Cold gas removal from the centre of a galaxy by a low-luminosity jet

Suma Murthy1,2,3✉, Raffaella Morganti1,2✉, Alexander Y. Wagner4, Tom Oosterloo1,2, Pierre Guillard5, Dipanjan Mukherjee6 and Geoffrey Bicknell7

The energy emitted by active galactic nuclei (AGNs) may provide a self-regulating process (AGN feedback) that shapes the evolution of galaxies. This is believed to operate along two modes, namely on galactic scales by clearing the interstellar medium via outflows, and on circumgalactic scales by preventing the cooling and accretion of gas onto the host galaxy. Radio jets associated with radiatively inefficient AGNs are known to contribute to the latter mode of feedback. However, such jets could also play a role on circumnuclear and galactic scales, blurring the distinction between the two modes. We have discovered a spatially resolved, massive molecular outflow, carrying ~75% of the gas in the central region of the host galaxy of a radiatively inefficient AGN. The outflow coincides with the radio jet 540 pc offset from the core, unambiguously pointing to the jet as the driver of this phenomenon. The modest luminosity of the radio source ($L_{1.4 \, \text{GHz}} = 2.1 \times 10^{23} \, \text{W Hz}^{-1}$) confirms predictions of simulations that jets of low-luminosity radio sources carry enough power to drive such outflows. Including kiloparsec-scale feedback from such sources, which comprise the majority of the radio AGN population, in cosmological simulations may assist in resolving some of their limitations.

The contribution of various classes of active galactic nuclei (AGNs) to feedback and the scales at which they operate are yet to be well characterized. In this context, the models of galaxy evolution consider only large, powerful radio AGNs that are capable of heating the intergalactic medium and thereby preventing the gas from accreting onto the host galaxy.

However, recently various studies have found that radio AGNs also have an impact on galactic scales where the radio jets interact strongly with the interstellar medium (ISM) and drive multiphase outflows, of which dense cold gas is the most massive component. Numerical simulations predict that such jet–ISM interactions could also be strong in low-luminosity radio AGNs where the jets spend more time embedded within the host galaxy. Observationally, to understand the impact of radio jets on the ISM, we need to spatially resolve the site of jet–ISM interaction and also be able to disentangle the contribution of the radiation from the optical AGN and of the radio jets to the observed impact on the cold gas. Such studies have so far not been possible. We present the case of a low-luminosity radio AGN where spatially resolved molecular gas observations have shown the presence of a massive outflow that is entirely driven by the radio jets.

The source under consideration, B2 0258+35, is a radio galaxy that consists of a bright, kiloparsec-scale structure and large, low-surface brightness radio lobes ~240 kpc in size. The kiloparsec-scale emission represents the current phase of activity, which started only between 400 thousand and 900 thousand years ago. The central radio source is nested in NGC 1167 ($z = 0.0165$), a gas-rich, massive, early-type galaxy, and the optical AGN in NGC 1167 is found to be radiatively inefficient. It has been suggested that the cold gas in the inner few kiloparsecs of the galaxy shows signatures of disturbed kinematics. Furthermore, the diffuse large-scale lobes are caused by a previous phase of activity and indicate that B2 0258+35 is a radio source that has undergone multiple episodes of activity. Thus, its properties make B2 0258+35 an important case for tracing the interaction between the radio jets and the ambient gas.

We use the cold molecular gas as a tracer for this purpose because it has been found to be typically the most massive component (that is, more massive than the warm ionized gas) of AGN-driven outflows.

A massive molecular outflow. To probe the distribution and kinematics of the cold molecular gas in the nuclear region of B2 0258+35, we carried out CO(1–0) observations with NOrthern Extended Millimeter Array (NOEMA) at an angular resolution of 1.9″ × 1.5″. At the redshift of the source, this corresponds to a spatial extent of 540 pc. We detect a circumnuclear molecular gas structure ~3 kpc in size and a quiescent CO ring ~10 kpc in radius (Fig. 1). Figure 2 shows that the kinematics of the ring is consistent with the regular rotation of the galaxy (Methods). The kinematics of the gas in the central few kiloparsecs, however, entirely deviates from this large-scale regular rotation.

