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 galaxy population above $M_* \sim 2 \times 10^{10}\ M_\odot$, where their numbers have increased by a factor of ~ 25 since $z \sim 2$[1–4]. Once star formation is initially shut down, perhaps during the quasar phase of rapid accretion onto a supermassive black hole[5–7], an unknown mechanism must remove or heat subsequently accreted gas from stellar mass loss[8] or mergers that would otherwise cool to form stars[9,10]. Energy output from a black hole accreting at a low rate has been proposed[11–13], but observational evidence for this in the form of expanding hot gas shells is indirect and limited to radio galaxies at the centers of clusters[14,15], which are too rare to explain the vast majority of the quiescent population[16]. 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 10% of the population at $M_* \sim 2 \times 10^{10}\ M_\odot$. In a prototypical example, we calculate that the energy input from the galaxy's low-level ac-

tive nucleus 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 Observatory[17] (SDSS-IV MaNGA) program, we define a new class of quiescent galaxies (required to have red rest-frame colors, $NUV - r > 5$) 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 $M_*/M_\odot \sim 10.3$.

To illuminate the salient features of this class, we focus on a prototypical example, nicknamed "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 (nicknamed "Tetsuo") at a projected separation of $\approx$ 32 kpc ($67''$); they are not classified as members of a larger galaxy group[18] 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 formation[19]. 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 map of Hα EW (which measures the line flux relative to the stellar continuum; Fig. 1c) reveals a prominent and somewhat twisted bisymmetric pattern with a position angle (PA) of $\sim$46°. The projected velocity shear ranges from $v_{\mathrm{ionized\ gas}} = -225$ km s^{-1} to $v_{\mathrm{ionized\ gas}} = 200$ km s^{-1} along the kinematic major axis, which is at a PA of $\sim$26° (Fig. 1h). We observe high ionized gas velocity dispersions across the galaxy with interesting internal structure and maxima that reach $\sigma_{\mathrm{ionized\ gas}}$ $\sim$200 km s^{-1} (Fig. 1i) and W_{80} $\sim$500 km s^{-1} (see Methods) perpendicular to the major kinematic axis. Meanwhile, stellar motions reveal a minimal shear ($\pm$30 km s^{-1}; Fig. 1f) that follows the PA of the galaxy's elliptical isophotes of $\sim$53° (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 center trace a separate and distinct velocity shear field across the offset absorption (Fig. 1e) that ranges from approximately $v_{\mathrm{Na\ D}} = -80$ km s^{-1} to $v_{\mathrm{Na\ D}} = 60$ 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 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[20–22]. The bisymmetric EW features represent enhanced emission due to shocks or over-densities along the wind's central axis. A distinct and cooler gas component is indicated by the Na D absorption. Because it is spatially confined with its own velocity structure, this cooler foreground material is likely to be within 1–2 R_e of Akira. Simulations of galaxy mergers constrained by the data (see Methods) indicate that the cool component is part of a tidal stream and is arcing towards the observer from the far West (blueshifted; Fig. 1e) before plunging back towards Akira's center (redshifted; Fig. 1e).

