Stellar feedback as the origin of an extended molecular outflow in a starburst galaxy

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Recent observations have revealed that starburst galaxies can drive molecular gas outflows through stellar radiation pressure\textsuperscript{1,2}. Molecular gas is the phase of the interstellar medium from which stars form, so these outflows curtail stellar mass growth in galaxies. Previously known outflows, however, involve small fractions of the total molecular gas content and have typical scales of less than a kiloparsec\textsuperscript{1-3}. In at least some cases, input from active galactic nuclei is dynamically important\textsuperscript{4-7}, so pure stellar feedback (the momentum return into the interstellar medium) has been considered incapable of rapidly terminating star formation on galactic scales. Molecular gas has been detected outside the galactic plane of the archetypal starburst galaxy M82 (refs 4 and 5), but so far there has been no evidence that starbursts can propel substantial quantities of cold molecular gas to the same galactocentric radius (about 10 kiloparsecs) as the warmer gas that has been traced by metal ion absorbers in the circumgalactic medium\textsuperscript{8}. Here we report observations of molecular gas in a compact (effective radius 100 parsecs) massive starburst galaxy at redshift 0.7, which is known to drive a fast outflow of ionized gas\textsuperscript{9}. We find that 35 per cent of the total molecular gas extends approximately 10 kiloparsecs, and one-third of this extended gas has a velocity of up to 1,000 kilometres per second. The kinetic energy associated with this high-velocity component is consistent with the momentum flux available from stellar radiation pressure\textsuperscript{10-12}. This demonstrates that nuclear bursts of star formation are capable of ejecting large amounts of cold gas from the central regions of galaxies, thereby strongly affecting their evolution by truncating star formation and redistributing matter\textsuperscript{13,14}.

SDSS J0905+57 (redshift $z = 0.712$) is a compact starburst galaxy with emission-line properties consistent with a star-forming galaxy and no observational evidence of a strong hot dust continuum in the mid-infrared part of the spectrum, indicating no significant black hole accretion activity\textsuperscript{4,15}. The galaxy is driving a wind with one of the highest velocities known for any star-forming galaxy, with the interstellar absorption lines of Ca ii, Fe ii and Mg ii blueshifted by 2,500 km s$^{-1}$ with respect to the Balmer stellar absorption lines. The total infrared luminosity is $L_{\text{IR}} \approx 1.2 \times 10^{10}$ W, corresponding to a star formation rate (SFR) of 260$M_{\odot}$ yr$^{-1}$, where $M_{\odot}$ is the mass of the Sun. Hubble Space Telescope observations reveal that SDSS J0905+57 is extremely compact in the rest-frame V band (475 nm), with an effective radius of $r_e = 94$ pc (comparable to the size of 30 Doradus). This implies an SFR density of $\Sigma_{\text{SFR}} \approx 4,700 M_{\odot}$ yr$^{-1}$ kpc$^{-2}$. The compact nature of the galaxy and the high density of central star formation suggest that SDSS J0905+57 is likely to be at the final stage of a major merger\textsuperscript{16} and is the progenitor of an elliptical galaxy.

We observed SDSS J0905+57 with the Institut de Radioastronomie Millimétrique Plateau de Bure Interferometer in the 2 mm band with receivers tuned to the frequency of the redshifted CO(2–1) emission line at $z = 0.712$ (134 GHz). At temperatures of the order of 10 K, the carbon monoxide $J = 2 \rightarrow 1$ rotational transition is excited at a critical density of $n_{\text{crit}} \approx 10^4$ cm$^{-3}$ and is a good tracer of the bulk of the cold molecular gas reservoir. The spectrum (Fig. 1) reveals a detection of the CO(2–1) emission line at observed frequency $\nu_{\text{obs}} = 134.666$ GHz, corresponding to $z_{\text{CO}} = 0.712$, which is consistent with the stellar redshift, with the full width at half maximum (FWHM) approximately 200 km s$^{-1}$.

We refer to this as the ‘core’ line. The spectrum also reveals CO emission in a broad wing extending up to 1,000 km s$^{-1}$ from the core line. When averaged over the velocity range $\Delta V = 200-1,000$ km s$^{-1}$, the emission is significant and peaks 1.2 $\pm$ 0.3 or $\pm$ 2 kpc from the core line with a flux density of $S = 0.43 \pm 0.09$ mJy (Figs 2 and 3). We interpret these observations as evidence that molecular gas is being driven out of the galaxy through stellar feedback processes.

