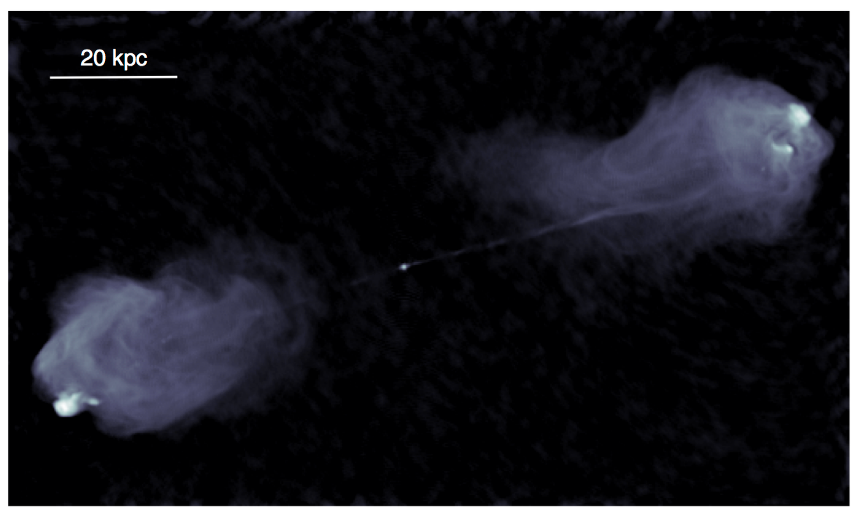
# Deflection of the Jet at Primary Hotspot E in Cygnus A

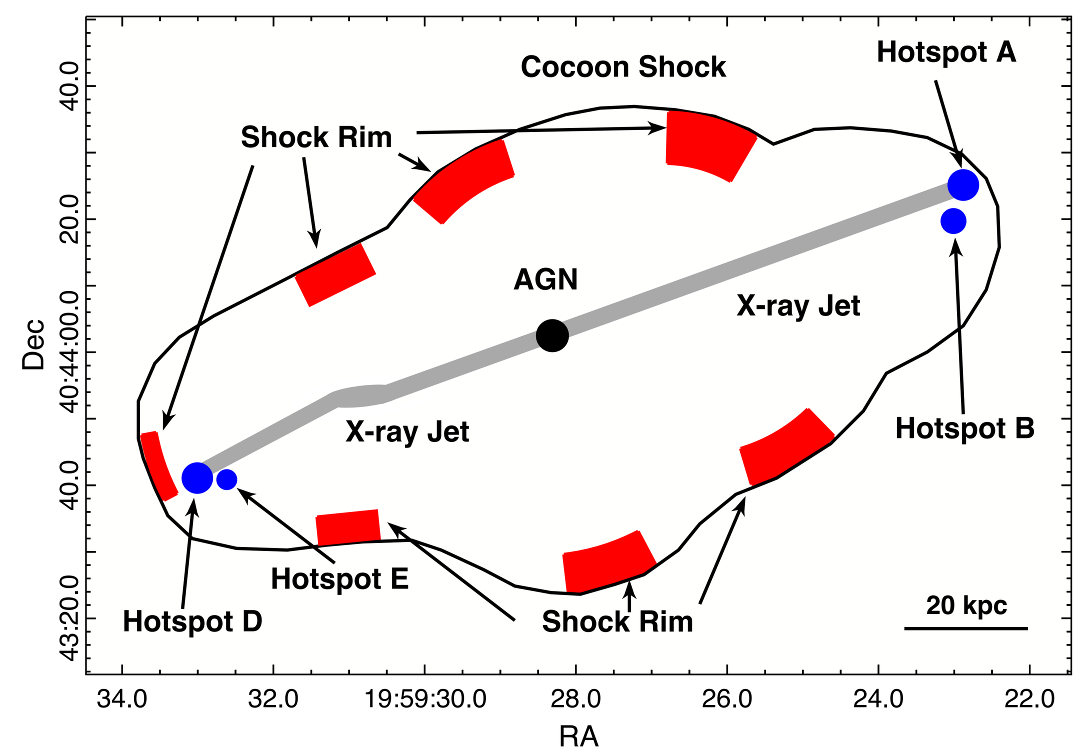
Paul Nulsen[1], Amalya Johnson[1,2], Bradford Snios[1], Ralph Kraft[1], John ZuHone[1], Martijn de Vries[3], Michael Wise[4], Brian McNamara[5], Richard Perley[6], Lerato Sebokolodi[6]