Previous work has noted similar objects[20,23–25] but has typically attributed their gaseous dynamics and unusual emission line features to accreted, rotating disks[26]. However, using a tight constraint on the total gravitational potential derived from the stellar kinematics, we find that the observed second velocity moments ($V_{\rm rms} \equiv \sqrt{V^2+\sigma^2}$) of the ionized gas in Akira are far too high to be consistent with disk-like 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 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 $i = 50°$ (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 theses galaxies, the disk interpretation also fails to explain why the bisymmetric Hα features are always in rough alignment with the major kinematic axis. If arising from internal structure in a moderately face-on disk, this 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 cone (2θ = 80°) reproduces several qualitative features in 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 center, we can explain the offsets between the projected kinematic major axis of the ionized gas and both the stellar position angle and the Hα flux orientation. Furthermore, the bisymmetric Hα 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 Hα 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 likely originates in Akira's radio active galactic nucleus (AGN), which is detected in FIRST (Faint Images of the Radio Sky at Twenty-Centimeters) data with a luminosity density of $L_{1.4\ \mathrm{GHz}} = 1.6 \times 10^{21}$ W Hz^{-1}, and is most consistent with being a point source according to higher-resolution (1.5″) follow-up Jansky VLA radio observations (W.R., in prep). Since this AGN lacks obvious extended radio jets, its feedback is most likely 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 ($P_{\mathrm{mech}} = 8.1 \times 10^{41}$ erg s^{-1}) is sufficient to supply the wind's kinetic power ($\dot{E}_{\mathrm{wind}} \sim 10^{39}$ erg s^{-1}; see Methods). Moreover, the wind can inject sufficient energy, coupled to the ambient gas through the turbulent dynamics observed (Fig. 1i and Fig. 3a-c), to balance cooling in both the ionized and cool gas ($\dot{E}_{\mathrm{gas}} \sim 10^{39}$ erg s^{-1}). Indeed, the amount of cool Na D gas ($M_{\mathrm{cool\ gas}} \sim 10^{8}\ M_{\odot}$) implies a star formation rate of $SFR \sim 1 \times 10^{-2}\ M_{\odot}\ \mathrm{yr}^{-1}$, which is much higher than the estimated[19] $SFR_{\mathrm{Akira}} = 7 \times 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$

that leverages well-detected WISE photometry. The picture that emerges is one in which cool gas inflow in Akira, triggered by the minor merger, 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 harbor similarly weak radio point sources (according to followup JVLA observations) that would 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 $\sim 10^7$ 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 $\sim 5\%$ occurrence rate (averaged over the full mass range) implies an episodic behavior that leads us to name these objects “red geysers.” Present primarily below $M_* \lesssim 10^{11}\ M_\odot$, these galaxies lie in isolated halos with moderate masses[18] ($M_{\rm halo} \sim 10^{12}\ M_\odot$) 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[30]) as well as central accretion of ambient hot gas from stellar mass loss[8]. These red geysers may represent how typical quiescent galaxies maintain their quiescence.

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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. fit JAM models. S.P. carried out numerical merger simulations to model the data. W.R. obtained and reduced the JVLA data. K.W. fit 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 modeled 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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MaNGA Name	MaNGA-ID	RA	DEC	z^{a}	$\log M_*^{b}$	$NUV-r^{c}$	$\log SFR^{d}$	R_e^{e}	$\log M_h^{f}$
		(J2000.0 deg)	(J2000.0 deg)		$(M_\odot)$		$(M_\odot\ \mathrm{yr}^{-1})$	(kpc)	$(M_\odot)$
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	0.0244647	9.18	3.0	-0.94	1.73	12.0

Table 1: **Galaxy properties**

[a] Spectroscopic redshift from NSA catalog.

[b] Stellar mass from MPA-JHU DR7 data release.

[c] Rest-frame $NUV-r$ color from NSA catalog.

[d] Star formation rate from SED fitting of SDSS optical and WISE infrared photometry[19]; the AGN contribution to the SED is negligible.

[e] Effective radius from NSA catalog.

[f] Halo mass from a public group catalog[18].

Figure 1: **Akira: the prototypical red geyser. a,** The SDSS *gri* color images of the quiescent galaxy (West; "Akira") and the star-forming galaxy (East; "Tetsuo") embedded in a larger SDSS *r* image, with the MaNGA footprint in pink. **b,** The rest-frame $NUV-r$ vs. $\log M_*$ diagram of the adopted MaNGA sample, with Akira and Tetsuo highlighted. **c,** The Hα EW, with contours tracing the stellar continuum. **d,** The Na D EW. **e,** The Na D velocity. **f,** The stellar velocity. **g,** The stellar velocity dispersion. **h,** The ionized gas velocity. **i,** The ionized gas velocity dispersion. The Hα EW contours are overplotted on panels **d-i**. **j,** The observed $V_{\rm rms}$ from the highlighted spaxels far exceeds the $V_{\rm rms}$ predicted from the gravitational potential, ruling out disk-like rotation. The error bars on the observed $V_{\rm rms}$ represent the 1σ measurement errors while the shaded regions around the predicted $V_{\rm rms}$ represent a conservative estimate of the systematic uncertainties.