The kinematics of the circumnuclear gas are of particular interest as this gas is spatially coincident with the radio jets. As can be seen from the velocity dispersion map (Fig. 1, bottom right) and the position–velocity plots of Fig. 2, the gas barely shows sign of regular rotation, suggesting that any disc structure that may have existed has been mostly disrupted. The velocity dispersion presented in Fig. 1 shows that the gas is particularly disturbed in the region 540 pc southeast of the radio core where the southern radio jet undergoes a sharp bend. At this location, the gas exhibits a particularly high velocity dispersion (with a maximum value of ~250 km s$^{-1}$) and is outflowing at high velocities, blueshifted up to ~500 km s$^{-1}$ with respect to the systemic velocity (Fig. 2). Furthermore, the CO...
emission is also notably brighter in this region compared to the rest of the circumnuclear structure (Fig. 1, top right). This CO ‘hotspot’, corresponding to the location of the outflowing gas, suggests that the gas in this region may have a different (higher) excitation temperature or originates from optically thin gas as a result of the mechanism that is producing the outflow\textsuperscript{12,13}. These findings, especially the spatial offset from the radio core, strongly suggest a link between the outflow and the radio jet instead of the outflow being driven by the nucleus itself.

Depending on the choice of CO-to-H\textsubscript{2} conversion factor, the mass of the molecular gas (M\textsubscript{H\textsubscript{2}}) in the entire circumnuclear structure ranges between (6.7 ± 0.7) × 10\textsuperscript{8} M\textsubscript{\odot} and (15.7 ± 1.6) × 10\textsuperscript{8} M\textsubscript{\odot} (see Methods for mass and outflow rate estimates). The mass of the gas that is disturbed by the interaction ranges between (5.0 ± 0.7) × 10\textsuperscript{8} M\textsubscript{\odot} and (11.7 ± 1.6) × 10\textsuperscript{8} M\textsubscript{\odot}. Thus, about 75% of the emission arising from this region is associated with the outflowing component. We derive a mass outflow rate ranging between 5 M\textsubscript{\odot}yr\textsuperscript{-1} and 10 M\textsubscript{\odot}yr\textsuperscript{-1}. This implies that within the short lifetime of the radio jet, which lasts for only a few million years, the kiloparsec-scale molecular gas reservoir will be depleted entirely. The escape velocity of the galaxy estimated based on the H\textsc{i} rotation curve\textsuperscript{12} is ~500 km s\textsuperscript{-1}, higher than the outflow velocities observed. Thus, the gas removed from the nuclear region will rain down onto the galaxy at a later time.

**Radio jet as the trigger of the molecular outflow.** The location and the properties of the molecular gas outflow suggest that the radio jet is responsible for the massive outflow observed in B2 0258+35. The energetics of the phenomena involved support this scenario.

The estimated kinetic power of the gas associated with the molecular gas outflow\textsuperscript{15} ranges between 1.8 × 10\textsuperscript{41} erg s\textsuperscript{-1} and 1.9 × 10\textsuperscript{41} erg s\textsuperscript{-1}. NGC 1167 has been classified as a low-luminosity optical AGN (LLAGN) with a spectrum typical of low-ionization nuclear emission-line region (LINER) galaxies, and the X-ray studies show that the AGN is not Compton-thick, confirming the low luminosity (G. Fabbiano et al., manuscript in preparation; see Methods for details on the luminosity estimates). Estimates of the bolometric luminosity of the AGN range between 3 × 10\textsuperscript{41} erg s\textsuperscript{-1} and 7 × 10\textsuperscript{41} erg s\textsuperscript{-1}. Thus, radiation can drive the outflow only if both the bolometric luminosity is at the higher end of the estimated range and the optical AGN transfers energy to the ISM with a very high efficiency. This, combined with the outflow being offset from the nucleus at the location where the jet is bent, makes it unlikely that radiation can explain the observed outflow and its properties.

However, estimates of the radio jet power\textsuperscript{16,17} range between 8.2 × 10\textsuperscript{40} erg s\textsuperscript{-1} and 1.3 × 10\textsuperscript{41} erg s\textsuperscript{-1} (Methods), about two orders of magnitude higher than the gas kinetic power. We note that the estimate of the jet power is based on various correlations (Methods) that may underestimate the actual jet power for low-luminosity radio sources\textsuperscript{15}. As such, the estimate obtained here should be regarded as a lower limit. Nevertheless, this shows that the radio jet can drive the observed outflow even at a low efficiency.