The core CO line emission is also marginally resolved beyond the 3$\sigma$ beam when averaged over the full core linewidth (full width at zero intensity, FWZI) ($\Delta V = 400$ km s$^{-1}$, Fig. 2). To confirm this, and to measure the size of the extended CO emission, we examine the $u$–$\nu$ plane visibilities to evaluate the average signal amplitude as a function of baseline separation (Methods). The data are inconsistent with a flat profile that would indicate an unresolved source, but are better fitted by a combination of a point source and circular Gaussian profile with a half
power radius of $1.6^{+0.8}_{-0.4}$ arcseconds. A point-source-only model can be ruled out at the 4.7σ level. The angular size of this extended component corresponds to a radius of $12^{+3.5}_{-2}$ kpc in physical projection, 130 times larger than the rest-frame V-band effective radius (Fig. 3). This extended low-velocity CO emission could also be associated with feedback processes (for example, previously ejected gas), but we cannot rule out the hypothesis that it represents molecular gas ejected from disks during previous stages of the merger.

We assume that the unresolved CO component is associated with dense gas still actively forming stars. The mass of this active component is estimated as $M_{\text{HI}} = (3.1 \pm 0.6) \times 10^8 M_\odot$, assuming thermalized CO J = 2 → 1 emission and $\alpha = 0.8 M_\odot (\text{K km s}^{-1} \text{pc}^2)^{-1}$, where $sL_{\text{CO}} = M_{\text{HI}} (L_\text{CO} \text{ is the CO luminosity in units of K km s}^{-1} \text{ pc}^2)$ and $\alpha$ is the the CO-to-H$_2$ conversion factor appropriate for the conditions in the nuclear regions of ultraluminous infrared galaxies.\textsuperscript{16} The infrared-to-CO luminosity ratio $L_\text{IR}/L'_{\text{CO}} \approx 800 L_\odot$ (K km s$^{-1}$ pc$^2$) is close to the upper limit predicted for star formation efficiency at radiation pressure.\textsuperscript{19} The masses in the extended low-velocity ($|\Delta V| < 200$ km s$^{-1}$) and high-velocity ($|\Delta V| = 200–1,000$ km s$^{-1}$) wing components are $M_{1\text{H}_2} = (1.1 \pm 0.5) \times 10^9 M_\odot$ and $M_{2\text{H}_2} = (0.6 \pm 0.2) \times 10^9 M_\odot$ respectively. Combined, the extended CO emission represents approximately 35% of the total gas mass. An uncertainty here is the choice of $\alpha$; we assume a conservative value of $\alpha = 0.34 M_\odot (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ for the extended components, which assumes local thermodynamic equilibrium and is applicable to the optically thin case of turbulent gas associated with a wind, assuming an CO/H$_2$ abundance of $10^{-4}$ and typical excitation temperature of 30 K (ref. 17).

If the extended CO-emitting gas forms a foreground screen, then the total hydrogen atom column density $N_{\text{HI}}$ can be inferred in the limit where the column is dominated by molecular gas. As with the molecular mass estimate, one must adopt a value for the ‘X-factor’ that relates CO emission to molecular hydrogen column density $X_{\text{CO}} = N_{\text{HI}}/W_{\text{CO}}$, with $N_{\text{HI}}$ in units of cm$^{-2}$ and the integrated line intensity $W_{\text{CO}}$ in units of K km s$^{-1}$. We assume $X_{\text{CO}} = 1.6 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$, for the same assumptions as for $\alpha$ for the extended components described above, which yields $N_{\text{HI}} \approx 2 \times 10^{20} \text{ cm}^{-2}$. Independently, the extinction of the stellar and nebular emission can be estimated from the relative intensities of the Balmer lines, which indicate an extinction of $A_V = 0.5$ mag to the young, compact stellar population (assuming Milky Way abundances).\textsuperscript{20} This corresponds to a column density of $N_{\text{HI}} \approx 10^{21} \text{ cm}^{-2}$, reasonable agreement with the value estimated from the cold gas. A plausible scenario is that an outflow, or series of outflows, launched from the nuclear starburst has purged the interstellar medium of the stellar bulge, sweeping cold gas and dust into the halo. This ‘blow out’ phase will rapidly truncate star formation in the bulge on a timescale comparable to the dynamical time, exposing a bright shell of young stars around the nuclear starburst, which will consume the remaining molecular gas within 10 million years given the gas supply and consumption rate.

