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A Kiloparsec-scale Internal Shock Collision in the Jet of a Nearby Radio Galaxy

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Jets of highly energized plasma with relativistic velocities are associated with black holes ranging in mass from a few times that of our sun to the billion-solar-mass black holes at the centers of galaxies¹. A popular but unconfirmed hypothesis to explain how the plasma is energized is the internal shock model, in which the relativistic flow is unsteady². Faster components in the jet catch up to and collide with slower ones, leading to internal shocks which accelerate particles and generate magnetic fields³. This mechanism can explain the variable, high-energy emission from a diverse set of objects^{4–7}, with the best indirect evidence the unseen fast relativistic flow inferred to energize slower components in X-ray binary jets^{8,9}.

Mapping of the kinematic profiles in resolved jets has revealed precessing and helical patterns in X-ray binaries^{10,11}, apparent superluminal (faster-than-light) motions^{12,13}, and the ejection of knots from standing shocks in the jets of active galaxies^{14,15}. However, observations revealing the structure and evolution of an internal shock in action have remained elusive, hindering measurement of the physical parameters and ultimate efficiency of the mechanism. Here we report observations of a collision between two knots in the jet of nearby radio galaxy 3C 264. A bright knot with an apparent speed (β_{app}) of $7.0 \pm 0.8c$ is in the incipient stages of a collision with a slower-moving knot ($\beta_{app}=1.8 \pm 0.5c$) just downstream, resulting in brightening of both knots as seen in the most recent epoch of imaging.

We obtained deep V-band imaging of radio galaxy 3C 264 (distance = 91 Mpc) with the Advanced Camera for Surveys (ACS) on board the Hubble Space Telescope (HST) in May of 2014. The comparatively deep ACS imaging provides a reference image to compare against previous HST imaging for evidence of proper motions of the four previously known optical knots within the $2''$ -long jet^{16–18}. We localized over 100 globular clusters in the host galaxy as a reference system on which to register previous V-band images taken with HST’s Wide Field Planetary Camera 2 (WFPC2) in 1994, 1996, and 2002. The systematic error in the registration of the WFPC2 images is generally on the order of 5 milliarcseconds (mas) or less. After aligning all images to a common reference frame, the fast proper motion of knot B is clearly visible, as shown in Figure 1, and the provided movies (see Supplementary Information). Previous radio observations have revealed that the initially narrowly collimated jet bends by $\sim 10^\circ$ at the location marked by the yellow cross¹⁹, which appears to align well with the central axis of the jet in our imaging, and which serves as our

reference point for all measured positions.

To measure their apparent speeds, the position of each knot was measured with a centroiding technique. In the case of knots B and C, we also modelled the jet as a constant-density conical jet with superimposed resolved knots, in order to better measure their fluxes and positions, particularly in the final epoch when they appear to overlap. We plotted the position of each knot along the direction of the jet axis versus time, and fitted the data with a least-squares linear model. A slope significantly larger than zero indicates significant proper motions, and we used the conversion factor $1.442c$ year/mas to convert angular speeds (μ_{app}) to units of c (see Table 1).

We found that knots A and D have a β_{app} consistent with zero (Extended Data Figures 1 and 2), while the inner knots B and C have $\beta_{app} = 7.0 \pm 0.8c$ and $1.8 \pm 0.5c$, respectively (Figure 2). The value for knot B exceeds the fastest speeds measured in the jet in M87, the only other source for which speeds on kpc scales have been measured^{20,21}. The current difference in speeds between knots B and C puts them on a collision course, an interaction which has already begun in the final epoch from 2014, where the knots begin to overlap (Figure 2).

In the internal shock model, the collision of two components results in particle acceleration, which will manifest in a significant brightening of the components as they combine into a single moving component. Our modelling results show that in the final 2014 epoch, both knots B and C brighten at the same time by approximately 40% over the mean flux level of the previous 3 epochs (Figure 3). The brightening can also be seen in Extended Data Figure 3, where we show the flux contour along the length of the jet (averaged transversely over a distance $0.1''$) for each epoch.

The flux increase is also corroborated by measuring the flux within a circular aperture centered on and enveloping knots B and C in all epochs, which shows a significant total flux change of approximately 20-40% over prior epochs. Under equipartition, the cooling length for the optical-emitting electrons for knots B and C is longer than the distance they travelled in our observations, consistent with the lack of any decay in flux levels for these knots over the first three epochs. This is not the case for stationary knot A, which can be seen to decay with a timescale of ~ 70 years. Knot A appears analogous to knot HST-1 in the M87 jet; the latter is thought to be a stationary reconfinement shock where the jet pressure drops below that of the external environment²². The event that energized knot A may have been the passage of fast-moving knot B circa 1971^{+8}_{-17} , comparable to the knot A decay time.

