Suppressing star formation in quiescent galaxies with supermassive black hole winds

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Quiescent galaxies with little or no ongoing star formation dominate the population of galaxies with masses above $2 \times 10^{10}$ times that of the Sun; the number of quiescent galaxies has increased by a factor of about 25 over the past ten billion years (refs 1–4). Once star formation has been shut down, perhaps during the quasar phase of rapid accretion onto a supermassive black hole5–7, an unknown mechanism must remove or heat the gas that is subsequently accreted from either stellar mass loss8 or mergers and that would otherwise cool to form stars9,10. Energy output from a black hole accreting at a low rate has been proposed11–14, but observational evidence for this in the form of expanding hot gas shells is indirect and limited to radio galaxies at the centres of clusters14,15, which are too rare to explain the vast majority of the quiescent population16. Here we report bisymmetric emission features co-aligned with strong ionized-gas velocity gradients from which we infer the presence of centrally driven winds in typical quiescent galaxies that host low-luminosity active nuclei. These galaxies are surprisingly common, accounting for as much as ten per cent of the quiescent population with masses around $2 \times 10^{10}$ times that of the Sun. In a prototypical example, we calculate that the energy input from the galaxy’s low-level active supermassive black hole is capable of driving the observed wind, which contains sufficient mechanical energy to heat ambient, cooler gas (also detected) and thereby suppress star formation.

Using optical imaging spectroscopy from the Sloan Digital Sky Survey–IV Mapping Nearby Galaxies at Apache Point Observatory17 (SDSS-IV MaNGA) programme, we define a new class of quiescent galaxies—selected to have red-frame colours, $NUV - r > 5$, where $NUV$ and $r$ are the magnitudes in the near-ultraviolet and $r$ band, respectively—that is characterized by the presence of narrow bisymmetric patterns in equivalent width (EW) maps of strong emission lines, such as Hα and [O iii]. Our selection employs multiband imaging to exclude galaxies with dust lanes and other disk signatures. The observed enhanced emission features are oriented randomly with respect to the optical surface brightness morphology, but roughly align with strong, systematic velocity gradients as traced by the ionized gas emission lines. The gas velocity fields in these galaxies are decoupled from their stellar motions. These galaxies are surprisingly common among the quiescent population, accounting for $\sim$10% of quiescent galaxies with $\log(M_*/M_\odot) \approx 10.3$ (here $M_*$ is the stellar mass and $M_\odot$ is the solar mass).

To illuminate the salient features of this class, we focus on a prototypical example, informally named ‘Akira’ (Fig. 1). The SDSS imaging shows Akira to be an unremarkable spheroidal galaxy of moderate stellar mass ($\log(M_*/M_\odot) = 10.78$) that is interacting with a low-mass companion (informally named ‘Tetsuo’) at a projected separation of $\sim 32$ kpc (67\"); they are not classified as members of a larger galaxy group18 and the properties of both galaxies are listed in Table 1. Spectral energy distribution (SED) fitting indicates that Akira is nearly dormant, with almost no detection of ongoing star formation19. Spatially resolved spectroscopy, however, reveals intriguing and complex patterns among spectral tracers of gas in Akira that point to a much more active internal state. With ionized-gas emission detected across the entire galaxy, the state of Hα EW (which measures the line flux relative to the stellar continuum; Fig. 1c) reveals a prominent and somewhat twisted bisymmetrical pattern with a position angle (PA) of $\sim 46^\circ$. The projected velocity gradient of ionized gas ranges from $v_{\text{ionized}} = -225 \text{ km s}^{-1}$ to $v_{\text{ionized}} = 200 \text{ km s}^{-1}$ along the kinematic major axis, which is at a PA of $\sim 26^\circ$ (Fig. 1h). We observe high ionized-gas velocity dispersions ($\sigma_{\text{ionized}}$) across the galaxy with interesting internal structure and maxima that reach $v_{\text{ionized}} = 200 \text{ km s}^{-1}$ (Fig. 1f). Using this to set a minimal spatial offset enhancement in Na D absorption (Fig. 1f), we find that the PA of the galaxy’s elliptical isophotes of $\sim 53^\circ$ (contours in Fig. 1c). We also detect a spatially offset enhancement in Na D absorption (Fig. 1d) that is coincident with excess dust in our derived extinction map (see Methods). Measurements of the Na D line centre trace a separate and distinct velocity gradient field across the offset absorption (Fig. 1e) that ranges from approximately $v_{\text{Na D}} = -80 \text{ km s}^{-1}$ to $v_{\text{Na D}} = 60 \text{ km s}^{-1}$.