The possibility of low-luminosity radio jets impacting the surrounding medium has been suggested by earlier studies, which,
The best example of the impact of a low-luminosity radio jet on the molecular gas has been observed in the Seyfert 2 galaxy IC 5063 (refs. 13,18,21). Here the jet–ISM interaction has been ‘caught in action’ by the high-spatial-resolution observations that enabled the localization of the cold gas outflow, which showed that radio jets could be the main driver of the outflow. However, in this case, the optical AGN is powerful and hence it is not possible to completely exclude the effect of the strong nuclear radiation on the outflow.

Thus, B2 0258+35 is the first and the clearest case in which a young, low-luminosity radio jet is unambiguously found to be responsible for driving a massive molecular gas outflow, which has also been spatially localized. Furthermore, detailed optical integral field unit mapping of the host galaxy31 shows that the rotation axis of the ionized gas is tilted with respect to the stellar axis, suggesting that the gas is disturbed. However, the velocity field of the ionized gas shows that the anomalous velocities are well below 500 km s$^{-1}$. Thus, even if present, the outflow of ionized gas would be weak and less massive compared to the molecular gas outflow, as often is the case with AGN-driven outflows.

**Comparison with a hydrodynamic jet–ISM simulation.** The results presented here are of particular relevance to theoretical models of jet–ISM interactions in that they confirm some of the model predictions. Numerical simulations3–6,18,32 have shown that radio jets, despite being collimated structures, can impact the host galaxy substantially over a large volume when expanding into a clumpy ISM. Broadly speaking, they predict that this impact is large in the early phase of their life, and that low-luminosity jets remain trapped in the ISM while trying to break through the gas, continuously injecting their energy into the ISM with their impact over time becoming very pronounced. Our results show that this is indeed the case in B2 0258+35.

To explore this further, we compare our observations with a relativistic hydrodynamical simulation of jet–ISM interactions from ref. 4. The simulation is not a tailored simulation for B2 0258+35, so this comparison is meant to qualitatively illuminate the underlying physics rather than represent a quantitatively accurate model of the source. The particular simulation we chose for the purpose is simulation D from ref. 6, in which a relativistic jet of power $P_{\text{jet}} = 10^{45}$ erg s$^{-1}$ propagates through a thick galactic disc with a clumpy gas distribution at a tilt angle of 45°, a choice based on the results from H I absorption studies8, which indicate that the radio jets are very likely in the process of expanding into a gaseous disc.

A jet with an order of magnitude lower power would be at the lower limit of being capable of generating the outflow seen in B2 0258+35, as velocities reached by clouds when dispersed in energy-driven jet bubbles typically scale as $P_{\text{jet}}^{0.2}$ (ref. 18). The jet power implied by the jet-driven ISM dynamics is between $10^{44}$ erg s$^{-1}$ and $10^{45}$ erg s$^{-1}$, and is therefore approximately an order of magnitude larger than the jet power obtained from radio power scaling relations.

Figure 3 shows a series of mid-plane density slices perpendicular to the $y$ axis of the simulation that highlight the evolution of the jet–disc system. The lower-density jet plasma of the backflow in the cocoon, the secondary jet streams within the disc and the bow-shock bounded bubble are also clearly visible. The disc in the simulation is 4 kpc in diameter, and by 0.2 Myr the jet has processed the ISM in the central 2 kpc. The jet–ISM interactions are quite complicated, and most of the gas in the central region is strongly dispersed by the jet. The dispersion of dense gas is the strongest during the first few 100 kyr, and by 0.8 Myr a substantial amount of jet plasma is venting through chimneys perpendicular to the disc, reducing the energy coupling between jet and gas. The main jet streams interact directly with clumps in their path and become deflected or split, brightening in radio emission as a result of shocks while generating strong gas velocity dispersions and outflows.
Fig. 3 | Snapshots from the simulations. Mid-plane logarithmic density slices of simulation D from ref. 6 at y = 0 showing the evolution of the jet-disc system. The jet plasma is in blue and the dense clouds in orange-red. Ablated gas and shocked ambient medium are in yellow. The strongest interactions occur within the disc where the main jet stream hits clouds head-on. These regions show enhanced velocity dispersions and bulk velocities up to 500 km s\(^{-1}\) (see PV diagrams in Methods), and are locations of sharp jet deflection and splitting. The outer disc is dispersed but remains largely intact, but the inner 0.5 kpc region is largely cleared of gas by the jet by ~1 Myr.