Figure 2: **Wind model. a,** A schematic diagram of the galaxy (gold) and the wind bicone (purple; $2\theta = 80°$) with the central $\pm 10°$ of the bicone highlighted in green. **b,** Akira's $v_{\rm ionized\ gas}$ 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.

Figure 3: **Diagnostic line ratio maps of Akira. a-c,** The log [N II] 6583/Hα, log [O III] 5007/Hβ, and log [S II] 6717,6731/Hα line ratio maps, with contours tracing the Hα EW pattern. **d-e,** The [N II] 6583 and [S II] 6717,6731 BPT diagrams; the error bars represent the 1σ measurement errors propagated to the log line ratios. Overplotted 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] 6583 and [S II] 6717,6731 BPT maps, i.e., each spaxel is colored by its location on their respective BPT diagram.

Methods

Observations. The data used in this work comes from the ongoing MaNGA survey[17,31,32] using the SDSS 2.5-in telescope[33]. One of three programs comprising the Sloan Digital Sky Survey-IV, MaNGA is obtaining spatially resolved spectroscopy for 10,000 nearby galaxies with log $M_*/M_\odot \gtrsim 9$ and a median redshift of $z \approx 0.04$. The r-band signal-to-noise ratio (S/N) in the outskirts of MaNGA galaxies is 4-8 Å^{-1}, and the wavelength coverage is 3600-10,300 Å. MaNGA's effective spatial resolution is 2.4″ (FWHM) with an instrumental spectral resolution of $\sigma \sim 60$ km s^{-1}. The MaNGA sample and data products used here were drawn from the internal MaNGA Product Launch-3 (MPL-3), which includes ≈ 700 galaxies observed before April 2015.

Ancillary data are from the NASA-Sloan Atlas (NSA[34]), MPA-JHU DR7 data release[35], and other recent works[18,19]. We assume a flat cosmological model with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.30$, and $\Omega_\Lambda = 0.70$, and all magnitudes are given in the AB magnitude system[36].

The MaNGA Data Analysis Pipeline (DAP), which uses `pPXF`[37] and the MIUSCAT stellar library[38], fits the stellar continuum in each spaxel and produces estimates of the stellar kinematics. Flux and EW measurements were measured through simple flux-summing[39] 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, i.e., $v_{\text{ionized gas}}$ and $\sigma_{\text{ionized gas}}$, were estimated by fitting a single Gaussian to the Hα emission line.

$\mathbf{W_{80}}$. W_{80} is a non-parametric measure of line widths; it is defined to contain 80% of the emission-line flux[40].

Na D measurements. The association of the offset Na D absorption (Fig. 1d) with cool foreground material is further supported by the dust extinction map presented in Extended Data Figure 1, which is derived using a recent spectral fitting code[41,42]: a region of enhanced extinction (darker spaxels) overlaps with the strong Na D absorption (white contours) on the right side of Akira.

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 would ideally model the Na D line profile after subtracting the stellar contribution. Indeed, Extended Data Figure 2a-c demonstrates the significant stellar contribution (red) to the Na D doublet (the two black vertical lines mark the expected locations of the Na D doublet). Extended Data Figure 2a shows data from a recent work[43], Extended Data Figure 2b shows the central spaxel of Akira, marked by the "x" in the Fig. 1d-e and Extended Data Figure 1, and Extended Data Figure 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 Figure 1. Unfortunately, template models of the stellar Na D component remain uncertain[43]. We proceed by first subtracting the stellar continuum fit determined for Akira by the DAP. We then examine the residual absorption as a function of wavelength, as shown in Extended Data Figure 2d-f. While the detailed shape and depth of the residual absorption profile may still contain an uncertain degree of (broad) stellar contamination, its line centroid should provide a good approximation of the typical velocity of the Na D-absorbing material.

Focusing on Extended Data Figure 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 for this reference[43], which is shown in the left panel. We define an at-rest line centroid for cool Na D gas by averaging the wavelengths 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 dotted grey vertical line, 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 Figure 2e-f.

Note that the stellar continuum of the recent work[43] exhibits a doublet absorption profile, while our's do not (red in Extended Data Figure 2a-c). This is because the higher stellar velocity dispersion of Akira (compared to the average galaxies studied by the recent work[43]) smears our the stellar Na D doublet.