These observations indicate the presence of multiple gas components with different temperatures and velocity structures. We interpret the ionized-gas velocity field as resulting from a centrally driven (volume-filling) wind with a wide opening angle. The projected flux

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distribution of this ionized component largely follows the stellar surface brightness, suggesting that its primary ionization source is the local radiation field from evolved stars. The bisymmetric EW features represent enhanced emission due to shocks or over-densities along the radiation field from evolved stars. The bisymmetric EW features represent enhanced emission due to shocks or over-densities along the radiation field from evolved stars.

Previous work has noted similar objects but has typically attributed their gaseous dynamics and unusual emission line features to accreted, rotating disks. However, using a tight constraint on the total gravitational potential derived from the stellar kinematics, we find that the observed second velocity moments, $V_{\text{rms}}$—defined as $V_{\text{rms}} = \sqrt{V^2 + \sigma^2}$, where $V$ is the velocity and $\sigma$ is the velocity dispersion—of the ionized gas in Akira are far too high to be consistent with motions under the influence of gravity alone (Fig. 1j; see Methods). Regardless of gas inclination or the degree of pressure support, we can rule out any kind of axisymmetric orbital distribution. Perturbations or torques from disk ‘settling’ are also very unlikely to drive discrepancies

Table 1 | Galaxy properties

| MaNGA name   | MaNGA-ID | RA (J2000.0 deg.) | Dec. (J2000.0 deg.) | $z'$ | log($M_*(M_\odot)$) | log(SFR ($M_\odot$ yr$^{-1}$)) | $R_1$ (kpc) | log($M_h(M_\odot)$) |
|---------------|----------|------------------|-------------------|-----|-------------------|-----------------------------|------------|-------------------|
| Akira (host)  | 1-217022 | 136.08961        | 41.48174          | 0.0244671 | 10.78          | 6.1                          | -4.17      | 3.88              | 12.0            |
| Tetsuo (companion) | 1-217015 | 136.11416        | 41.48621          | 0.0244671 | 9.18           | 3.0                          | -0.94      | 1.73              | 12.0            |

RA, right ascension; Dec., declination.

* Spectroscopic redshift from NSA catalogue (http://www.nsatlas.org/data).
† Stellar mass from MPA-JHU DR7 data release (http://wwwmpa.mpa-garching.mpg.de/SDSS/DR7/Data/stellarmass.html).
‡ Rest-frame NUV – r colour from NSA catalogue (http://www.nsatlas.org/data).
§ Star formation rate (SFR) from SED fitting of SDSS optical and WISE infrared photometry; the AGN contribution to the SED is negligible.
¶ Halo mass, $M_h$, from a public group catalogue.
**Figure 2 | Wind model.** a, A schematic diagram of the galaxy (gold) and the wind bicone (purple; $2\theta = 80^\circ$) with the central $\pm 10^\circ$ of the bicone highlighted in green (vertical axis shows distance in arbitrary units). b, Akira’s $V_{\text{misred,gal}}$ map, overplotted with its Hα EW contours. c, The projected velocity field derived from the wind model, with the white contours outlining the central axis of the wind. In b and c, x axis shows offset in arcsec from galaxy centre (marked with cross).

**Figure 3 | Diagnostic line-ratio maps of Akira.** a–c, Maps of line ratios. a, log([N II] 6,583/Hα), b, log([O III] 5,007/Hβ) and c, log([S II] 6,717, 6,731/Hα), with contours tracing the Hα EW pattern. d, e, The [N II] 6,583 and [S II] 6,717, Baldwin-Phillips-Terlevich (BPT) diagrams; error bars represent the 1σ measurement errors propagated to the log line ratios. The solid and dashed lines separate the H II (blue points), AGN (red points), Seyfert (red points), Composite (green points), and LINER (green points) classifications. Overplotted (orange curves labelled with shock velocity in km s$^{-1}$) are shock models$^{27}$, and the black points correspond to the spaxels highlighted by black boxes in the other panels. f, g, The resolved [N II] 6,583 and [S II] 6,717, 6,731 BPT maps, that is, each spaxel is coloured by its location on their respective BPT diagram, with contours tracing the Hα EW pattern.
that reach as high as ~100 km s\(^{-1}\). We can express the dynamical inconsistency of the disk hypothesis another way. If we assume such a disk were inclined at \(i = 50^\circ\) (see Methods), we estimate that 15%–20% of the disk would be moving at velocities sufficient to escape the galaxy. With similar velocity properties observed for the rest of this new class of galaxies, the disk interpretation also fails to explain why the bismetric H\(_\alpha\) features are always in rough alignment with the major kinematic axis. If arising from internal structure in a moderately face-on disk, this H\(_\alpha\) EW structure should be randomly oriented compared to the kinematic axis, which is instead determined by the observer's viewing angle.