1. Harvard-Smithsonian Center for Astrophysics; 2. Columbia; 3. Amsterdam; 4. SRON; 5. Waterloo; 6. NRAO

**Abstract:** The archetypal Fanaroff-Riley class II radio galaxy Cygnus A is hosted by the central galaxy of a cool core cluster. In addition to the X-ray emission from its AGN, hotspots, and cocoon shocks, a deep Chandra image reveals strong diffuse emission from its radio lobes, primarily due to inverse-Compton scattered radio synchrotron photons, with a distinct circular hole of radius 3.9 kpc around hotspot E. The distribution of X-ray emission on our line-of-sight implies the hole is excavated from within the radio lobe and its depth is at least 1.7 times its projected width, or 13.3±2.3 kpc, implying that the jet is deflected by the shocked intracluster gas back into the lobe at hotspot E, continuing onward, possibly to where it terminates at hotspot D. This favors deflected jets, rather than the dentist drill model for multiple hotspots.



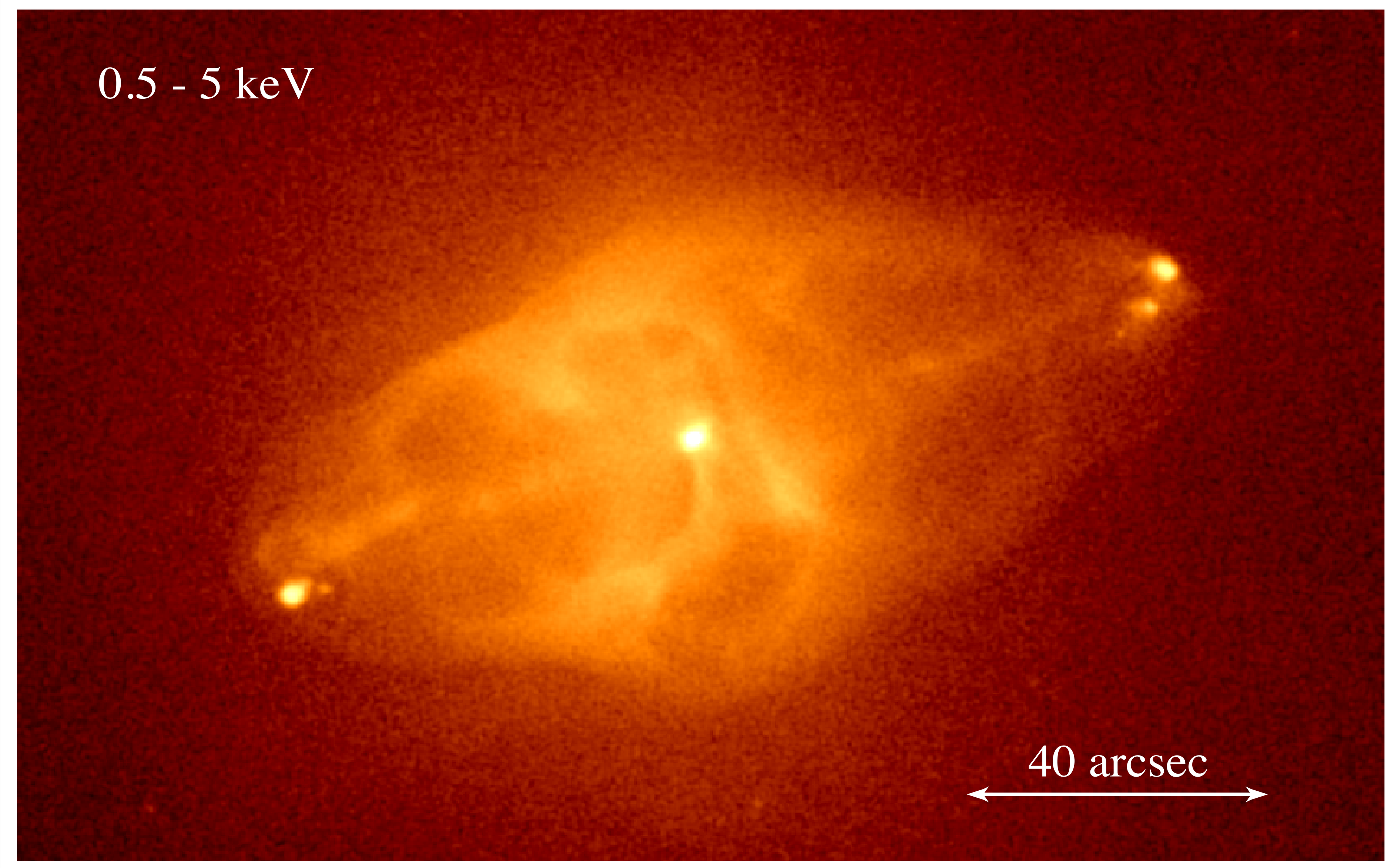

6cm radio radio image showing the primary and larger secondary hotspot in each lobe (Perley et al. 1984).