For cold gas to be driven to large galactocentric distances, the wind driving mechanism must be favourable to the survival of cold clouds.\textsuperscript{21} Originally it was thought that cold material would be ejected along with the hot gas associated with the explosions of supernovae,\textsuperscript{22} but cold clouds entrained in such outflows are predicted to be destroyed on timescales of millions of years and quickly incorporated into the hot flow.\textsuperscript{23} Alternatively, stellar radiation pressure on dust grains can accelerate cold gas several million years before the first cluster supernovae explode, without subjecting it to the deleterious effects of a hot conductive atmosphere.\textsuperscript{24} This mechanism has already been shown to be the most likely driver in local starbursts exhibiting subkiloparsec molecular outflows.\textsuperscript{25} After exiting the galaxy, the cold gas interacts with the potentially hot halo atmosphere. Although the hydrodynamic interaction between a hot (10$^6$ K) atmosphere and high-velocity cold (10 K) to cool (10$^3$ K) clouds is complex,\textsuperscript{26} these observations suggest that ejected molecular gas can survive in such an environment for timescales of at least approximately 10 million years.
If the maximum velocity ($V \approx 1,000$ km s$^{-1}$) in the redshifted wing is representative of the deprojected velocity of the outflow$^{22}$, then the extended CO emitting gas carries kinetic power $P_{k} = (2.6 \pm 0.8) \times 10^{36}$ W. The mass outflow rate is $M_{\text{out}} = 80 \pm 25 M_{\odot}$ yr$^{-1}$, implying a ‘mass-loading’ factor of $M_{\text{out}} / SFR = 30\%$. In a momentum-driven wind, the mass loading factor scales inversely with outflow velocity$^{23}$, and our results are roughly consistent with an extrapolation of the linear correlation between $M_{\text{out}} / SFR$ and $v$ that has been found for local pure starbursts$^{9}$. The rate of momentum input available from stellar radiation pressure in the single scattering limit is $L/c = 4 \times 10^{-38}$ N (ref. 24), where $L$ is the bolometric luminosity, but note that this will be larger when the medium is optically thick to far-infrared photons, scaling with the optical depth $\tau_{\text{IR}}$ (ref. 9). The outflow momentum flux is $\nu M_{\text{out}} = (4.8 \pm 1.9) \times 10^{38}$ N, implying that the energy of the outflow is compatible with what is available from star formation alone. Material travelling at 1,000 km s$^{-1}$ takes less than 10 million years to reach the measured radial extent ($r > 8 \pm 2$ kpc) of the outflow. Again, this estimate is uncertain owing to projection effects, but the timescale is in broad agreement with the age of the young stellar population. Fitting of the rest-frame ultraviolet/optical spectra reveals that 90% of the stellar luminosity is contributed by a population of age 6 million years or younger. We cannot rule out the possibility that the outflow was launched by an active galactic nucleus (AGN) that has since ‘switched off’, but the current observations indicate that the outflow is compatible with pure stellar feedback.

A key goal in galaxy evolution studies has been to understand the coupling between various forms of energy and momentum injection and the cold interstellar medium, as well as their relative efficacies as feedback channels. The molecular outflow in SDSS J0905$+57$ at $z = 0.7$ is extended on a much larger scale than has been previously observed in local starburst galaxies exhibiting molecular winds$^{1-2}$. In part, this could be related to the ultra-compact morphology and extreme nature of the system, which has a star-formation-rate density that is orders of magnitude larger than the local systems. In local galaxies, where small-scale radiatively driven molecular winds have been observed, only a few per cent of the total gas reservoir is involved in the outflow$^{1-2}$, whereas in SDSS J0905$+57$ up to a third of the total molecular gas reservoir appears to have been ejected. These observations are evidence that pure stellar feedback can affect the evolution of a galaxy as a whole on short (millions of years) timescales by directly removing the dense material required for star formation, and is therefore competitive with AGN feedback$^{23-27}$ as a mechanism for regulating stellar mass growth and redistributing baryons in massive galaxies.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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METHODS