A relatively simple wind model with a constant radially-outward velocity of 310 km s\(^{-1}\) confined to a wide-angle (\(\theta\)) cone (20° = 80°) reproduces several qualitative features of the data (Fig. 2; see Methods). The model captures the overall shape of the ionized-gas velocity field and associates the extended (horizontal) zones of high ionized-gas velocity dispersion along the kinematic minor axis with the overlapping projection of approaching and receding surfaces of the inclined wind cone. By assigning somewhat greater wind densities to the cone centre, we can explain the offsets between the projected kinematic major axis of the ionized gas and both the stellar position angle and the H\(_\alpha\) flux orientation. Furthermore, the bismetric H\(_\alpha\) EW features can be explained by enhanced gas over-densities or shock ionization along the central wind axis. Indeed, Fig. 3d, e demonstrates that line ratios in the H\(_\alpha\) EW feature (black points and boxes throughout Fig. 3) tend to cluster and are consistent with those predicted by fast shock models\(^{27}\) with velocities of 200–400 km s\(^{-1}\).

The wind's driving mechanism probably originates in Akira’s active (at radio wavelengths) galactic nucleus (AGN), which is detected in FIRST (Faint Images of the Radio Sky at Twenty-Centimeters) data with a luminosity density of \(L_{1.4\,\text{GHz}} = 1.6 \times 10^{21}\) W Hz\(^{-1}\), and is most consistent with being a point source according to higher-resolution (1.5") follow-up Jansky VLA (Very Large Array) radio observations (W.R., manuscript in preparation). Since this AGN lacks obvious extended radio jets, the feedback of this AGN is most likely to manifest in small-scale jets (<1 kpc) or uncollimated winds\(^{28,29}\). Despite an Eddington ratio of \(\lambda = 3.9 \times 10^{-4}\), energetics arguments show that the AGN's mechanical output (\(P_{\text{mech}} = 8.1 \times 10^{41}\) erg s\(^{-1}\)) is sufficient to supply the wind's kinetic power (\(P_{\text{wind}} \approx 10^{39}\) erg s\(^{-1}\); see Methods). Moreover, the wind can inject sufficient energy, coupled to the ambient gas through the turbulent dynamics observed (Figs 1i, 3a–c), to balance the cooling rate (\(E_{\text{cool}} \approx 10^{39}\) erg s\(^{-1}\)). Indeed, the amount of cool Na D gas (\(M_{\text{cool}} \approx 10^{13}\) M\(_{\odot}\)) implies a star formation rate of \(SFR \approx 1 \times 10^{-2}\) M\(_{\odot}\) yr\(^{-1}\), which is much higher than the estimated\(^{19}\) SFR\(_{\text{AKira}} \approx 7 \times 10^{-5}\) M\(_{\odot}\) yr\(^{-1}\) that is derived from well-detected WISE photometry. The picture that emerges is one in which cool gas inflow to Akira, triggered by the interaction with Tetsuo, has initiated a relatively low-power AGN-driven wind that is nonetheless able to heat the surrounding gas through turbulence and shocks and thereby prevent any substantial star formation.

As with Akira, the other galaxies in this class show little or no ongoing star formation, and the majority harbour similarly weak radio point sources (according to follow-up Jansky VLA observations) that could be classified as 'jet mode', 'kinetic mode' or 'radio mode' AGN\(^{7,15}\). With similar levels of fast-moving ionized gas oriented along enhanced ionized emission, we conclude that AGN-driven winds are present in these systems as well, and represent an important heating source. Because the full spatial extent of these winds may exceed the field-of-view of our observations, a lower limit of \(~10^5\) yr for the timescale of this phenomenon is given by the radial extent divided by the typical wind velocity. Assuming all quiescent galaxies experience these AGN-driven winds, the \(~5\%\) occurrence rate (averaged over the full mass range) implies an episodic behaviour that leads us to name these objects 'red geysers'. Present primarily below \(M_*> 10^{11} M_\odot\), these galaxies lie in isolated haloes with moderate masses\(^{18}\) (\(M_{\text{halo}} \approx 10^{12} M_\odot\)) and exhibit no signs of major interactions. Their implied trigger rate (at most, a few episodes per Gyr) may be related to minor mergers (approximately one per Gyr; ref. 30) as well as central accretion of ambient hot gas from stellar mass loss\(^8\). These red geysers may exemplify how typical quiescent galaxies maintain their quiescence.