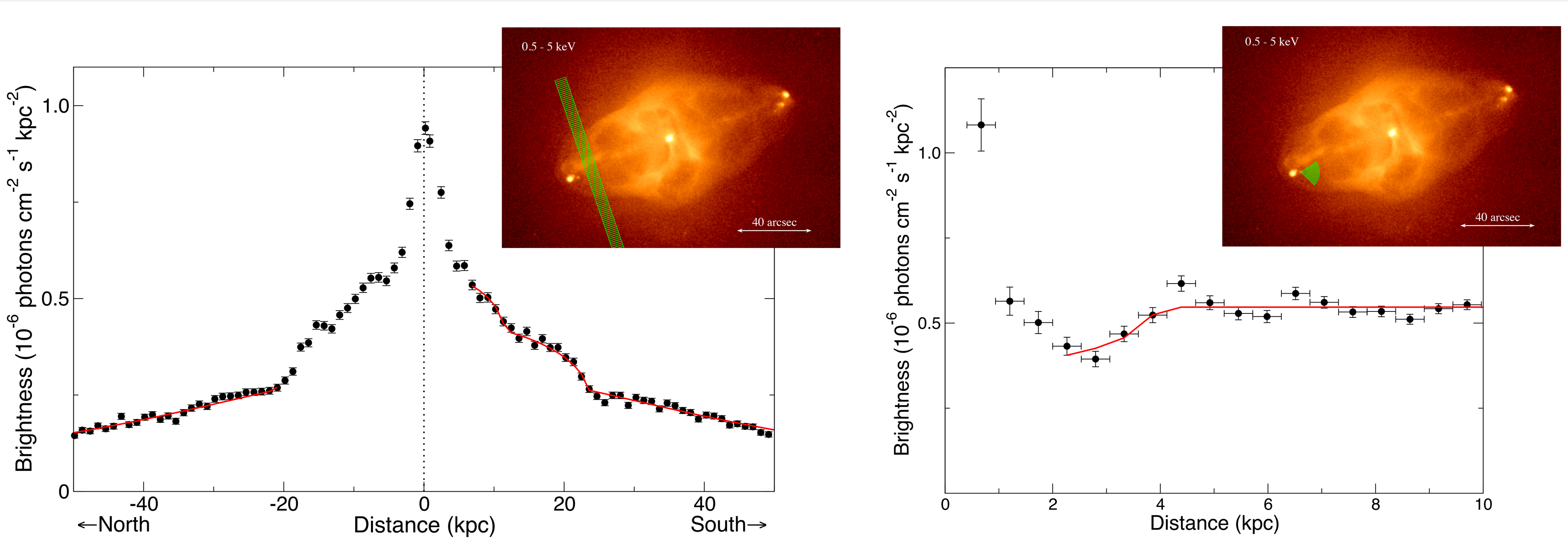



Schematic layout of X-ray features within the cocoon shocks of Cygnus A.

## X-ray Image of Cygnus A

The 6 cm radio image shows the hotspots lying near the outer ends of the radio lobes, characteristic of FRII radio galaxies (Perley et al. 1984). The 2 Msec *Chandra* image (panel to the right) also reveals cocoon shocks, an "X-ray jet," a "rim" of gas compressed between the expanding radio lobe and the shocks, and diffuse nonthermal X-ray emission from the lobes (de Vries et al. 2018). Each lobe contains primary and secondary hotspots. The primary hotspots are believed to be where the jets most recently had their first encounter with the intracluster medium (ICM). A circular "hole," with a radius of 3.9 kpc is clearly visible around hotspot E, the primary hotspot in the eastern lobe.



