(2,803 \, \text{Å}\), we also detect neutral gas of temperature \(T = 10^4 \, \text{K}\) in the velocity range \(\pm 500 \, \text{km s}^{-1}\) (Fig. 3b). This emission correlates with some regions of faint, extended CO and \[\text{O} \, \text{ii}\] emission. Although these velocities are modest, resonant emission on 10-kpc scales has so far been detected.
only in galactic winds, and because of strong radiation transfer effects such emission is not highly shifted from the redshift of the Makani galaxy’s centre of mass.\(^ {25,26} \) Blueshifted Fe\(^ {\text{ii}} \) absorption is detected in the nuclear spectrum (Extended Data Fig. 2), but tracing its physical extent requires deeper observations.

Estimates of the mass contained within the wind would complete its portrait. However, the mass of the ionized gas is uncertain without spatially resolved recombination line measurements. Bootstrapping from single-aperture H\(_{\alpha} \) and H\(_{\beta} \) measurements, we estimate \( 6.3\times10^8(200 \text{ cm}^{-3}/n_e) \) M\(_{\odot} \) of ionized gas in the nebula, with unquantified systematic errors (electron density \( n_e \) and ionization state) probably exceeding the measurement error. Although it is confined to the inner 10 kpc, the mass of the molecular gas in the \( |v| = 500-1,500 \text{ km s}^{-1} \) flow (that is, episode II) is substantial \( (2.4^{+6}_{-4}\times10^9M_\odot) \), with four times as much in the more extended \( \pm 500 \text{ km s}^{-1} \) component. The ionized gas plus molecular wind thus contains 1–10% of the galaxy’s baryonic mass, a fraction that will be even larger when all phases are accounted for. The resulting mass flow rate for the molecular episode II component is \( \frac{dM}{dt} = \frac{Mv}{r} = 245 \) M\(_{\odot} \) yr\(^{-1} \) for \( v = 1,000 \text{ km s}^{-1} \) and \( r = 10 \) kpc, which is roughly one to two times the star-formation rate. This is consistent with molecular outflow rates\(^ {35} \) from other compact starburst mergers at \( z > 0.5 \).

The huge, metal-enriched outflows in Makani—a key component of the host galaxy’s dynamically and chemically evolving circumgalactic medium (CGM)—are consistent with the types of star-formation...
or AGN-driven winds that populate and enrich the CGM in theoretical models. A model galaxy forming stars at 100M yr−1 in a baryonic halo of 2×10^11 M☉ and supernova-driven winds propelling gas with initial velocity 1,000 km s⁻¹ produce a 10^10 M☉ (or 10^9 kpc) shell at r = 10 kpc (or 100 kpc) in t = 10 Myr (or 400 Myr), with velocities at this time of the order of 1,000 km s⁻¹ (100 km s⁻¹). These numbers bear a striking resemblance to the observations in the context of the two-episode outflow we propose. The wind will continue to expand, diffuse, and virialize over longer timescales, as this nebula is denser and more structured than virialized CGM gas and has reached perhaps only about 10% of the virial radius of a galaxy with log(M/M☉) = 11.1 at z = 0.46.

The size of this wind makes it the one of the largest -scale galaxy-scale outflows yet observed, with scales much larger than in other compact or high-z starbursts. The morphology and velocity of the wind in the Teacup AGN make it a cousin of Makani, but on scales five to ten times smaller. Although the Teacup also hosts diffuse gas over 100-kpc scales, this gas has a different physical origin than does the gas in Makani. The most comparable system may be a merger with compact star formation at a cosmic distance ten times closer than Makani. NGC 6240 (z = 0.04) has an ionized outflow that reaches a 40-kpc radius. However, the outflow size relative to the stellar half-light radius (inside which half of the galaxy's starlight resides) is only 1/12 in NGC 6240 (ref. 27), versus 1/12 in Makani, and much of the NGC 6240 nebula coincides with tidal features, unlike Makani. Furthermore, the Hα luminosity of the NGC 6240 nebula is four times smaller than in Makani if the core Hα emission follows the oxygen emission at a constant [O II]/Hα line ratio.