Merger simulations. We modeled the interaction between Akira and Tetsuo using the GADGET-2[44] code and the methodology described in a recent work[45]. These simulations are constrained by the available data and contain more than 4 million particles that 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 or the proposed wind. The initial total mass merger ratio is $\sim$1:10, but because Tetsuo loses mass during the interaction, this ratio falls to $\sim$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 Figure 3a-d). After a glancing blow with Akira, a tidal bridge is generated that loops back and passes through the more massive galaxy to form the shell structure seen to the lower-right (Extended Data Figure 3d). This snapshot at t=0.56 Gyr best matches the SDSS *r* image (Extended Data Figure 3f), and it indicates that Tetsuo is behind Akira. Extended Data Figure 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 back towards the observer, penetrated close to Akira's center, and emerged in front of Akira on its lower-right side.

The shape of the tidal bridge and shell to the south-west in the SDSS image (Extended Data Figure 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 with 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 orientation is also more horizontal while the simulation predicts the gas stream stretches further (Extended Data Figure 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, etc.), 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 modeling evidence against the presence of disks. Jeans Anisotropic MGE (JAM[46]), where MGE stands for Multi-Gaussian Expansion[47,48], was performed on Akira and other red geysers 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 modeled potential includes an NFW[49] dark matter halo. The JAM model has four free parameters: the inclination i, anisotropy β_z, stellar M/L, and halo mass. These are optimized by fitting the model prediction for the second velocity moments, $V_{\rm rms} \equiv \sqrt{V^2+\sigma^2}$, to the observed MaNGA stellar kinematics. Through a number of systematics tests, we find that the best-fit stellar inclination is $i = 41^\circ$, with an upper limit of $i = 50^\circ$. Although there is some covariance between the model parameters, the resulting total mass profile, is extremely robust.

With the total gravitational potential defined from the JAM modeling above, we can predict projected second velocity moment ($V_{\rm rms}$) maps of gas under the assumption of axisymmetric orbital distributions. We treat the Hα flux as a "tracer" population of the underlying potential. Its flux distribution is modeled by a separate MGE (distinct from the stellar component) enabling de-projection of the observed Hα surface brightness. The Jeans equations are then integrated along the line of sight, weighted by the tracer population, to produce maps of $V_{\rm rms}$ allowed by the potential. We emphasize that the second moments are independent of the degree of circular motion versus "pressure" support in the hypothesized disk. In Extended Data Figure 4 (see also Fig. 1j) we show results for gaseous inclinations of $i = 46°$ (based on the $b/a = 0.7$ from GALFIT fits of the Hα flux, assuming an intrinsic axis ratio $q = 0.1$; see below) and the most extreme case of $i = 90°$ (an edge-on disk). In either case, the allowed $V_{\rm rms}$ is far below the observed $V_{\rm rms}$.

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 velocity shear of the kind observed seems unlikely. Such a scenario would also struggle to explain how the high dispersions are generated and why enhanced Hα flux is observed along the gradient in the shear field. Similarly, because line widths of W_{80} $\sim$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. 1i) while maintaining an ordered velocity shear pattern. A similar set of coincidences would be required for each galaxy in the rest of the red geyser sample.

Not surprisingly, tilted-disk models[50] that fit the ionized velocity field alone do a poor job for the red geyser 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 centers, 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 escape velocity, $v_{\rm esc} \sim 400 \pm 50$ km s^{-1}, by integrating the potential from a projected radius of 7$''$ (3.4 kpc or just under 1 $R_{\rm e}$) to 4 $R_{\rm e}$ (16 kpc) and assuming a gentle decline in the circular velocity at large radius. We then use GALFIT[51] to model the observed Hα flux surface brightness, finding a consistent projected axis ratio of $b/a = 0.7 \pm 0.02$, regardless of the assumed model profile (exponential, de Vaucouleurs', or free Sérsic) and despite significant structure in the residuals (of order $\sim 10-15\%$). Hypothesizing a disk with an intrinsic axis ratio, $q = 0.4$, roughly twice as "fat" as typical disks[52], we estimate an inclination of $i = 50°$. This is also the upper limit of inclinations allowed for the stellar kinematics, and precession should align accreted material with the stellar distribution in roughly a few dynamical times[53] (unless there is a source of incoming misaligned gas[54]). We de-project the observed mean velocities using this inclination and consider the distribution of velocities about this mean. Roughly 15-20% of the gas, i.e., with velocities greater than 1σ from the mean, would exceed the escape velocity under these assumptions.