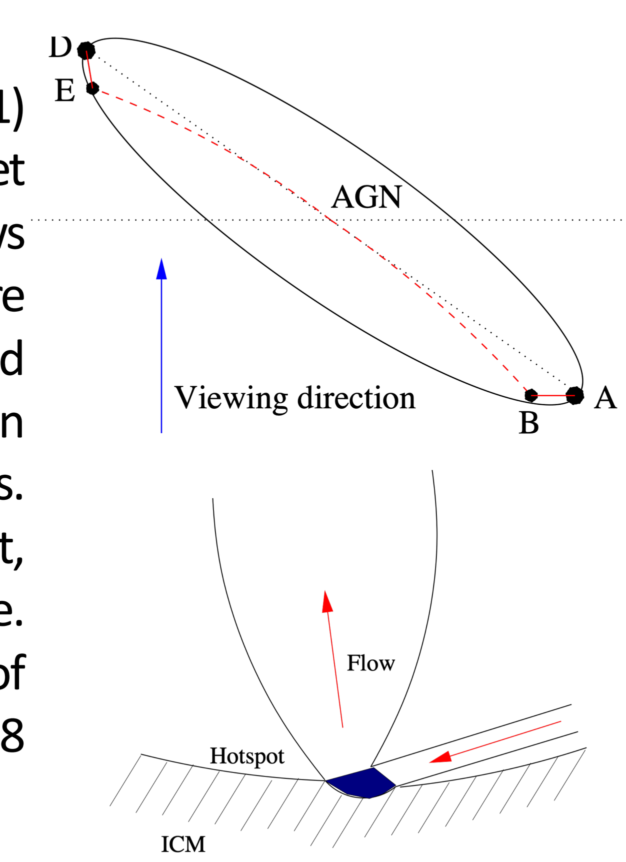




## Surface brightness profiles

For the lobe (left), taking the emission in each of two concentric shells to be uniform and using a beta model for the ICM gives the best fit in red (ignoring the X-ray jet and northern side of the lobe), with emission per unit volume of $0.68\pm0.03\times10^{-8}$ ct cm$^{-2}$ s$^{-1}$ arcsec$^{-3}$ and $1.42\pm0.07\times10^{-8}$ ct cm$^{-2}$ s$^{-1}$ arcsec$^{-3}$ for the outer and inner shells, resp. If the hole (right) is spherical, within a region of uniform emission, the best fit emission deficit is $2.45\pm0.34\times10^{-8}$ ct cm$^{-2}$ s$^{-1}$ arcsec$^{-3}$ (red; ignoring the hotspot). For the deficit to exceed the lobe emission by 70%, the hole must be elongated on our line of sight, at least 70% deeper than its diameter (Snios et al., in prep.), implying that the jet is deflected back into the lobe at the hotspot.

## Cause of the Hole

If the jet is deflected off the ICM at hotspot E (Tregillis et al. 2001) and the hotspot is on the near side of the lobe, the outgoing jet may flow almost directly away along our line of sight. As it flows into the hotspot, the supersonic jet passes through one or more shocks that convert kinetic energy to particle energy, heat and magnetic fields. Particles and field produce synchrotron emission in the radio and synchrotron-self-Compton X-rays. The high pressure drives outflow along the deflected jet, causing it to expand until its pressure matches that of the lobe. The 0.5 kpc width of the hotspot at 43 GHz reflects the size of the inflowing jet. The outflowing jet inflates to a width of ~8 kpc, creating the X-ray hole.




## Conclusions

- A circular hole with a radius of 3.9 kpc in the X-ray emission from the lobe of Cygnus A surrounds the eastern primary hotspot
- The jet is deflected off the ICM at primary hotspot E and the outflow from the hotspot recedes almost directly away from us
- Orientation and Doppler beaming can account for differences between hotspots B and E
- The existence of the hole favors multiple hotspots being formed by a jet being deflected between a sequence of impact sites, rather than the dentist drill model

## Discussion

The inclination of the radio axis (Vestergaard & Barthel 1983; Boccardi et al. 2016) affects the appearance of the flow. A different orientation for the jet flow in the west may account for western primary hotspot B being brighter and lacking an X-ray hole. Abrupt changes in rotation measure associated with hotspot B imply that it lies on the near side of the lobe (Carilli et al. 1988). If the outgoing jet from hotspot B is viewed more side on than E , the line-of-sight depth, hence contrast, of the cavity is reduced. Different Doppler dimming may also account for at least part of the contrast in brightness between hotspots B and E.

The outflow from hotspot E must persist for at least ~40,000 yr to excavate the hole, considerably longer than the time required for hotspot D to dissipate, indicating that the outflow must be powering D. This suggests that the multiple hotspots seen in FRII radio galaxies form as the jet flow is terminated in a sequence of impacts on the ICM, rather than reflecting independent impact sites of a rapidly hopping jet, as in the dentist drill model.

## References

Boccardi, B, Krichbaun, TP, Bach, U, et al., 2016. A&A, 585, A33
Carilli CL, Perley RA, Dreher JH, 1988. ApJ, 334, L73
de Vries MN, Wise MW, Huppenkothen D, Nulsen PEJ, et al., 2018. MNRAS, 478, 4010
Perley RA, Dreher JW, Cowan JJ, 1984. ApJ, 285, L35
Tregillis I, Jones TW, Ryu D, 2001. ApJ, 557, 475
Vestergaard M, Barthel PD, 1983. AJ, 105, 456