Fig. 4 | Synthetic position–velocity diagrams. Top row: PV diagrams of the dense gas (number density greater than 100 cm\(^{-3}\)) in simulation D from ref. 6 along the line of sight (LOS) and the slits shown in the corresponding panels of the bottom row. The jet–cloud interactions at 0.2 Myr produce signatures of enhanced velocity dispersions with some clumps accelerated to beyond 500 km s\(^{-1}\), seen as strong spiky features in the PV diagrams. Bottom row: the left panel shows the line-of-sight velocity dispersion (second moment) of dense gas (number density greater than 100 cm\(^{-3}\)). The right panel shows the mean velocity (first moment) and the rotating disc; the broadband radio emission is shown in grey scale. The emissivity of the jet plasma is assumed to be proportional to \(p^{1.8}\), where \(p\) is the plasma pressure.23.
Intriguingly, we see a similar effect in B2 0258+35, where the massive outflow and a strong deflection in the radio continuum are located co-spatially along the southern jet. Moreover, we also do not see a disturbance in the gas along the much weaker counterjet. As the simulation shows, asymmetric signatures of jet–ISM interactions are expected if the ISM is clumpy. In one direction, northern in this case, the main jet stream may be propagating through a diffuse inter-cloud medium while the southern jet may be directly hitting a molecular cloud. Such asymmetries in radio morphology is often seen in radio sources, for example IC 5063 (ref. 21).

The density slices also show a largely evacuated central 0.5 kpc region that was cleared by the jet, a feature reminiscent of the apparent eradication of the inner kiloparsec disc of B2 0258+35 in the observations.

We looked for signatures of high-velocity bulk outflows at different time snapshots of the simulation and at different lines of sight through the simulation box to compare with the observations (see Fig. 4 and Methods for more details). We find that regions of jet–ISM interactions show enhanced velocity dispersions of the dense phase (gas with densities \( n > 100 \, \text{cm}^{-3} \)), and that clouds hit directly by the main jet streams may be accelerated to beyond 500 km s\(^{-1} \), consistent with our observations. The signatures of cloud acceleration from our simulations are also offset from the centre. These dense gas dispersion and outflow signatures are the strongest at around 200 kyr since the start of the jet activity, and drop as jet plasma gradually leaks out of the galaxy. The simulation suggests, therefore, that the inner jet in B2 0258+35 driving the outflow shown in Fig. 2 is likely younger than a million years, in line with the estimated age of 0.9 Myr or less by various observational studies 8. Bulk outflow velocities are also higher the closer the jet is aligned with the line of sight. Together with the imposed 38° inclination of the disc to the line of sight, a simulation similar to that used in the comparison study here, but fully tailored in its initial conditions to B2 0258+35, can constrain the three-dimensional orientation of the jet.

Relevance of radio jets for feedback. The results on B2 0258+35 are relevant in the broader context of AGN feedback. Radio-loud AGNs are commonly found in massive galaxies such as NGC 1117 (that is, \( M_\star \geq 10^{10.5} M_\odot \)), that has been shown that 30% of massive galaxies host radio sources with luminosities less than \( 10^{23} \, \text{W Hz}^{-1} \), whereas less than 1% of the massive galaxies host powerful radio sources \((\log \{ L_{\nu, 1400} (\, \text{W Hz}^{-1}) \} \geq 25 \)) (refs. 30,36). Furthermore, various studies have also shown that cold gas is more commonly present in the nuclear region of young radio sources 31. Thus, our results highlight that the galactic-scale impact of low-power radio galaxies may represent an important component—so far largely neglected—for models of AGN feedback, provided the radio emission can efficiently couple with the surrounding medium, which our results suggest to be the case.

This makes these AGNs (and their impact) relevant for cosmological simulations. B2 0258+35 is a restarted radio galaxy with a short time gap of a few tens of millions of years between the dimming of one phase of radio emission and the start of the new episode 5. Our results illustrate that even in the renewed phase of activity, the radio jet is able to impact the host galaxy substantially. This recurrent impact of the AGN on the host galaxy over multiple cycles is one of the requirements of cosmological simulations to explain the observations 30–41.