**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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**Author Contributions**

E.C. and K.B. discovered the described sources, interpreted the observations, built the wind model, and wrote the manuscript. M.C. constructed dynamical models. S.P. carried out numerical merger simulations to model the data. W.R. obtained and reduced the JVLA data. K.W. fitted disk models. K.B., R.Y., M.B., N.D., D.R.L., D.A.W., K.Z., A.W., K.L.M. and D.T. contributed to the design and execution of the survey. F.B. provided initial velocity and line-ratio maps. B.V. provided the modelled extinction map. Y.C. and K.R. contributed to the Na D interpretation. All authors contributed to the interpretation of the observations and the writing of the paper.

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methods

Observations. The data used in this work come from the ongoing MaNGA survey31-33, using the SDSS 2.5-metre telescope34. One of three programs comprising SDSS-IV, MaNGA is obtaining spatially resolved spectroscopy for 10,000 nearby galaxies with log(M/M_⊙) ≥ 9 and a median redshift of z ≈ 0.04. The r-band signal-to-noise ratio (S/N) in the galaxy outskirts is 4-8 Å⁻¹, and the wavelength coverage is 3,600–10,300 Å. The effective spatial resolution is 2.4′′ (full width at half maximum; FWHM) with an instrumental spectral resolution of σ ≈ 60 km s⁻¹. The sample of data products used here were drawn from the internal MaNGA Product Launch-3 (MLP-3), which includes ~700 galaxies observed before April 2015 and will be publicly available in the thirteenth SDSS data release.

Ancillary data are from the NASA-Sloan Atlas (NSA)34, MPA-JHU DR7 data release35, and other recent works36-38. We assume a flat cosmological model with H₀ = 70 km s⁻¹ Mpc⁻¹, Ω₀ = 0.30 and Ωₐ₀ = 0.70, and all magnitudes are given in the AB magnitude system39.

The Data Analysis Pipeline (DAP), which uses pPXF37 and the MIUSCAT stellar library40, fits the stellar continuum in each spaxel and produces estimates of the stellar kinematics. Flux and EW measurements were measured through simple flux-summing41 after we subtract the stellar continuum. We only show flux and EW measurements with S/N > 3 Å⁻¹ in the wavelength range around a given line. Ionized gas kinematics, that is, velocity (v_ionised), and velocity dispersion (σ_ionised), were estimated by fitting a single Gaussian to the Hα emission line. W_{Wα}, W_{Hβ} is a non-parametric measure of line widths; it is defined to contain 80% of the emission-line flux42.

Na D measurements. Using a spectral fitting code39,42, we present the dust extinction map of Akira in Extended Data Fig. 1. The superimposed Na D contours (from Fig. 1d) overlap with enhanced extinction (darker spaxels), supporting the association of the offset Na D absorption with cool foreground material.

To measure the line-of-sight (LOS) velocity of this Na D-absorbing material, which we defined as spaxels with Na D EW > 3.5 Å, we first subtract the stellar continuum fit determined for Akira by the DAP. Extended Data Fig. 2a-c shows the stellar continuum fits (red) around the Na D doublet (the two black vertical lines mark the expected locations of the Na D doublet) for three spectra. Extended Data Fig. 2a shows data from a recent work41, Extended Data Fig. 2b shows the central spaxel of Akira, marked by the “x” in Fig. 1d, e and Extended Data Fig. 1, and Extended Data Fig. 2c shows a spaxel to the northwest of Akira, marked by the single box in the upper right of Fig. 1d, e and Extended Data Fig. 1. We then examine the residual absorption as a function of wavelength, as shown in Extended Data Fig. 2d-f.