With a maximum extent of more than twenty times the stellar half-light radius, the oxygen nebula observed here has propagated well into the galaxy halos, placing it solidly in the CGM. The cool gas and metals in the flow are thus contributing to the buildup and enrichment of the CGM. This cool gas can be propelled by hot gas, radiation pressure or cosmic rays. The classic model of hot gas acceleration faces the problem that cold clouds may be destroyed during acceleration. These clouds may simply reform after being shredded and mixed in the hot wind or the clouds may survive the acceleration through fast radiative cooling. The mixing layers in shredded clouds can also cool hot gas from the halo or CGM, enhancing the amount of cool gas injected into the CGM. If the cool outflow is accelerated by a hot wind, the existence of [O II]-emitting gas at all radii argues for either cloud reformation on very short timescales or for cloud survival (coupled with enhancement from hot gas). The outflow we observe is thus feeding the CGM by directly depositing gas from the galaxy or by entraining and cooling hot halo and circumgalactic gas.

Connecting the CGM with ongoing galactic winds has been challenging because of the lack of clear evidence for such winds on large enough scales. Previous evidence came from theory and the statistical characteristics of the CGM as measured from single quasar absorption lines over large galaxy populations. We have now observed a single galaxy, with all lines of sight accounted for, whose wind has entered the CGM. Our measurement provides one of the first direct windows into the dynamically and chemically evolving, multiphase CGM being created around a massive galaxy.

Online content
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Methods

**KCWI observations and data analysis**

SDSS J211824.06+001729.4 was originally selected as an intermediate-redshift starburst galaxy with broad but spatially unresolved line emission\(^{13}\), part of a population known to host strong outflows\(^{32}\). We observed it with KCWI on the Keck II telescope on 6 November 2018 UT (Universal Time) for 40 min. We used the blue low-dispersion (BL) grating and medium slicer with KCWI, yielding a resolution of 2.5 Å and wavelength coverage of 3,435–5,525 Å. We chose a central wavelength of 4,500 Å and detector binning of 2 × 2. Conditions were photometric, with 0.6" seeing. Two exposures were dithered 0.3" along sides to subsample the long spatial dimension of the output spaxels (0.69" × 0.29"). The field of view of the reduced data cube is 15.4" × 19.4".

We reduced the data using the KCWI data reduction pipeline and the IFSRED library\(^{13}\). As the default scattered light subtraction in the pipeline leaves visible residuals, we use a routine (IFSR_KCWISCAT-SUB) to subtract scattered light by summing the data in 100-pixel increments along columns (parallel to the dispersion direction) and fitting the least-contaminated inter-slice regions along rows (parallel to the spatial direction) with low-order polynomials. The default wavelength calibration also produces large root-mean-square (r.m.s.) residuals because of a mismatch with the pipeline thourium-argon (ThAr) atlas, so we extract a representative spectrum from our data and find its wavelength solution using IDENTIFY in PyRAF (www.stsci.edu/institute/software_hardware/pyraf). 16/20 lines in the 3,500–4,000 Å and 5,000–5,600 Å ranges are from Th; the other 38 lines (including most of the brightest lines) are from Ar. The resulting r.m.s. residual is 0.18 Å. We then input this calibrated spectrum as the atlas into the pipeline, yielding a 0.07 Å r.m.s. Following the pipeline stages, we resample the data (IFSR_KCWIRESAMPLE) onto a 0.29" × 0.29" spaxel grid; align the two exposures by fitting the galaxy centroid (IFSR_PEAK); and mosaic the data (IFSR_MOSAIC). The resulting stacked and resampled field of view at 5,000 Å is 53 × 67 spaxels. The reconstructed KCWI continuum image (rest-frame near-ultraviolet) is consistent with the Hubble Space Telescope WFC3/F141W image (rest-frame V) when convolved with a 15-pixel Gaussian kernel to match the measured seeing. Finally, we sum the nebula’s core emission in a 3.0° circular aperture to match the Sloan Digital Sky Survey (SDSS)\(^{34}\) spectrum.