The inclusion of kiloparsec-scale feedback from low-luminosity radio sources may also help resolve some of the tensions that exist between observations and simulations 42. At the moment, cosmological simulations have neither the spatial resolution nor the dynamic range in density to capture kiloparsec-scale outflows in detail. However, the first steps in including these features are being taken 31–34 and they highlight the importance of jet-driven outflows. In the future, as computational power increases and AGN feedback will be modelled in more detail with zoom-in simulations, observations of multiphase outflows, and in particular observations of cold molecular outflows similar to those in our study, will provide invaluable constraints on parameters such as the amount of gas affected, interaction timescales, energy deposition rate, gas redistribution and turbulence generated.

Methods

Target input. B2 0258+35 is a low-luminosity radio AGN \((L_{\text{c, 1400}} = 2.1 \times 10^{21} \, \text{W Hz}^{-1}) \). It consists of a compact steep-spectrum source about 1 kpc in size and diffuse 240 kpc, low-surface brightness radio lobes 36. The radio spectrum of the central compact steep-spectrum source peaks at 70 MHz, typical of sources belonging to this class. The kiloparsec-sized inner source consists of a core and asymmetric jets (Fig. 1). The radio emission is the brightest in the region where this jet is bent. The age of the central source is estimated to range between 0.4 Myr and 0.9 Myr (ref. 7). The large-scale low-surface-brightness radio lobes have been estimated to be about 110 Myr old 9. A detailed spectral index study suggests that they are not old remnants but instead are still being fuelled at a very low rate, perhaps from some ‘leakage’ form the central source 41. It has also been suggested that the duty cycle of this AGN is short, with a time gap between the two episodes of activity of no more than a few tens of millions of years 7.

We chose a host galaxy, NGC 1167, that has a mass of \( M_\star = 1.5 \times 10^{11} M_\odot \), is a \( z = 0.038 \) early-type galaxy with a 160 kpc diameter regularly rotating H i disc. The disc has very regular kinematics within a radius of 65 kpc, and shows signs of interactions, perhaps with a satellite galaxy, only in the very outer parts. This suggests that the galaxy has not undergone a major merger in the last few billion years 41. CO(1–0) emission at a velocity resolution of 3 km s\(^{-1} \) from a region 8 kpc of the galaxy has been detected earlier using single-dish observations 42, and very faint CO emission from a region outside the central 8 kpc was detected using interferometric observations of poorer sensitivity than the single-dish studies 43. Our observations at higher spatial resolution and sensitivity show that the CO emission at large scales arises from a large ring of molecular gas (Fig. 1) of >10 kpc radius. This ring shows regular rotation consistent with that of the large H i disc and overlaps with low-level star formation activity along faint spiral arm-like structures 44. We assume a flat Universe with \( \Omega_\Lambda = 0.7, \Omega_M = 0.3 \) and a dark energy density of \( \Omega_\Lambda = 0.7, \Omega_M = 0.3 \) for all our calculations. At \( z = 0.0165 \), 1° corresponds to 0.349 kpc.

Observations and data reduction. The NOEMA observations of CO(1–0) in B2 0258+35 (project ID S20BH) were carried out over five observing runs in October and November 2020 with the telescope in C configuration with either nine or ten antennas. The set-up included the lower and the upper sidebands centred at 96.7 GHz and 112.24 GHz, respectively, each of bandwidth 7.72 GHz subdivided into 3,859 channels, giving us a spectral resolution of 2 MHz or 5.2 km s\(^{-1} \). We used 3C94 for bandpass calibration, 2010+273, LK1A101, MWC349, 0420-014 and 081+202 for flux calibration over different observing runs and J0304+338 for phase and amplitude calibration. We observed the target source, B2 0258+35, for 10.5 h in total.

We carried out calibration, flagging of bad visibilities, and averaging of the two polarizations using standard pipelines in Gildas Image and Line Data Analysis Software (GILDAS). Then we exported the calibrated ‘uv’ tables in uvfits format for further reduction and analysis in Astronomical Image Processing Software (AIPS) 45. As our primary focus is on the CO(1–0) emission, we further reduced only the data from the upper sideband, which covered the frequencies of interest. We first self-calibrated the data with initially a few cycles of phase-only self-calibration followed by a round of amplitude and phase self-calibration. Then we subtracted a first-order polynomial from each calibrated visibility spectrum to obtain the continuum-subtracted ‘uv’ data.