Target information. The target SDSS J0905+57 at 0.09 h 05 min 23.7 s, +57° 59′ 12.6″ (z = 0.712) is a galaxy with the fastest Mg II outflow velocity of a larger sample of similar galaxies originally selected on the basis of post-starburst spectral features.34–36 The total stellar mass, estimated from fitting of the rest-frame ultraviolet-to-near-infrared spectral energy distribution, is M* = 5.5 × 10^10 M☉, and analysis of the rest-frame near-ultraviolet/optical spectra show that 90% of the stellar emission is contributed by populations younger than 6 million years, representing 20% of the stellar mass. The rest-frame V-band size in the Hubble Space Telescope imaging was measured following methods presented elsewhere,18 which we briefly describe here. To parameterize the compactness of the galaxy, we fitted Sérsic and Sérsic + PSF (point spread function) models to the galaxy, with the Sérsic index frozen to n = 4, and its nearby masked field (a 28′′ × 28′′ box centred on the galaxy) with GALFIT version 3 (ref. 29). The effective radius is r_e = 94 pc, with two-thirds of the rest-frame ultraviolet/optical light unresolved by the Hubble Space Telescope.

The bolometric luminosity was estimated through extrapolation of the mid-infrared (Wide-Field Infrared Survey Explorer 12 μm, 22μm) photometry, using appropriate spectral energy distribution templates that provide an estimate of the far-infrared emission, assuming these compact star-forming galaxies conform to the typical cool dust emission seen in star-forming galaxies.37–40 The SFR derived from the total (integrated over 8–1,000 μm) dust emission is in agreement with that derived from the near-infrared detection of the rest-frame 0.1–3 μm spectral energy distribution, with proper treatment of differential dust obscuration of the stellar emission.41,42 The measured L_IR = 1.2 × 10^10 L☉ corresponds to an SFR of 260 M☉ yr⁻¹, suggesting a Chabrier initial mass function (2.5 σ, Salpeter initial mass function would increase the SFR by 80%). If 50% of the star formation occurs within the effective radius measured above, then the projected SFR density is Σ_sfr = 4.7 M⊙ yr⁻¹ kpc⁻². As a guide to the level of uncertainty in derived properties, which depend largely on template fitting, both the stellar mass and infrared luminosity are estimated to be accurate within a factor of two.

IRAM observations and data reduction. SDSS J0905+57 was observed on 6–12 May 2013 and 10 December 2013 as part of IRAM Plateau de Bure Interferometer projects W09A and X09C. PdBI was in compact (D) configuration with baselines of 25–140 m. We used the Wide-X correlator, re-targeting the redshifted CO(2–1) line at νobs = 134 GHz in the 2 mm band, recording dual polarization. The mean system temperature was Tsys = 80–120 K and precipitable water vapour was in the range 2–6 mm. The sources 3C84, 3C279, 3C454.3, 2200+420 and 0851+202 were used for bandpass calibration, and sources 0954+658 and 0971+624 were used for phase/amplitude calibration. We rejected scans for which the phase root mean square deviation exceeded more than 45° from the calibration solution. Finally, the source MWC349 was used for flux calibration (accuracy 5%–10% at 2 mm). The final root mean square noise in 20 Hz (45 km s⁻¹ ) channels is σ = 0.4 mJy. The package GILDAS was used for data calibration, mapping and analysis.

Line detection. We first mapped the ν–ν visibilities into the image plane to create a spectral cube from which we extract a spectrum from a single 0.6° pixel at the phase tracking centre. This spectrum is shown in Fig. 1, with the CO(2–1) emission line strongly detected at the expected frequency. The line is well modelled by a single Gaussian, with peak S = 2.8 ± 0.3 mJy and FWHM = 200 ± 35 km s⁻¹. Uncertainties on the profile fitting parameters such as line centres and widths were estimated in the following way: first, we estimated the uncertainty per channel by extracting spectra from 100 random locations close to the phase tracking centre, but in line-free parts of the data cube, and then evaluated the root mean squared variation in the signal for each channel. Under the assumption that the noise is drawn from a Gaussian distribution N with a mean of zero and a 1σ scale equivalent to the root mean square, we generated 1,000 realizations of the target spectrum, each time adding flux drawn randomly from N to each channel. The integrated flux and line fits were reevaluated for each of the 1,000 realizations, and the standard deviation of the derived values were taken to be the 1σ uncertainties on the fitting parameters. The integrated line flux over the 200–1,000 km s⁻¹ wing is S/V = 0.26 ± 0.07 Jy km s⁻¹, corresponding to L_500 = (1.8 ± 0.5) × 10^10 L☉ km s⁻¹ pc⁻². When integrated over the core line, |ΔV| < 200 km s⁻¹, the integrated line fluxes in the extended and unresolved components (see below) are S/V = 0.46 ± 0.20 Jy km s⁻¹ and S/V = 0.56 ± 0.12 Jy km s⁻¹, respectively, corresponding to L_500 = (3.1 ± 1.3) × 10^10 L☉ km s⁻¹ pc⁻² and L_500 = (3.8 ± 0.8) × 10^10 L☉ km s⁻¹ pc⁻².