We created initial [O II] linemaps by integrating over [O II] and subtracting nearby continuum windows on either side. The wavelength interval of each map is calculated from the doublet average wavelength at a given velocity. We then used ±300 km s\(^{-1}\) flux and error maps to create Voronoi bins (where the velocity applies to the centroid of the [O II] doublet; the doublet lines are 2.6 Å apart, which corresponds to 200 km s\(^{-1}\)). The IDL routine VORONOI_2D_BINNING\(^{35}\) is used to construct the bins, with a target signal-to-noise ratio of 10 and a threshold signal-to-noise ratio of 1. We fit the core spectrum, the full data cube, and the Voronoi binned data cube with IFSFIT\(^{34}\). Because very few strong stellar lines arise in our spectra (rest-frame 2,350–3,790 Å), we use a scaled continuum derived from the fit to the rest-frame 2,550–5,600 Å spectrum\(^{46}\) (see below). We fit two velocity components to the [O II] and [Ne V] lines. If any component falls below 2σ in a spaxel, the spectrum is re-fitted with fewer components. Allowing the [O II] line ratio to float freely in the narrow component of the core spectrum results in an [O II]/[O III] 3,729 Å/[O II] 3,726 Å ratio of 1.2 (corresponding to n\(_e\) = 200 cm\(^{-3}\)), while the broad component ratio is unconstrained. We thus fix the [O II] ratio to 1.2 in all fits. In the core spectrum, Mg I 2,852 Å, Mg II 2,796 Å, 2,803 Å, and Fe II* 2,612 Å, 2,626 Å are tied to the same wavelength and width and fitted with a single component. The continuum fits to each spaxel are used to subtract the stellar continuum around [O II] or Mg II to produce the linemaps shown in Figs. 1–3. The [O II] linemaps have a limiting 1σ surface brightness per pixel of 1.0 × 10\(^{-16}\) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\). For display purposes only, these maps are interpolated to a grid ten times finer and the ±300 km s\(^{-1}\) maps are clipped at 1.5% of peak flux (or 4σ).

The core spectrum yields detections of [O III] 3,426 Å, Mg I 2,852 Å, Mg II 2,796 Å, 2,803 Å, and Fe II* 2,612 Å, 2,626 Å in emission, and Fe II 3,586 Å in absorption. The emission lines break into two distinct components: a narrow feature at the systemic velocity of the host galaxy (z = 0.45916; σ = 143 km s\(^{-1}\) in [O III], 197 km s\(^{-1}\) in Mg and Fe emission) and a broad, blueshifted feature that is outflowing (z = −0.45736, v = −540 km s\(^{-1}\); σ = 500 km s\(^{-1}\) in [O III]; z = 0.45666, v = −750 km s\(^{-1}\); σ = 392 km s\(^{-1}\) in [Ne V]).

We correct upward spatially integrated line fluxes and luminosities for Galactic extinction as above. Because of the lower signal-to-noise ratio in these spectra compared to the KCWI spectrum, we fix the velocities and extinction as above. Because of the lower signal-to-noise ratio in these spectra compared to the KCWI spectrum, we fix the velocities and extinction as above. Because of the lower signal-to-noise ratio in these spectra compared to the KCWI spectrum, we fix the velocities and extinction as above. Because of the lower signal-to-noise ratio in these spectra compared to the KCWI spectrum, we fix the velocities and extinction as above. Because of the lower signal-to-noise ratio in these spectra compared to the KCWI spectrum, we fix the velocities and extinction as above. Because of the lower signal-to-noise ratio in these spectra compared to the KCWI spectrum, we fix the velocities and extinction as above. Because of the lower signal-to-noise ratio in these spectra compared to the KCWI spectrum, we fix the velocities and extinction as above.