To improve the signal-to-noise ratio, we Hanning-smoothed the data and averaged two channels together, and we imaged the continuum-subtracted ‘uv’ data to obtain the spectral cube. We made the cube with natural weighting to obtain maximum sensitivity. The cube has an angular resolution of 1.93″ × 1.5″ with a position angle of 29.2°, a spectral resolution of 42 kms\(^{-1} \) and an r.m.s. noise of 0.4 mJy per beam per 42 kms\(^{-1} \) channel. We extracted the moment maps from this cube by using a mask to include emission above 3σ in the line channels.

Molecular gas mass, mass outflow rate and kinetic power. We detect a large-scale CO ring as well as a circumnuclear structure. We estimated the molecular gas mass of the entire circumnuclear gas, the outflow (that is, the gas mass corresponding to the CO hotspot (Fig. 1)) and also the CO ring. This was done using the relation \( M_{\text{CO}} = nCO \times \Delta v \times D^2 \), where \( nCO \) is the molecular mass in total mass units, \( L_{\text{CO}} \) is the CO line luminosity and \( \Delta v \) is the conversion factor. We estimated the CO line luminosity and \( \Delta v \) using the standard relation \( L_{\text{CO}} = 3.25 \times 10^{9} S_{\nu, 1152} \Delta v D^2 \) Kms\(^{-1} \) pc\(^{-2} \), where \( S_{\nu, 1152} \) is the velocity-integrated CO line flux, \( D \) is the luminosity distance and \( z_{\text{emb}} \) is the redshifted CO(1–0) line frequency 48. To estimate the molecular gas masses, we first extracted the flux from the large ring, the circumnuclear gas and the outflowing component in the circumnuclear gas. For the outflowing component, we extracted the flux from the CO hotspot that overlaps with the southern radio jet, marked in the Fig. 1 top-right panel, because the outflowing gas...
offset from the radio core as seen in the PV diagram (Fig. 2) arises entirely from this hot spot.

We assumed a range of values for the conversion factor: typical for Milky Way-like galaxies $\alpha = 3.4 M_\odot (\text{K} \text{km} \text{s}^{-1} \text{pc})^{-1}$; for ultraluminous infrared galaxies where the ISM is more turbulent due to star formation activity $\alpha = 0.8 M_\odot (\text{K} \text{km} \text{s}^{-1} \text{pc})^{-1}$; and for highly turbulent optically thin gas $\alpha = 0.34 M_\odot (\text{K} \text{km} \text{s}^{-1} \text{pc})^{-1}$. For the regularly rotating large ring, we used $\alpha = 3.4 M_\odot (\text{K} \text{km} \text{s}^{-1} \text{pc})^{-1}$, which is typical of quenched gas. For the gas in the circumnuclear region, including the outflow, we estimated $\alpha$, mass using the other two conversion factors more suitable for turbulent gas. The resulting $M_\odot$ masses are presented in Table 1. We find that the mass associated with the outflowing component corresponds to 75% of the CO emission from the circumnuclear region.

We followed the prescription in ref. 20 to estimate the mass outflow rate. Following Fig. 2, the centroid of the outflowing gas is ~1.5" offset from the radio core. This corresponds to an offset of ~540 kpc from the core. We estimated the outflow velocity using the expression $v_{\text{out}} = v_{\text{rot}} + 2\alpha$, where $v_{\text{rot}}$, the velocity offset of the broad emission wing of the spectrum with respect to the systemic velocity, is 93 km s$^{-1}$, and $\alpha$ of the line was estimated via a Gaussian fit to the blueshifted emission wing, is 182 km s$^{-1}$. We obtain an outflow velocity of ~458 km s$^{-1}$. That gives a timescale of $t_{\text{out}} = 1.1$ Myr for the gas to reach its present location from the core. The mass outflow rate will then be $M = M_\odot (t_{\text{out}})$, $M_\odot$ yr$^{-1}$. We obtain a mass outflow rate between 4.5 $M_\odot$ yr$^{-1}$ and 10.5 $M_\odot$ yr$^{-1}$ depending on the choice of $\alpha$, as mentioned previously. The ranges of values for different values of $\alpha$ are tabulated in Table 1.