Wind model. We construct a simple wind model that reproduces many qualitative features of the MaNGA observations. In this model, the wind assumes a wide-angle biconical form centered on the galaxy nucleus. Within the bicone, the wind has a constant amplitude, radially-outward velocity[55]. We assume that warm gas clouds entrained by the wind trace this velocity structure and emit flux in strong emission lines primarily in response to the local ionization field supplied by the stars[20–22]. The projected wind velocity field to first order is therefore a convolution of the wind geometry with the galaxy's 3D luminosity profile.

To realize the model, we populate a randomized 3D cartesian grid of points with the galaxy at the center and assign each point a weight equal the value of an axisymmetric Hernquist density profile sampled at that point[56]. This density profile is fixed to reproduce the imaging and JAM constrains on the stellar component, namely an intrinsic (3D) axis ratio of 0.4, an inclination of 41°, a projected major-axis effective radius of $R_e \approx 7''$, and an on-sky PA of 53°. For a given wind opening angle and inclination, we weight the projected line-of-sight component of the wind velocity at each point inside the bicone by its Hernquist profile value. Projected quantities are smoothed to the spatial resolution of the MaNGA data (2.4″, FWHM). To model a potential enhancement of gas densities or shocks along the central axis of the bicone, we implement a second set of weights defined with respect to the bicone that decrease exponentially (with a variable characteristic angle) as a function of the angular distance from the bicone's axis.

By experimenting with different choices for the wind's opening angle, inclination, length, intrinsic velocity, (and central weighting, if desired), we explored possible wind model solutions. Most have opening angles of $2\theta \sim 80°$ and steep inclinations ($\sim$70°) toward the line-of-sight. One example is shown in Fig. 2. This wind model has an opening angle of $2\theta = 80°$, an inclination of 75°, PA

= 55°, and a length of $2R_e$. We have assumed a constant radially outward velocity within the wind of $v_{\rm wind}$ = 310 km s^{-1}. We associate the observed, bisymmetric regions of enhanced Hα (white contours on the observed velocity field; Fig. 2b) with the wind's central axis. The projection of this $\pm 10°$ region is overplotted with white contours on the modeled velocity field (Fig. 2c). The wind density is assumed to decline as an exponential function of the angular distance with a characteristic angle of $\alpha = 10°$.

A key success of the wind model is explaining the displacement between the ionized gas major kinematic axis, the orientation angle of the Hα flux (which is traced by the Hα EW pattern), and the stellar position angle. The kinematic axis arises from the projection of the geometric intersection between the galaxy and the wind cone. The Hα flux distribution differs from the stellar surface brightness profile in a manner that is reflected in the EW map. By associating shocks or over-densities with the central axis of the bicone, we can explain the location of the Hα EW features with respect to the shape of the velocity field as well as the overall Hα orientation. This comparison is demonstrated in Fig. 2 by plotting contours describing the central $2\theta = 20°$ of the bicone. In the wind model interpretation, the kinematic field and Hα EW are only indirectly related to the galaxy's position angle. Finally, the wind's broad opening angle explains the relatively high gas velocity dispersion across the galaxy. The higher values associated with the horizontal "ridge line" along the minor kinematic axis may owe to regions of projected overlap between approaching and receding bicone surfaces.

In future work, we will statistically quantify how well wind models fit the data for Akira and other red geysers and explore what degeneracies may exist. An interesting question is whether varying the wind velocity with radius enables better fits and constraints on the wind's driving mechanisms[57]. Addressing such issues requires overcoming important limitations in the current model. First, the modeled (weighted) velocity field is only approximately what is observed. The next step is to forward model a 3D datacube containing the line-of-sight velocity distribution at each point and fit this information with the same Gaussian fitting techniques used on the strong emission lines (e.g., Hα) in the MaNGA datacube. Secondly, the current model does not account for the sensitivity of the observations. Grid points that are far from the model center should be further down-weighted because they will contribute at very low S/N. This issue can be addressed in the model by adding the effects of noise and covariance in the MaNGA data.