We combine our KCWI spectrum with two other spectra to constrain the integrated gas excitation, reddening and gas mass. The first is the SDSS spectrum that, along with [O II], covers the [Ne V] 3,869 Å, H\(_\beta\), and [O III] 4,959 Å, 5,007 Å emission lines. The second is a spectrum acquired with Keck/NIRSPEC, which covers the Ha, [N II] 6,548 Å, 6,583 Å, and [S II] 6,717 Å, 6,731 Å lines. The latter was observed with a 0.76" wide slit at a position angle of 83° east of north. We scale the NIRSPEC data to match the SDSS spectrum where they overlap and correct for Galactic extinction as above. Because of the lower signal-to-noise ratio in these spectra compared to the KCWI spectrum, we fix the velocities and linewidths of each emission line using the fit to the KCWI core spectrum.

We measure an H\(_\alpha\) flux of 1.90 ± 0.10 erg s\(^{-1}\) cm\(^{-2}\) and an extinction of E(B−V) = 0.4 ± 0.03 (we refer the reader to the original data for the specific values). We use the 50th and 98th percentiles of the CVDF (\(v_{50}\) and \(v_{98}\)) as a single component is the usual Gaussian \(\sigma\). We combine our KCWI spectrum with two other spectra to constrain the integrated gas excitation, reddening and gas mass. The first is the SDSS spectrum that, along with [O II], covers the [Ne V] 3,869 Å, H\(_\beta\), and [O III] 4,959 Å, 5,007 Å emission lines. The second is a spectrum acquired with Keck/NIRSPEC, which covers the Ha, [N II] 6,548 Å, 6,583 Å, and [S II] 6,717 Å, 6,731 Å lines. The latter was observed with a 0.76" wide slit at a position angle of 83° east of north. We scale the NIRSPEC data to match the SDSS spectrum where they overlap and correct for Galactic extinction as above. Because of the lower signal-to-noise ratio in these spectra compared to the KCWI spectrum, we fix the velocities and linewidths of each emission line using the fit to the KCWI core spectrum.

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Article

Luminosity in Makani, $3.6(\pm1.0) \times 10^{40}$ erg s$^{-1}$, is three times lower than the average for typical [Ne v] emitters detected at $z = 0.6 - 1.2$ (ref. 3), it may therefore be emitted in shocks41,42. The line ratios in the broad component of the core KCWI and SDSS spectra of log([Ne v]/[Ne iii] 3,869 Å) $= -0.77^{+0.11}_{-0.20}$, log (O ii)/[O iii]) $= -0.11^{+0.03}_{-0.05}$, log ([Ne v]/[O ii]) $= -1.07^{+0.17}_{-0.19}$ and log (Ne ii 4,686 Å/Hβ) $< -0.87^{+0.03}_{-0.01}$ are also consistent with either AGN photo-ionization39 or ionization in shocks with velocities $0.45^{+0.20}_{-0.44}$ of at least 300–400 km s$^{-1}$.

ALMA observations, data reduction and analysis

Makani was observed by the ALMA 12-m array as part of projects 2016.1.01072.S and 2017.1.01318.S on 11 March 2017, 10 April 2018 and 15 December 2017 in antenna configurations C40-1 (baselines 15–287 m) and C43–3 (baselines 15–500 m) and C43–6 (baselines 15–2,517 m) respectively. We used the Band 4 receivers with a representative frequency of 158.01 GHz to detect CO (2–1) at the redshift of the target. The total integration time on source was 212 min. The average precipitable water vapour column during observations was approximately 2.5 mm and the average system temperature was approximately 75 K. The atmospheric, bandpass, pointing, phase and flux calibrators included the sources J2148+0657, J2134–0153 and Neptune.