We estimated the kinetic power of the outflow following ref. 21, using the expression $E = 6.34 \times 10^{33} M_\odot (v_{\text{out}} + \text{FWHM/1.85}) \text{erg s}^{-1}$, where $M_\odot$ is the mass outflow rate, $v_{\text{out}}$, is the rest-frame outflow velocity and FWHM is the full width at half maximum of the emission profile of the outflow. We measured the FWHM of the outflow to be 4030 kpc$^{-1}$ by fitting a Gaussian profile to the emission spectrum. For the range of mass outflow rates, we obtain a kinetic power in the range 1.8 $\times 10^{43}$ erg s$^{-1}$ to 1.9 $\times 10^{43}$ erg s$^{-1}$ (Table 1).

### Table 1 | Estimates of molecular gas masses, mass outflow rate and kinetic power of the outflow

| $\alpha$ ($\text{K} \text{km} \text{s}^{-1} \text{pc}^{-1}$) | $M_{\text{H}_2}$ (ring) ($\times 10^4 M_\odot$) | $M_{\text{H}_2}$ (circuit) ($\times 10^4 M_\odot$) | $M_{\text{jet}}$ (outflow) ($\times 10^3 M_\odot$) | $M$ ($M_\odot$ yr$^{-1}$) | E ($\times 10^{43}$ erg s$^{-1}$) |
|---|---|---|---|---|---|
| 3.4 | 18.0 ± 0.7 | 15.7 ± 1.6 | 11.7 ± 1.6 | 10.5 ± 1.4 | 41 ± 0.6 |
| 0.8 | - | 6.7 ± 0.7 | 5.0 ± 0.7 | 4.5 ± 0.6 | 1.75 ± 0.24 |
| 0.34 | - | - | - | - | - |

First column: the CO-to-H$_2$ conversion factor for Milky Way-like galaxies $\alpha = 3.4 M_\odot (\text{K} \text{km} \text{s}^{-1} \text{pc})^{-1}$; for ultraluminous infrared galaxies where the ISM is more turbulent due to star formation activity $\alpha = 0.8 M_\odot (\text{K} \text{km} \text{s}^{-1} \text{pc})^{-1}$; and for highly turbulent optically thin gas $\alpha = 0.34 M_\odot (\text{K} \text{km} \text{s}^{-1} \text{pc})^{-1}$. Next three columns: the molecular gas masses of the large ring, the circumnuclear disc and the outflow, respectively, corresponding to the value of $\alpha$ in the first column. Fifth column: the mass outflow rate corresponding to the $\alpha$ value. Last column: the kinetic power of the outflow, also corresponding to the $\alpha$ value. $t_{\text{out}}$ values for the ring, the circumnuclear gas and the outflow are (3.8 ± 0.2) kpc yr$^{-1}$, (1.5 ± 0.2) kpc yr$^{-1}$ and (11 ± 0.2) kpc yr$^{-1}$, respectively.

Simulations: properties and synthetic position–velocity diagrams. The simulation we used to support the interpretation of our observations is simulation D in ref. 21. This is a three-dimensional grid-based single-fluid simulation whose numerical scheme is capable of treating a large dynamic range in density, temperature and velocity; it is therefore capable of tracing fast, hot, diffuse outflows, of capturing shocks propagating into rapidly cooling media, of following dense turbulent gas and of tracing cold outflows. For details on the set-up of simulation D, see Section 2 in ref. 21 and its Table 2 for relevant parameters. The simulation employs a jet with a power of $10^{43}$ erg s$^{-1}$ interacting with the ISM of a gas-rich disc galaxy in a volume of $4 \times 4 \times 8$ kpc$^3$ with a grid resolution of 6 pc. The system consists of radio jets propagating through a thick galactic disc of diameter 4 kpc. The radio jets are tilted at an angle of 45° with respect to the disc, and for the construction of PV diagrams described below, the disc itself is seen at an angle of 38° from the edge-on view.