Previous radio observations of the 3C 264 jet show that the locations of the knots in contemporaneous radio and optical imaging are very similar^{18,23}. The earliest radio image of 3C 264 taken in October 1983 with the VLA clearly shows three distinct features (see contour comparison in Extended Data Figure 4). While knot D appears completely stationary over this time-frame, the data suggest the possibility that knots B and C were moving faster in the past and may have decelerated (Extended Data Figure 5).

In the internal shock model, the efficiency (η) of the conversion of the dissipated kinetic energy (E_{diss}) into radiation is generally unknown. For the collision in 3C 264 we can estimate that from our observations (further details are in Methods): we take the minimum possible value $\Gamma_B=7.1$ for knot B so that the jet is observed at an angle of 8.1° , and the Lorentz factor of slower

knot C is $\Gamma_C = 2.8$. We assume an equipartition magnetic field and one proton per electron in the plasma to obtain masses of 2.5×10^{30} and 6.7×10^{30} g for knots B and C. After the collision, the single combined component will move with Lorentz factor $\Gamma_m = 3.7$. The total energy dissipated is taken as the difference in kinetic energy before and after the collision and is $E_{diss} = 2.6 \times 10^{51}$ erg. If the knot B+C complex stays at the flux level observed in 2014 through the duration of the collision (which we take to be the knot superposition time of 30 years in the observer's frame, as one expects in the case the cooling time of the optically emitting electrons is shorter than the collision time), the efficiency of conversion is only $\eta = 10^{-3}$, considerably lower than usually assumed in models. This, however, is a lower limit for two reasons. First, theoretical modelling²⁴ of internal shocks suggests that the flux should steadily rise to a peak occurring half-way through the collision, which would increase η . Second, it is possible that the cooling time of the optically emitting electrons is longer than the collision time, which would increase the duration of the elevated optical-UV emission, and therefore η . The rate of cooling depends on the magnetic field in the shocked plasma. Long-term monitoring of the collision in 3C 264 over the coming decades can probe the evolution of the flux and through this constrain two free parameters of the internal shock model: the fraction of E_{diss} that goes to radiating electrons and the fraction that goes to generating the magnetic field in the shocked plasma.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature

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Author Contributions E.T.M. performed the HST data analysis and wrote the paper. B.S., J.A., R.v.d.M. and S.S. were consulted on and contributed to the HST data analysis. M.G. contributed to the interpretation and contributed the theoretical calculations in consultation with E.T.M. E.P. contributed radio data. J.B., C.N. and M.C. provided insight in the design of the observations and interpretation. All authors discussed the results and commented on the manuscript.

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Table 1 | Summary of Knot Positions and Speeds

	Distance along the jet [†]		Proper motion	
	Initial (1994)	Final (2014)	μ_{app}	β_{app}
	(mas)	(mas)	(mas year ⁻¹)	c
Knot A	148±5	149±1	0.07±0.20	0.1±0.3
Knot B	257±5	359±2	4.85±0.58	7.0±0.8
Knot C	450±6	478±2	1.27±0.32	1.8±0.5
Knot D	582±5	581±1	−0.13±0.31	−0.2±0.5

Knots A, D by contour method; Knots B, C from maximum likelihood model.

[†] Measured from the bend in the radio jet noted in Figure 1.

Figure 1 — A Comparison of HST images of the jet in 3C 264 from 1994 to 2014.

The galaxy and core emission from 3C 264 have been subtracted, with a white star representing the location of the black hole, and a yellow cross indicating the location of a bend in the jet seen with radio interferometry¹⁹. The contours show the 30% flux-over-background isophotes around each peak and are overlaid along with vertical guidelines to aid the eye. The first three images were taken with WFPC2, and the final epoch is a deep ACS/WFC image taken for the purposes of measuring proper motions in the jet.

Figure 2 — Position versus time for knots B and C. The position of the centre of each knot is noted by thick red and blue lines, respectively, with line extent corresponding to the $3\sigma \chi^2$ modelling error plus the systematic error on the mean from the image registration. The gray extensions show the best-fit size of the resolved knot from the model. As shown, the best-fit linear slope yields a speed of $7 \pm 0.8c$ for knot B and $1.8 \pm 0.5c$ for knot C. In the final epoch the knots are directly adjacent and possibly overlapping, within the errors.

Figure 3 — Change in optical flux at 6000 Å in the colliding knots B and C over 20 years. The knots show a simultaneous significant increase in flux in the 2014 image. Errors are the $3\sigma \chi^2$ modelling error.