We use the quality-checked ALMA pipeline-calibrated products, concatenating the observations into a single multi-epoch set. We image the data using CASA (version 5.1.0-74), producing three versions of the data cube: naturally weighted, 1$''$ tapered and 0.6$''$ restored. The latter uses a circular Gaussian restoring beam with a full-width at half-maximum (FWHM) of 0.6$''$ to match the seeing of the KCWI data. We produce a tapered image in order to maximize sensitivity to potentially extended but weak CO emission around the target. We produce clean cubes by first generating dirty cubes and assess the r.m.s. noise per channel in each version. This value is then used in an iterative cleaning step (CASA clean) where we set a cleaning threshold of 3$\sigma$, chosen to maintain a balance between producing a clean image while ensuring that real faint extended structure is not removed. We use multi-scale cleaning with scales of 0$''$, 0.4$''$, 0.8$''$ and 1.6$''$. The FWHM of the synthesized clean beams in the naturally weighted, 1$''$ tapered and 0.6$''$ restored. The latter uses a circular Gaussian restoring beam with a full-width at half-maximum (FWHM) of 0.6$''$ to match the seeing of the KCWI data. We produce a tapered image in order to maximize sensitivity to potentially extended but weak CO emission around the target. We produce clean cubes by first generating dirty cubes and assess the r.m.s. noise per channel in each version. This value is then used in an iterative cleaning step (CASA clean) where we set a cleaning threshold of 3$\sigma$, chosen to maintain a balance between producing a clean image while ensuring that real faint extended structure is not removed. We use multi-scale cleaning with scales of 0$''$, 0.4$''$, 0.8$''$ and 1.6$''$. The FWHM of the synthesized clean beams in the naturally weighted, 1$''$ tapered and 0.6$''$ restored. The latter uses a circular Gaussian restoring beam with a full-width at half-maximum (FWHM) of 0.6$''$ to match the seeing of the KCWI data. We produce a tapered image in order to maximize sensitivity to potentially extended but weak CO emission around the target. We produce clean cubes by first generating dirty cubes and assess the r.m.s. noise per channel in each version. This value is then used in an iterative cleaning step (CASA clean) where we set a cleaning threshold of 3$\sigma$, chosen to maintain a balance between producing a clean image while ensuring that real faint extended structure is not removed. We use multi-scale cleaning with scales of 0$''$, 0.4$''$, 0.8$''$ and 1.6$''$. The FWHM of the synthesized clean beams in the naturally weighted, 1$''$ tapered and 0.6$''$ restored. The latter uses a circular Gaussian restoring beam with a full-width at half-maximum (FWHM) of 0.6$''$ to match the seeing of the KCWI data. We produce a tapered image in order to maximize sensitivity to potentially extended but weak CO emission around the target. We produce clean cubes by first generating dirty cubes and assess the r.m.s. noise per channel in each version. This value is then used in an iterative cleaning step (CASA clean) where we set a cleaning threshold of 3$\sigma$, chosen to maintain a balance between producing a clean image while ensuring that real faint extended structure is not removed. We use multi-scale cleaning with scales of 0$''$, 0.4$''$, 0.8$''$ and 1.6$''$. The FWHM of the synthesized clean beams in the naturally weighted, 1$''$ tapered and 0.6$''$ restored. The latter uses a circular Gaussian restoring beam with a full-width at half-maximum (FWHM) of 0.6$''$ to match the seeing of the KCWI data. We produce a tapered image in order to maximize sensitivity to potentially extended but weak CO emission around the target. We produce clean cubes by first generating dirty cubes and assess the r.m.s. noise per channel in each version. This value is then used in an iterative cleaning step (CASA clean) where we set a cleaning threshold of 3$\sigma$, chosen to maintain a balance between producing a clean image while ensuring that real faint extended structure is not removed. We use multi-scale cleaning with scales of 0$''$, 0.4$''$, 0.8$''$ and 1.6$''$. The FWHM of the synthesized clean beams in the naturally weighted, 1$''$ tapered and 0.6$''$ restored.