Focusing on Extended Data Fig. 2d-f, we determine the line centroids in Akira by first defining a reference Na D profile for typical, cold interstellar medium gas at rest. We use the stacked, continuum-subtracted spectrum of Na D from a large set of highly inclined disk galaxies from this reference43, which is shown in the left panel. We define an at-rest line centroid for cool Na D gas by averaging the wave-lengths in this profile, each weighted by the amplitude of the residual absorption at that wavelength (weighting is performed within the green region). The resulting centroid is marked by the blue grey vertical lines, which is repeated in the two right panels for reference. In the same way, we determine line centroids for the observed residual profiles across the Na D-absorbing material in Akira, which is marked by the blue vertical lines in the two right panels. We then calculate the velocity difference between the reference Na D centroid and the observed Na D centroid in these spaxels of Akira; this velocity difference is shown in the upper left in Extended Data Fig. 2e, f.

Merger simulations. We modelled the interaction between Akira and Tetsuo using the GADGET-24 code and the methodology described in a recent work45. These simulations are constrained by the available data and contain more than four million particle account for stars, dark matter, and gas (we only consider gas in Tetsuo). These simulations also include cooling, star formation, and supernova feedback, but not AGN feedback nor the proposed wind. The initial total mass merger ratio is 1:10, but because Tetsuo loses mass during the interaction, this ratio falls to ~1:20 at the time most closely matching the observations (the observed stellar mass merger ratio is 1:40). According to the best-matching viewing angle for this prograde encounter, Tetsuo starts in the foreground to the lower-right of Akira and begins arcing over the top and away from the observer (see Extended Data Fig. 3a–d). After a glancing blow with Akira, a tidal bridge is generated that loops back and passes through Akira to form the shell structure seen to the lower right (Extended Data Fig. 3d). This snapshot at t = 0.56 Gyr best matches the SDSS r image (Extended Data Fig. 3f), and it indicates that Tetsuo is behind Akira. Extended Data Fig. 3e shows a composite stars-gas representation at this snapshot; it indicates that a stream of cool gas from Tetsuo has followed the stellar bridge that is behind Akira, penetrated close to Akira’s centre, emerged in front of Akira on its lower-right side, and approaches the observer.

The shape of the tidal bridge and shell to the southwest in the SDSS image (Extended Data Fig. 3f) provides the most significant constraints on the simulation and its viewing angle. An important cross-check is that the orientation of Tetsuo’s stellar and ionized gas velocity fields (also observed by MaNGA) are reproduced as well. The geometry and velocity scale of the cool gas is similar to the observed Na D component (Fig. 1d, e), but there are differences from the observations. Portions of the observed Na D gas appear to be falling back into Akira (redshift; Fig. 1e), but these are not seen in the simulation until a later time step. The observed cool gas stream is also horizontal, while the simulation predicts the gas stream stretches further (Extended Data Fig. 3e). But we emphasize that we only detect cool gas in absorption where there are background stars from host galaxy, whereas the simulation allows us to see the full extent of the cool gas. Differences between the simulations and observations may also arise from inaccuracies in the initialization of the merger simulation (mass ratios, gas mass fractions, angular momentum alignment, and so on), limitations in the hydrodynamic gas treatment, or missing components in the simulation such as Akira’s gas supply and the proposed AGN-driven wind.

Dynamical modelling evidence against the presence of disks. Jeans Anisotropic Modelling (JAM46), which uses the Multi-Gaussian Expansion (MGE47,48) parametrization for mass and light distributions, was performed on Akira and other red galaxies to model their stellar kinematics and gravitational potential. The JAM model derives a 3D stellar density by de-projecting the observed SDSS r-band photometry using an MGE fit. The modelled potential includes an NFW49 dark matter halo. The JAM model has four free parameters: the inclination i, anisotropy β, stellar M/L (that is, mass-to-light ratio) and halo mass. These are optimized by fitting the prediction for the second velocity moment, \(V_{\text{rms}} = \sqrt{\sigma^2 + \sigma^2_i} \), to the observed MaNGA stellar kinematics. Through a number of systematics tests, we find that the best-fit stellar inclination i = 41°, with an upper limit of i = 50°. Although there is some covariance between the model parameters, the resulting total mass profile is extremely robust40.