Red, spatially offset high-velocity wing emission. The spectrum shown in Fig. 1 reveals evidence of CO emission redward of the core Gaussian line in a broad wing that extends to approximately 1,000 km s⁻¹. Averaging the one-dimensional spectrum shown in Fig. 1 over 200–1,000 km s⁻¹ yields an average flux density of S = 0.34 ± 0.09 mJy for the core line. When this spectral slice is collapsed over the same 1,000 km s⁻¹ channels, the peak of this wing emission is spatially offset 1.2 ± 0.3″ from the peak of the core line, with an average flux density of S = 0.43 ± 0.09 mJy (Fig. 2). The positional uncertainty was estimated as σ = 0.3 × FWHM/SNR, where SNR is the signal-to-noise ratio of S/σ, which is consistent with the positional error derived from a simulation involving the input of 1,000 model sources of the same flux level into the noise map. The scatter (standard deviation) in recovered positions is 0.3″ in right ascension and declination with no systematic positional offset.

An alternative way of assessing the significance of this feature is to use the random noise realizations of the data cube as described above, but excluding the source; that is, just considering the noise component. This takes into account the possibility that the noise in consecutive channels might be correlated. We then evaluated the rate at which we measure flux densities of S ≥ 0.43 mJy averaged over the same channels as the observed wing feature. Using 10' noise realizations, we found a rate of 1.4 × 10⁻⁶ with consistent the 80% significance of the detection (we found the same rate of negative fluctuations of equivalent magnitude).

Resolved core line emission. When averaged over the core Gaussian line, the map suggests that the CO emission is extended compared to the beam (Fig. 2). To verify this, and to evaluate the size of the emitting region, we examined the velocity averaged signal amplitude as a function of baseline separation (that is, synthetic aperture size) in the u–v plane, since an unresolved source will have a flat amplitude–radius profile. We averaged over the full linewidth, |ΔV| < FWHM, approximately corresponding to the FWZI (400 km s⁻¹). Extended Data Fig. 1 shows that the flux distribution, evaluated as the average amplitude in radial bins of width 50 m, deviates from a flat distribution at baseline separations shorter than approximately 100 m.

We see evidence for this in both independent observations of the target. As described above, and derived without any model of the step function, rejections of the fit were used to measure the average amplitude as a function of u–v separation for the main calibration common to both projects source 0917+624. Extended Data Figs 2 and 3 summarize the results with the map and amplitude–radius profile of the main calibrator, with the master phase calibration solution applied, indicating consistency with an unresolved source. During project X09C, two calibrators were observed: 0917+624 and 0954+658. This gave us the opportunity to derive a phase calibration solution excluding one of these sources (0954+658) and then apply that solution to the excluded source. This is a robust test, since 0954+658 has not contributed to the phase solution, and can be treated as an independent source. We show the map for 0917+624 and 0954+658 (with the latter ‘blindly’ treated with the phase solution derived from the main calibrator) in Extended Data Fig. 2, and the corresponding amplitude–radius profiles in Extended Data Fig. 3. Again, the results indicate unresolved sources, which would not be the case if phase calibration errors are the phase root mean square deviated more than 45° from the calibration solution, and therefore any smearing of the signal related to phase calibration errors will occur on scales of approximately 1.5″ (roughly half the size of the synthesized beam). This is a strong indication that the extended emission is real and not a result of seeing; however, as an additional check, we examined the profiles of the phase calibrators themselves.

If the extended emission is due to a phase calibration issue, in which point source is artificially smeared out, then we would expect to see a similar extended profile around the calibrators as well as the target. The first test we performed was to measure the average amplitude as a function of u–v separation for the main calibration common to both projects source 0917+624. We found that the amplitude for one degree of freedom, implying that the data are over-fitted. Additional observations that would allow us to increase the number of bins in the plane would improve our constraints on the size of the extended emission. Nevertheless, the χ² for the null hypothesis (that the source is unresolved) is χ² = 20.8,
with the $\Delta v^2$ corresponding to a significance of 4.76. Thus, we can rule out the point-source-only model with reasonable confidence.