After examining the cubes and extracting spectra, we detect a weak line of [O ii] at $z = 0.673$. We quote gas masses $M_{\text{gas}} = 11.07 \pm 0.20$ M$\odot$ and image the full spectral coverage including basebands placed to ensure the highest signal-to-noise features, but masking them lowers these masses by factors of <2. As in previous work37, we adopt $\alpha = 0.34M^{1.75}_{\text{Mpc}}(\text{K} \text{km s}^{-1} \text{pc})^{-1}$, which is lower than both the standard Galactic and ULIRG conversions because high-velocity extended and/or CO emission might be optically thin if it is tracing molecular gas in a turbulent outflow46. This provides a conservative estimate of the molecular gas mass.

Size measurements

A Sérsic fit to the Hubble Space Telescope image of Makani yields an effective radius $R_e = 2.24$ kpc for a Sérsic index of $n = 4.4$. For a pure Sérsic profile, $R_e$ is equivalent to the stellar half-light radius $r_{1/2}$, or the radius within which half of the stellar light arises47. The substantial extended, asymmetric tidal structure in a merger like Makani will affect the determination of any Sérsic component, although in this case it appears not to be a large effect; a direct measure of the half-light radius from integration of the stellar light yields $r_{1/2} = 2.75$ kpc. We take the average of these estimates, 2.5 kpc, to be the half-light radius.

Makani has a peaked core that is well interior of the half-light radius. An estimate of its size is the radial width at half-maximum of the radial light profile. This measure yields a core radius of 400 pc, within which 10% of the galaxy’s stellar light resides. This radius is comparable to other starbursts and post-starbursts without extended tidal structure48.

For comparison, Extended Data Fig. 3 shows the radial profile of the [O ii] nebula, determined from azimuthal averages over pixels in bins of radial width 2 kpc. Integrating over the nebula from the centre outward as a fraction of the total flux within 50 kpc yields a half-light radius in [O ii] of 17 kpc. The short (east-to-west) and long (north-to-south) axis profiles, averaged in the direction perpendicular to each profile over bins 2 kpc wide, decrease less steeply, with maximum nuclear distances of about 40 kpc and 50 kpc along the short and long axes, respectively. When doubled, these yield the quoted size of 100 kpc $\times$ 80 kpc. These measurements approach the size of the KCWI field of view, from which we infer that the nebula could be larger.

Stellar mass estimation

We estimate the stellar mass of Makani using the Bayesian stellar population synthesis modelling code Prospector49 and the Flexible Stellar Population Synthesis (FSPS)50 models (Extended Data Fig. 4). We assemble the spectral energy distribution at rest-frame wavelengths between 0.1 μm and 15 μm from the Galaxy Evolution Explorer45, the SDSS46, the Spitzer Space Telescope45 and the Wide-field Infrared Survey Explorer (WISE)57. We adopt a Salpeter initial mass function from the range (0.1–100) M$\odot$, and assume a ‘delayed $r$’ backbone star-formation history (t is the e-folding star-formation timescale) with a late-time burst of star formation superimposed. We assume a power-law dust attenuation curve (proportional to $1.4^{+0.5}_{-0.5}$) and allow differential attenuation between the light from young stars relative to the diffuse interstellar medium45. Finally, we compute the infrared spectrum using energy balance arguments and basic assumptions about the re-radiated infrared spectrum45. The median value of the marginalized posterior probability for stellar mass is $\log(M_*/M_\odot) = 11.07$ with an interquartile range of 10.98–11.14. To account for systematic uncertainties in the star formation history and other prior parameters we adopt an average stellar mass and uncertainty of $\log(M_*/M_\odot) = 11.1(\pm0.2)$.

We assume that the mid-infrared dust emission in Makani arises from star formation in order to fit the spectral energy distribution. WISE mid-infrared colours — $W1 - W2 = 0.74(\pm0.03)$ and $W2 - W3 = 3.64(\pm0.08)$, in Vega magnitudes53,56—place this galaxy in a region occupied partly by starbursts, but also characteristic of obscured AGN in merging galaxies53. The present data do not distinguish between these possibilities.