Shock models. Shock models[27] with twice the solar atomic abundances, shock velocities of 200-400 km s^{-1}, magnetic fields of 0.5-10 μG, and preshock densities of unity, were used in Fig. 3.

Inferring the presence of an AGN in Akira. The presence of a central radio source and the absence of star formation in Akira imply the presence of an AGN. Quantitatively, we can confirm the presence of an AGN by comparing the expected SFR inferred from the radio luminosity of Akira to the estimated SFR from SED fitting of SDSS and WISE photometry[19]. We first calculate the radio luminosity density of Akira using $L_{1.4\ \mathrm{GHz}} = 4\pi d_{\mathrm{L}}^2 F_{1.4\ \mathrm{GHz}}$, where $F_{1.4\ \mathrm{GHz}}$ is the integrated flux density (of 1.2 mJy) from FIRST[58], and d_{L} is the luminosity distance. This calculation yields $L_{1.4\ \mathrm{GHz}} = 1.6 \times 10^{21}$ W Hz^{-1}. Using the radio star formation rate calibration[59], we infer $SFR =$ 1 $M_{\odot}$ yr^{-1}. This level of star formation in Akira is ruled out at more than 97.5% confidence[19] (the catalog only provides *SFR* values up to the 97.5 percentile value of the *SFR* posterior distribution function), indicating that the most likely source of this radio emission is an AGN.

Eddington ratio and AGN power. To calculate the Eddington ratio (λ) of Akira, we use the Eddington-scaled accretion rate[60], which is more applicable to radio-detected AGN: $\lambda = (L_{\mathrm{rad}} + L_{\mathrm{mech}})/L_{\mathrm{Edd}}$, where L_{rad} is the bolometric radiative luminosity, L_{mech} is the jet mechanical luminosity, and L_{Edd} is the Eddington limit. To calculate L_{rad}, we converted the [O III] 5007 flux from the central $2''$ (≈ 1 kpc) radius aperture of Akira, $F_{[\mathrm{O\,III}]}$, to a luminosity: $L_{[\mathrm{O\,III}]} = 4\pi d_{\mathrm{L}}^2 F_{[\mathrm{O\,III}]} = 1.7 \times 10^{39}$ erg s^{-1}. Even though the central [O III] 5007 flux is probably not entirely due to AGN photoionization (evolved stars and shocks probably contribute), for this order-of-magnitude calculation we will make the simplifying assumption that it does. Using the relation[61] $L_{\mathrm{rad}} = 3500 L_{[\mathrm{O\,III}]}$, we obtain $L_{\mathrm{rad}} = 5.9 \times 10^{42}$ erg s^{-1}.

Acknowledging that Akira is in a lower mass and energy output regime than those in which expanding X-ray bubbles have been observed, we nonetheless applied the following relation[62] to calculate the jet mechanical luminosity: $L_{\mathrm{mech}} = 7.3 \times 10^{36} (L_{1.4\ \mathrm{GHz}}/10^{24}\ \mathrm{W\ Hz^{-1}})^{0.70}$ W, which results in $L_{\mathrm{mech}} = 8.1 \times 10^{34}\ W = 8.1 \times 10^{41}$ erg s^{-1}.

Finally, to calculate L_{Edd}, we first estimate the black hole mass, M_{BH}, using the relation[63] $\log(M_{\mathrm{BH}}/M_{\odot}) = 8.32 + 5.64 \log[\sigma_{\mathrm{star}}/(200\ \mathrm{km\ s^{-1}})]$, with $\sigma_{\mathrm{star}} = 185.5$ km s^{-1} from the central $2''$ radius aperture, yielding $\log(M_{\mathrm{BH}}/M_{\odot}) = 8.1$. We calculate the classical Eddington limit with $L_{\mathrm{Edd}} = 3.3 \times 10^4 M_{\mathrm{BH}} = 4.5 \times 10^{12}\ L_{\odot} = 1.7 \times 10^{46}$ erg s^{-1}.