**Feedback energetics.** SDSS J0905+57 is forming stars close to the theoretical upper limit for radiation pressure (Eddington-limited) star formation, with $L_{\text{IR}} \approx L_{\text{Ed}} \propto \text{GAL} L_{\text{CO}}/c$ for optically thick dust emission ($\tau_{100\mu m} > 1$). Here $L_{\text{IR}}$ is the measured total infrared luminosity (see above), $L_{\text{Ed}}$ is the Eddington luminosity, $c$ is the speed of light in vacuum, $G$ is the gravitational constant and $s$ is the Rosseland-mean dust opacity ($\kappa \approx 1,000 \text{cm}^2 \text{g}^{-1}$), where $L_{\text{Ed}}$ is the dust-to-gas mass ratio, typically $L_{\text{Ed}} < 1$ [37, ref. 10]. The high SFR density of SDSS J0905+57 is above the threshold necessary for launching a radiation-pressure-driven wind [38,39].

The clear evidence that the galaxy has a high velocity outflow, traced by Ca ii, Fe ii and Mg ii (A.M.D.-S., J.M., C.A.T., A.L.C., R.G.H., P.H.S. & J.E.G., manuscript in preparation) is an unambiguous sign of an energetic, gaseous outflow launched in the recent past. The observations presented here imply that molecular gas has also been ejected by feedback processes. In the following we estimate the rate of momentum input from the starburst and compare this to the energetics of the winds in order to determine whether radiation pressure is a viable power source for the outflow. Considering the gas associated with the high-velocity wing, we determine the mass outflow rate as follows:

$$M_{\text{out}} = \frac{M_{\text{vir}} v}{r}$$

where $M_{\text{vir}}$ is the gas mass in the outflow, $v$ is the outflow velocity, and $r$ is the radius of the outflow. We make the conservative assumption that the gas is travelling at 1,000 km s$^{-1}$, assuming that the maximum velocity extent of the wing is representative of the deprojected (that is, three-dimensional) velocity of the outflow. The mass outflow rate is $M_{\text{vir}} = 8.0 \pm 2.5 M_{\odot}$ yr$^{-1}$ and it follows that the kinetic power in the outflow is

$$P_{K} = \frac{M_{\text{vir}} v^2}{2}$$

which yields $P_{K} = (2.6 \pm 0.8) \times 10^{45}$ W, several orders of magnitude lower than the bolometric luminosity. Again, it is important to highlight that the error bars do not reflect the systematic uncertainty from the choice of $z$ that we use to estimate $M_{\text{vir}}$ from $L_{\text{IR}}$. In these calculations we have assumed an $z = 0.34 M_{\odot}$ (K km$^{-1}$ s$^{-1}$) that could be appropriate for the optically thin conditions in a turbulent molecular outflow. The conversion factor $x$ is defined as $M_{\text{out}}/L_{\text{IR}}$ for $f = 1$, where $f$ is a correction factor for higher-order transitions (as are often measured in high-redshift galaxies) to account for the shape of the spectral line energy distribution that describes the excitation of the gas. We have no constraints on the excitation state of the molecular gas in this galaxy (a wider range of transitions will be needed to constrain the spectral line energy distribution), and so for all components we have assumed thermalized CO emission such that $f_{\text{L}1} = (2.02 \pm 0.1) L_{\text{CO}}^\text{L1}$.

We argue that the outflow can be driven by radiation pressure from the compact starburst, so it is critical to assess the momentum injection available to drive cold gas out of the bulge and into the halo, clearing low-density `escape paths' for warmer gas that is then driven out by supernova detonations, several million years later.

What of the other extended, low-velocity CO component associated with the core line? It is difficult to infer feedback energetics associated with this gas, which is extended on scales of 12 kpc. This gas is moving with lower velocity than the outflow (the velocity towards the $v_{\text{LSR}}$ = 150 km s$^{-1}$ with $v < 0$). If this gas were ejected in a shell that has been radiatively driven into the halo in a previous outflow event, it is likely to have fragmented and decelerated; at late times the cold clouds are subject to lower radiation and ram-pressure. In this case an instantaneous measure of mass outflow rate and its connotations loses the intended meaning, and the previously expelled cold gas merely represents the time-integrated feedback history.