Stellar continuum modelling

To obtain the best constraints on the young stellar populations in Makani we fit its rest-frame ultraviolet–optical spectrum with stellar population synthesis models. This fitting is very sensitive to both the quality of the spectrophotometry and the strong stellar absorption...
lines in the 3,700–5,000 Å range. Since the KCWI spectrum does not extend redwards of rest-frame 3,800 Å, we use a spectrum obtained with the Blue Channel Spectrograph on the MMT with a 1′ slit. To further extend the wavelength coverage, we join the MMT and SDSS spectra near 4,600 Å. These spectra have similar spectral resolutions ($R \approx 1,500$). The combined spectrum (Extended Data Fig. 5) matches the SDSS $ugriz$ photometry well, indicating good spectrophotometric calibration.

We fit the MMT+SDSS spectrum with a combination of single stellar population models and the Salten attenuation curve. We use FSPS to generate simple stellar populations with Padova 2008 isochrones, a Salpeter initial mass function, and a new theoretical stellar library C3K (C. Conroy et al., manuscript in preparation) with a resolution of $R = 10,000$. We use solar-metallicity simple stellar population templates with 42 ages spanning 1 Myr to 7.9 Gyr. We perform the fit with the Penalized Pixel-Fitting (pPXF) code. Because the galaxy is very compact and much of its dust is likely to be in the outflow, we require all stellar populations to share the same attenuation. The best-fitting model has $\tau = 0.4590$, a stellar velocity dispersion $\sigma = 170$ km $s^{-1}$, and $E(B-V) = 0.19$. The spectrum is dominated by a mixture of young and intermediate-age stellar populations, with approximately 50% of the continuum emission at rest-frame 5,500 Å contributed by populations less than 7 Myr old. An additional 40% comes from a 0.4-Gyr-old stellar population. This implies two major starburst episodes, with the 0.4-Gyr burst perhaps corresponding to the first passage of the merger and the recent burst to the final coalescence. The 10-Myr-averaged star-formation rate inferred from the simple stellar population modelling is 175 M$\odot$ yr$^{-1}$, after converting to a Chabrier initial mass function.

**Data availability**

Raw data generated at the Keck Observatory are available at the Keck Observatory Archive (https://koa.ipac.caltech.edu/) following the standard 18-month proprietary period after the date of observation. This paper makes use of the ALMA data ADS/JAO.ALMA#2016.1.01072.S and ADS/JAO.ALMA#2017.1.01315.S, which are available at the ALMA Science Archive (https://almascience.nrao.edu/). Some of the data presented here were obtained from the SDSS (https://www.sdss.org). The Hubble Space Telescope observations described here were obtained from the Hubble Legacy Archive (https://hla.stsci.edu/). Derived data supporting the findings of this study are available from the corresponding author upon request.