With the total gravitational potential defined from the stellar JAM modelling above, we can predict projected second velocity moment (\(V_{\text{rms}}\)) maps of gas under the assumption of axisymmetric orbital distributions. We treat the Hα-emitting gas clouds as a ‘tracer’ population of the underlying potential. Its flux distribution is modelled by a separate MGE (distinct from the stellar component) enabling de-projection of the observed Hα surface brightness. The Jeans equations are then solved for this tracer, within the fixed potential, to predict the \(V_{\text{rms}}\) allowed by the given mass distribution. We emphasize that the second moments are independent of the degree of circular motion versus ‘random’ motion in the hypothesized disk. The analysis does not account for non-gravitational drivers of turbulent pressure, such as from the AGN-driven wind we propose. In Extended Data Fig. 4 see also Fig. 1) we show results for gaseous inclinations of i = 46° (the minimum allowed by the b/a = 0.7 from GALFIT fits of the Hα flux, corresponding to an intrinsic axis ratio q = 0.12; see below) and the most extreme case of i = 90° (an edge-on axisymmetric density). In either case, the allowed \(V_{\text{rms}}\) is far below the observed \(V_{\text{rms}}\).

With discrepancies as high as ~100 km s⁻¹, torques of the same order as the gravitational potential itself would be required to explain the data, making a ‘disturbed’ disk a highly unlikely explanation. It is possible to imagine a very chaotic accretion scenario where the JAM assumptions of axisymmetry and stability completely break down, although in this case an ordered ionized-gas velocity gradient of the kind observed seems unlikely. Such a scenario would also struggle to explain how the high ionized-gas velocity dispersions are generated and why enhanced Hα flux is observed along the gradient in the ionized-gas velocity field. Similarly, because line widths of \(W_{\text{Wα}}\) ≈ 500 km s⁻¹ could not be sustained by accreting tidal streams or caused by tidal torques, multiple overlapping gas streams would have to conspire to produce the widespread high velocity dispersion observed (Fig. 11) while maintaining an ordered velocity gradient pattern. A similar set of coincidences would be required for each galaxy in the rest of the red guyser sample.

Not surprisingly, tilted-disk models40 that fit the ionized velocity field alone do a poor job for the red guyser sample. Characterizing the goodness-of-fit by an error-weighted average residual, the majority of red geysers exhibit residuals that place them among the worst 5% of fitted MaNGA galaxies with ‘disk-like’ kinematics. Here, disk-like refers to galaxies with reasonable agreement between stellar and gaseous systemic velocities, dynamical centres, position angles, and inclinations.

Finally, we use the dynamically constrained potential to estimate a local escape velocity and compare this to the inferred velocity distribution of a putative disk. Several assumptions are required, but the results are informative. We obtain a rough estimate of the local escape velocity \(v_{\text{esc}} = \sqrt{2GM/R} \) by integrating the potential from a projected radius of \(7'' (3.4 \text{kpc}) \) or just under \(1 \text{kpc} \) to \(4 \text{kpc} \), and assuming a gentle decline in the circular velocity at large radius. We then use GALFIT52 to model the observed Hα line surface brightness, finding a consistent projected axis ratio of b/a = 0.7 ± 0.02, regardless of the assumed model profile (exponential, de Vaucouleurs’, or free Sérsic) and despite significant structure in the residuals.
Finally, to calculate $L_{\text{Edd}}$, we first estimate the black hole mass, $M_{\text{BH}}$, using the relation
$$\log(L_{\text{Edd}}/M_{\odot}) = 8.32 + 5.64\log(M_{\text{BH}}/M_{\odot}) - 8.1$$
with $M_{\text{BH}} = 185.5$ kpc $^{-2}$ from the central 2" radius aperture, yielding $\log(M_{\text{BH}}/M_{\odot}) = 8.1$. We calculate the classical Eddington limit with
$$L_{\text{Edd}} = 3.3 \times 10^{36} \times M_{\odot} \times 4.5 \times 10^{12} \times L_{\odot} = 1.7 \times 10^{46} \text{ erg s}^{-1}.$$ Inserting these numbers into $\lambda = (L_{\text{Edd}} + L_{\text{mech}})/L_{\text{Edd}}$ yields $\lambda = 3.9 \times 10^{-4}$, suggesting that the accretion onto this black hole is at a low rate and/or radiatively inefficient; these types of AGN have been termed low-energy, kinetic mode, jet mode, or radio mode AGN.

