Famous Black Hole Has Jet Pushing Cosmic Speed Limit

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Superluminal velocity and synchrotron cooling of X-ray knots

- Knot HST-1 and knot D of the M87 jet moving with apparent superluminal velocities of 6.3c and 2.4c.
- Actual jet velocities are 0.997c (HST-1) and 0.927c (D)
- Consistent with the previously measured motions of the optical, ultraviolet, and radio components.
- Knot HST-1 shows significant temporal variability consistent with synchrotron cooling
- **Strongest direct evidence to date that underlying flow is relativistic**
- Relativistic flow can carry enormous energy
Jets, black holes, and the formation of structure – a question of scales

- M87 – central galaxy of Virgo cluster – SMBH at center
- Impact of BH extends 8 orders of magnitude in scales!
- Similar to something that is the size of a penny affecting an entire continent!
- Relativistic flow key to massive energy transport through small jet

ESO VLT observation of M87 and optical jet

Chandra X-ray image of Virgo cluster and M87 jet
Overview – Jet Physics and X-ray Observations

- Jets are collimated flows launched from central SMBH
- We typically measure morphology, synchrotron spectrum, impact on surrounding medium, etc., but not fundamental jet properties
- We try to infer fundamental jet properties from observables – *definitely not a direct relation!*
- Understanding how jets work is *central* to our understanding of key astrophysical process including how SMBHs form and grow, how galaxies form and evolve, and why the local Universe looks the way it does today!
Chandra/HRC search for proper motions of the X-ray knots in the M87 jet

• M87 is the brightest and second closest (after Centaurus A) AGN jet
  • Proximity means that we have a resolution and sensitivity unmatched with any other target
• Two Chandra High Resolution Camera (HRC) observations of M87 jet taken 5 years apart
• The HRC has highest imaging resolution (<0.5") on Chandra – this measurement is at the edge of Chandra’s capabilities.
• Two primary science goals:
  • Are the X-ray knots moving with the same velocity as the optical and radio knots?
  • What does this tell us about the underlying physics of jets?
Broadband view M87 jet

- M87 is the second closest (d = 17 Mpc) AGN jet – 1”~86 pc
- 3x10⁹ M☉ SMBH at center
- Image on right is radio (top), optical (2nd), Chandra/ACIS (3rd), and radio contours on Chandra image (4th) (Marshall+2002)
- Strong correspondence between the three bands
Multi-epoch Chandra/HRC observations of M87 jet (Snios+2019)

- 2012 (left) and 2017 (right) Chandra/HRC observations of M87 jet
- Bottom left – difference of the two images – red corresponds to brighter in 2012, blue to brighter in 2017
- Bottom right – S/N map
Proper motions, superluminal motions, and variability

- The flux from the core and some of the knots show significant variability between the two epochs
- The core and HST-1 were modeled with 2D Gaussians

**Results**

Knot HST-1 moving 24.1 mas yr\(^{-1}\) -> 6.3c!  
Knot D moving at 9.4 mas yr\(^{-1}\) or 2.4c!  
HST-1 variability consistent with synchrotron cooling
Superluminal velocity of X-ray knots

- Comparison of Chandra/HRC and HST (red contours – F275 filter) during the same years.
- The shifts in position of the X-ray knots (HST-1 and D) and optical knots are consistent with each other
- X-ray and optical-emitting electrons are the same population
Superluminal velocity of X-ray knots

- We detect proper motions in knot HST-1 and knot D of 24.1 mas yr\(^{-1}\) and 9.2 mas yr\(^{-1}\), respectively, corresponding to *apparent superluminal velocities* of 6.3c and 2.4c.
- Actual jet velocities are 0.997c (HST-1) and 0.927c (D).
- These velocities are consistent with the previously measured motions of the optical, ultraviolet, and radio components.
- Knot HST-1 shows significant temporal variability
  - Modeling of synchrotron losses consistent with spectral variability for equipartition magnetic field
- **Strongest direct evidence to date that underlying flow is relativistic**
- Relativistic flow can carry enormous energy