Our observations suggest that the gas in the central few kiloparsecs of the galaxy is entirely disturbed and the disc, if there was any, is destroyed to a large extent. Thus, assuming there was a gas disc to begin with, we need to assume its orientation. The host galaxy NGC 1167 has an inclination angle of 38°. It can be seen from Fig. 1 that the kinematics of the gas in the central few kiloparsecs are distinct from the large-scale rotation of the galaxy, suggesting that it could have a different orientation compared to the large disc. The first stable plane of orientation possible for the circumnuclear disc is the same as the large-scale disc; the second is perpendicular to the large-scale disc. The latter possibility would imply that the disc is much more edge-on compared to the large disc. However, the observed velocity gradient does not agree with this possibility if a part of the disc is in regular rotation. Thus, it is more likely that the circumnuclear disc is along the same plane as the large disc. Hence, we chose an inclination angle for the galactic disc that is close to that of NGC 1167. We further note that the precise angle between the jet and the disc is not known. However, the jet in B2 0258+35 is unlikely to be perpendicular to the disc and is likely inclined substantially towards the disc$^{19}$, and hence we chose a simulation with a jet tilt angle of 45° for this comparison.

The estimation of the jet power of B2 0258+35 involves uncertainties (see the previous subsection). As deduced for the case of IC 5063$^{23}$, the jet power may be an order of magnitude higher than what is inferred from the radio power, justifying the choice of a simulation with higher jet power. We emphasize that this simulation is not a precise representation of the jet–disc system of B2 0258+35, and a comparison is meant to be illustrative of how jets can generate cold dense outflows that may resemble the observed outflow in B2 0258+35.

In the top two panels of Fig. 4 we show the rotation field of dense gas above a number density $n = 100$ cm$^{-3}$, with temperatures typically in the range of a few tens to a few thousand Kelvin, together with synthetic broadband radio emission contours and the two slit orientations used to produce the PV diagrams. The simulation times is $t = 0.2$ Myr after jet injection (Fig. 1, second panel). The slit placements are equivalent to the region used for the observational data to produce Fig. 2. The rickslits are 2 kpc long and 0.45 kpc high.

In the bottom two panels of Fig. 4 we show position–velocity diagrams of the dense gas ($n > 100$ cm$^{-3}$) in the simulation extracted from the slits placed along the major axis of the disc or along the jet (see corresponding top–row panels) at time $t = 0.2$ Myr since jet injection. Strong gas dispersion along the region
The results in ref. 1 show that jets that are more closely aligned with the disc exert stronger feedback onto the disc ISM, and the jet may indeed be closer to the plane of the disc than at the 45° of the simulation. The uncertainty in the inclination of jet to disc must always be considered in conjunction with the uncertainty in the inclination of the line of sight to the disc and to that jet. Assuming a disc inclination of 38° with respect to the line of sight, we found that the closer the main jet streams are aligned with the line of sight, the stronger the outflow signatures become. A stronger alignment to the jet, for which the disc inclination to the line of sight was 38°. We found that snapshots at approximately 200 kyr since jet injection show the strongest velocity dispersions, with values exceeding 150 km s\(^{-1}\) in regions of jet–ISM interactions and exceeding 400 km s\(^{-1}\) around clouds directly impacted by the jet. Near the jet head, where the main jet stream is strongly deflected, bulk outflows exceeding 500 km s\(^{-1}\) are generated. At later times, for example at 0.8 Myr (Fig. 3, third panel), only weak bulk outflows were seen, as jet plasma increasingly vents through the porous ISM into the galactic halo.

The synthetic PV diagrams from the simulation display signatures of dispersed gas and accelerated clouds in both the redshifted and the blueshifted halves, whereas the observations show only a one-sided outflow. There are two possible reasons for this discrepancy. One reason is that, in generating the synthetic PV diagrams, we did not take into account absorption along the line of sight. The CO gas is likely optically thick, and a redshifted outflow may exist but be obscured by the disc. The other reason is that the ISM in B2 0258+35 is even clumpier than the ISM in the simulations and that the approaching jet encounters a large clump, leading to brightening and deflection of the radio plasma, whereas the receding jet is propagating through much lower-density media.

Although the inclination we used for comparison was not specifically tailored to B2 0258+35, the strong off-centre outflow features and the timescales they are generated on, the jet deflections, and the clearance of gas in the central regions indicate that some of the physics of the jet–ISM interactions captured in the simulation are indeed operating in B2 0258+35.
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Author contributions

S.M. and R.M. conceived the project. S.M. reduced the data. S.M., R.M. and T.O. carried out the analysis. A.Y.W., S.M. and R.M. wrote the observing proposal. S.M. and R.M. wrote the manuscript. All the authors discussed the results and commented on the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Suma Murthy or Raffaella Morganti.

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