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44. Vagi, M., et al. The VIMOS Public Extragalactic Redshift Survey (VIPERS). AGN feedback here were obtained from the SDSS (https://www.sdss.org). The Hubble Space Telescope (https://hsto.isaipa.edu/aq/) and its successor, the James Webb Space Telescope, will be used to study the formation of galaxies in detail. Some of the data presented herein were obtained at the 10.4-m Keck Observatory, which is operated as a collaborative project among the California Institute of Technology, the University of California, the National Aeronautics and Space Administration, and the National Science Foundation. The authors wish to acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. MAO is a partnership of the European Southern Observatory (ESO, representing its member states), NSF (USA) and the National Institutes of Natural Sciences (Japan), together with the National Research Council (Canada), the Ministry of Science and Technology and Academia Sinica Institute of Astronomy and Astrophysics (Taiwan), and the Korea Astronomy and Space Science Institute (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is supported by ESO, the Associated Universities, Inc. (AUI) / National Radio Astronomy Observatory (NRAO) and the National Astronomical Observatory of Japan (NAOJ). NAOJ is a facility supported under cooperative agreement by AUI. The Hubble Legacy Archive is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA) and the Canadian Astronomy Data Centre (CADC/NRC/CSA). Some of the data presented here were obtained at the MMT Observatory, a joint facility of the University of Arizona and the Smithsonian Institution. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the NSF, the US Department of Energy, NASA, the Japanese Monbukagakusho, the Max-Planck Gesellschaft, and the Higher Education Funding Council for England. The SDSS is managed by the Astrophysical Research Consortium (ARC), which is a collaboration of the NSF, the Department of Energy, and the Sloan Foundation. SDSSII is being managed by the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institut für Astronomie (MPIA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.
Author contributions A.C. and J.E.G. conceived the observations of a sample developed by C.T. A.C., G.L., and D.S.N.R. performed the KCWI observations, and J.E.G. led the ALMA data acquisition. D.S.N.R. led data reduction and analysis of the KCWI data, and J.E.G. led data reduction and analysis of the ALMA data. C.T. and E.R.G. fitted ancillary spectra. D.S.N.R. wrote the manuscript, with contributions from A.C. throughout. J.E.G. contributed to the section on ALMA observations, A.M.D.-S. and J.M. contributed to the section on stellar mass, and C.T. contributed to the section on stellar populations. D.S.N.R., G.L., E.R.G., J.M. and C.T. produced the figures, with A.C. and J.E.G. contributing to their design. J.M. performed the spectral energy distribution modelling, and P.H.S. handled the structural analysis of the Hubble Space Telescope data. All co-authors provided critical feedback to the text and helped to shape the manuscript.

Competing interests The authors declare no competing interests.

Additional information
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Extended Data Fig. 1 | Line ratio diagrams of the core spectrum. In a, the green solid line demarcates the edge of the $z = 0$ pure star-formation locus; in both panels, blue long-dashed lines denote the limits of young star photo-ionization; and in b, the green short-dashed line separates Seyfert galaxies (AGNs) from low-ionization nuclear emission-line regions (LINERs). Error bars are 1σ. The red narrow component is consistent with star formation at near-solar metallicity, while the broad, outflowing component is ionized by either an AGN or high velocity shocks.
Extended Data Fig. 2 | Comparison of velocity profiles among gas phases. Tracers are shown as coloured lines, while the CO(2–1) profile is shaded in grey. The data are smoothed by three pixels and the coloured shadings indicate 1σ errors on the line fluxes. The ultraviolet–optical nebular lines are shown with the correct relative fluxes (uncorrected for reddening in the host galaxy), while the CO(2–1) line is arbitrarily scaled. The spatially integrated velocity profiles probe different gas phases and spatial scales but show remarkable overall consistency.
Extended Data Fig. 3 | [O ii] spatial profiles. Profiles are averaged and then plotted versus distance from the galaxy nucleus along circular radii (black); the short axis of the nebula, or east-to-west axis (blue); and the long axis of the nebula, or north-to-south axis (purple). The averages are taken in directions perpendicular to these: in azimuth around the nucleus; along the long axis; and along the short axis, respectively. The short and long axis profiles are shifted upward in flux so that the three profiles match in the lowest distance bin. Errors are standard errors of the mean. Plotted as dashed lines are the stellar half-light radius (orange), the [O ii] half-light radius within 50 kpc (black), and the [O ii] maximum radius along the short and long axes (blue and purple).
Extended Data Fig. 4 | Fit to the ultraviolet-to-mid-infrared spectral energy distribution. The best-fit model and 1σ error are shown with a black line and grey shading; observed fluxes with 1σ errors (usually smaller than the symbols) are yellow circles; and model fluxes are open cyan boxes. Flux is given in AB magnitudes and observed-frame wavelengths in micrometres. The posterior probability $P(M)$ for stellar mass $M$ is shown in the inset.
Extended Data Fig. 5 | Stellar population model fit. Spectral data from SDSS and the MMT and 1σ errors are shown as the black line and grey shading. SDSS ugriz photometry and 1σ errors are the cyan squares and grey vertical bars. The best-fit model is a magenta line; the stellar population components summed to produce this model are shown as coloured lines, with ages as shown. SSP, simple stellar population.