### Ionized gas energetics
Assuming warm ionized gas clouds with a temperature of $10^5$ K and using the observed [Si] ratio, we estimate an electron density, $n_e$, of 100 cm$^{-3}$. With this value of $n_e$, we estimate the lower limits on the ionized gas mass from the H$\alpha$ line flux, $M_{\text{ion}, \odot} \approx 6 \times 10^3 M_{\odot}$. We can derive similar estimates based on the [O]$\beta$ and [O]$\beta$ flux, obtaining $M_{\text{ion}, \odot} \approx 4 \times 10^5 M_{\odot}$ and $M_{\text{ion}, \odot} \approx 2 \times 10^4 M_{\odot}$. We adopt an approximate $M_{\text{ion}, \odot} \approx 10^5 M_{\odot}$.

To approximate the energy associated with a wind driving the observed velocities in the ionized gas, we adopt the kinetic energy $E_{\text{wind}} \approx 0.5 M_{\text{ion}} c^2$, with $c = 300$ km s$^{-1}$. To estimate the wind power, we divide $E_{\text{wind}}$ by the characteristic wind timescale of $10^7$ yr, leading to a wind energy density of $2 \times 10^{-12} M_{\odot} c^2$.

### Star formation in the Na D cool gas
To estimate the expected star formation rate associated with the cool Na D gas, we first estimate the total hydrogen column density ($N_{\text{HI}} + 2N_{\text{Na}}$), where $N$ is the column density, from the dust extinction presented in Extended Data Fig. 1. Integrating over the $\sim$1 kpc region of enhanced extinction, we find a total gas mass of $M_{\text{cool}} \approx 10^8 M_{\odot}$, or a surface mass density of $\Sigma_{\text{cool}} \approx 3 \times 10^3 M_{\odot} \text{ kpc}^{-2}$. To apply the Kennicutt relation (20), we first account for face-on, non-axisymmetric galaxies via anisotropic Jeans models of stellar kinematics. Assuming the Kennicutt relation holds with respect to volumetric density, we scale $\Sigma_{\text{cool}}$ by the ratio of scale heights between a typical star-forming spiral ($H_{\text{Kensicutt}} \approx 0.6 kpc$) and an estimate for the Na D material's scale height, $H_{\text{Na D}}$. We set $H_{\text{Na D}} \sim 3$ kpc, which is approximately the effective radius ($R_e$) of Akira. These assumptions yield SFR $\approx 10^2 M_{\odot}$ yr$^{-1}$, roughly 100 times higher than the estimate for the AGN (SFR$_{\text{AGN}} = 7 \times 10^3 M_{\odot}$ yr$^{-1}$).

### Sample size
No statistical methods were used to predetermine sample size.

### Code availability
The JAM code is available at http://www.astro.physics.ox.ac.uk/~mxc/software/#jam

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Extended Data Figure 1 | $A(V)$ map. The estimated $A(V)$ map (with $A(V)$ colour coded, see key), with contours of Na D EW > 3.5 Å from Fig. 1d.

The spatial overlap between regions of high extinction and the Na D EW absorption confirms that there is cool material in the foreground of Akira.

Here and below, axes show offset in arcsec from map centre, marked with a cross.
Extended Data Figure 2 | Na D line-of-sight measurement. 

a–c, The spectrum around the Na D doublet at $\lambda = 5,890, 5,896$ Å and best-fit stellar continuum. The two vertical lines mark the locations of the Na D doublet.
d–f, The residual of the spectrum and stellar continuum. Considering only the wavelength range enclosed by the green region, we calculate the residual-weighted central wavelengths of these Na D doublets, which is marked by the dashed grey vertical line and blue vertical lines. The dashed grey vertical represents the reference Na D centroid while the blue vertical lines represent the observed Na D centroid from the two spaxels of Akira. See Methods for details. The horizontal dashed line is a reference point and the $\Delta v$ in e and f represents the residual-weighted velocities. Data in a from ref. 43 with permission.

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Extended Data Figure 3 | Merger simulation. a–d, Evolution of the stars from $t = 0$ Gyr to $t = 0.56$ Gyr; each panel is $90 \times 90$ kpc. e, Composite image of stars and gas at $t = 0.56$ Gyr; this panel is also $90 \times 90$ kpc. f, The SDSS $r$ image of Akira and Tetsuo.
Extended Data Figure 4 | $V_{\text{rms}}$ maps. a, Observed $V_{\text{rms}}$ map (key at top shows colour coded $V_{\text{rms}}$). b, Predicted $V_{\text{rms}}$ map, assuming $i = 46^\circ$. c, Predicted $V_{\text{rms}}$ map, assuming $i = 90^\circ$. 