**Arguments for starburst feedback and against AGN feedback.** The arguments for star formation as opposed to AGN feedback for this galaxy and others like it are discussed in previous work [36,37]. For this source, we have shown that the compact starburst can produce the observed outflows, but cannot conclusively rule out that they were launched by an AGN that has since switched off. However, the larger population of compact starbursts shows ubiquitous outflows with no correlation with AGN activity, pointing to star formation as the most likely driver for the observed feedback in this and similar systems. Furthermore, there are two main pieces of observational evidence that imply that SDSS J0905+57 does not contain an energetically dominant AGN:

1. AGN activity is usually diagnosed via high-excitation emission lines, especially when X-ray observations are unavailable (as is the case for SDSS J0905+57) because it is typically assumed that the AGN is the only possible source for considerable numbers of high-energy photons. We have observational constraints on the emission lines [O III] $\lambda = 5.8\,\text{nm}, [\text{Ne V}] \lambda = 3.8\,\text{nm}$ and [Ne IV] $\lambda = 3.4\,\text{nm}$. We measure $\log (L/\text{Hz} \beta) = 0.19$ and $L_{\text{Ne IV}} = 7 \times 10^{46}$ W. No [Ne IV] $\lambda = 3.4\,\text{nm}$ is detected ($L_{\text{Ne IV}} < 2.25 \times 10^{45}$ W, 1σ upper limit), and the [Ne III] line is weak, $L_{\text{Ne III}} < 1.64 \times 10^{45}$ W (3σ detection). Very compact starburst galaxies can produce slightly elevated excitation emission lines with these observed properties and these observations are consistent with a starburst-dominated system at $z = 0.7$.

2. Mid-infrared observations can be used to assess obscured AGN activity. The 3.6–4.5 μm colour from Spitzer observations of SDSS J0905+57 is [3.6] – [4.5] = 0.48 (in Y Vega magnitudes), which is in a transition region between star-forming galaxies and AGNs [38,39]. Note that the 5.8–8.0 μm colour was unavailable in the Spitzer Warm Mission observations. We can also estimate $L_{\text{IR}}$ from $L_{\text{IR}}^{\text{bol}}$, in the limit where all the [O III] is produced from an AGN. Keeping in mind that $L_{\text{IR}}^{\text{bol}}$ is probably heavily contaminated by star formation, using $L_{\text{IR}}^{\text{bol}} = 600$ (ref. 40), we find $L_{\text{IR}}^{\text{bol}} = 4 \times 10^{46}$ W, which is approximately 4% of the total infrared luminosity.

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Extended Data Figure 1 | Average signal amplitude as a function of baseline separation for CO emission over the core line, $\Delta V = \pm 200 \text{ km s}^{-1}$. This reveals a significant deviation from a flat profile, indicating that the CO emission is partially resolved. The profile is accurately modelled by a combination of a point source (a delta function in the $u-v$ plane) and a Gaussian profile with half-power radius of $\sim 2''$. A point-source-only model can be ruled out at the 4.7$\sigma$ level. Error bars show the 1$\sigma$ confidence range, and are derived as $w^{-0.5}$, where $w = \Delta v t / T_{\text{sys}}$, where $\Delta v$ is the channel width, $t$ is the integration time and $T_{\text{sys}}$ is the product of the system temperature of two antennas. $r_{\text{uv}}$ is the separation of antennas in the $u-v$ plane.
Extended Data Figure 2 | Clean maps of the phase calibrators 0917+624 and 0954+658. The FWHM beam shape is indicated as a yellow ellipse. Contours are at levels of 10% to 90% of the peak flux, with the 90% flux line closest to the centre. a, Phases were calibrated with a solution derived from calibrators observed over both projects. b, The same phase solution was applied to observations of 0917+624 observed in project X09C only. c, The calibrator 0954+658 was calibrated with a phase solution derived from 0917+624 observed during project X09C only. All sources have a profile that is matched to the synthesized beam, with no evidence of extended emission.
Extended Data Figure 3 | Circularly averaged amplitude–radius profiles of the maps shown in Extended Data Fig. 2 in the u–v plane. All profiles are consistent with unresolved emission (flat profiles). Note that observing conditions were slightly better during project X09C than during W09A. Dashed lines indicate the mean amplitude. 0954+658 X09C ‘blind’ refers to the calibration solution derived from source 0917+624 only (see Methods).