Inserting these numbers into $\lambda = (L_{\rm rad} + L_{\rm mech})/L_{\rm Edd}$ 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[7,15,60]. We used MaNGA data for this calculation; a similar value is obtained when using the MPA-JHU DR7 value added catalog.

Ionized gas energetics. Assuming warm ionized gas clouds with a temperature of 10^4 K and using the observed [S II] ratio, we estimate[64] an electron density, n_e, of 100 cm^{-3}. With this value of n_e, we estimate[65] the lower limits on the ionized gas mass from the Hα line flux, $M_{\rm warm,\ H\alpha} \sim 6 \times 10^5$ $M_\odot$. We can derive similar estimates[66] based on the Hβ and [O III] flux, obtaining $M_{\rm warm,\ H\beta} \sim 4 \times 10^5$ $M_\odot$ and $M_{\rm warm,\ [O\,III]} \sim 2 \times 10^4$ $M_\odot$. We adopt an approximate $M_{\rm warm} \sim 10^5$ $M_\odot$.

To approximate the energy associated with a wind driving the observed velocities in the ionized gas, we simply adopt the kinetic energy[40], $E_{\rm wind} \sim {}^1\!/\!{}_2 M_{\rm warm} v_{\rm wind}^2$, with $v_{\rm wind}$ = 300 km s^{-1}. To estimate the wind power, we divide $E_{\rm wind}$ by the characteristic wind timescale of 10^7 yr, derived by dividing the Akira's optical radius (the observed extent of the wind) by $v_{\rm wind}$. We obtain $\dot{E}_{\rm wind} \sim 10^{39}$ erg s^{-1}. Because the ionized gas mass is likely a lower limit, $\dot{E}_{\rm wind}$ is likely an underestimate. The gas cooling rate is estimated using a method from the literature[67].

Star formation in the Na D cool gas. To estimate the expected star formation rate associated with the cool Na D gas—under the assumption of no external heating mechanisms—we first estimate the total hydrogen column density ($N_{HI} + 2N_{H_2}$) from the dust extinction presented in Extended

Data Figure 1, following[68]. Integrating over the $\sim$4 kpc^2 region of enhanced extinction, we find a total gas mass of $M_{\rm cool} \sim 10^8\ M_\odot$ or a surface mass density of $\Sigma_{\rm cool} \sim 3 \times 10^7\ M_\odot$ kpc^{-2}. To apply the Kennicutt relation[69], we first account for fact that the Na D material is unlikely to be distributed in a thin, face-on disk. Assuming the Kennicut relation holds with respect to volumetric density, we scale $\Sigma_{\rm cool}$ by the ratio of scale heights between a typical star-forming spiral ($H_{\rm Kennicut} \sim 0.6$ kpc[70]) and an estimate for the Na D material's scale height, $H_{\rm NaD}$. We set $H_{\rm NaD}$ to $\sim$3 kpc, which is approximately the effective radius ($R_{\rm e}$) of Akira. These assumptions yield $SFR \sim 10^{-2}\ M_\odot$ yr^{-1}, roughly 100 times higher than the estimate for Akira ($SFR_{\rm Akira} = 7 \times 10^{-5}\ M_\odot$ yr^{-1})[19].

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

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Extended Data Figure 1: $A(V)$ **map.** The estimated $A(V)$ map, 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.

Extended Data Figure 2: **Na D LOS measurement. a-c,** The spectrum around the Na D doublet at $\lambda = 5890, 5896$ 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 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).

Extended Data Figure 3: **Merger simulation. a-d,** Evolution of the stars from t=0 Gyr to t=0.56 Gyr. **e,** Composite image of stars and gas at t=0.56. **f,** The SDSS *r* image of Akira and Tetsuo.

Extended Data Figure 4: $V_{\rm rms}$ **maps. a,** Observed $V_{\rm rms}$ map. **b,** Predicted $V_{\rm rms}$ map, assuming $i = 46°$. **c,** Predicted $V_{\rm rms}$ map, assuming $i = 90°$.