An Origin of the Radio Jet in M87 at the Location of the Central Black Hole

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Abstract: Relativistic jets ejected from active galactic nuclei (AGN) are thought to be powered by a central engine which consists of a supermassive black hole and an accretion disk. Specifying the location of the central engine is a crucial key for understanding the jet formation, the structure and the emission mechanism. Here we report the high-precision VLBI astrometry observations of the nearby radio galaxy M87. The measurements of the 'core-shift' reveal that the central engine of M87 is located in the immediate vicinity of the radio core at 43GHz with the distance ∼20 Schwarzschild radii (R_s) or even could be closer, which is much smaller than ∼$10^{4\text{-}6}$ R_s reported for other radio jets.

M87 (Virgo A)

The nearby radio galaxy M87 is an ideal laboratory to investigate the detailed jet physics. Owing to its proximity (16.7 Mpc) and large black hole mass ($M = (6.0\pm0.5) \times 10^9 M_{sun}$), its jet structure is resolved on a scale of 100 Schwarzschild radii (R_s) with VLBI observations (1 milliarcsecond = 0.08 pc = 140 R_s). **However, the location of the central engine launching the jet remain still elusive (Fig.1).** Because the 'radio core' at the apparent jet origin corresponds to the optically thick surface of the synchrotron-self-absorption (SSA) or the standing shock structure, the location of the central engine can be offset from the core by unknown amount.

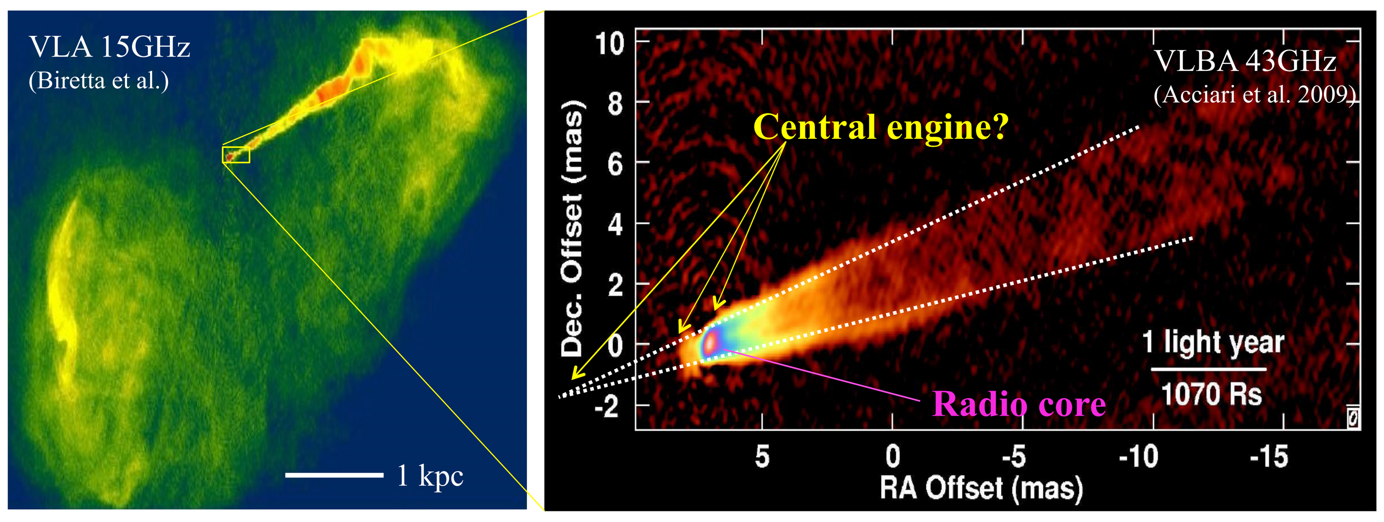

Fig.1 Radio images of M87. (right) kpc-scale image obtained by VLA at 15GHz. (left) Inner jet image obtained by VLBA at 43GHz.

Pinpointing the central engine with high-precision VLBI astrometry

■Optical depth for SSA (τ_{SSA}) is frequency dependent

→ Position of the radio core moves toward the upstream side of the jet with increasing frequency (**'Core-shift' effect**; Blandford&Konigl 1979) if the core corresponds to τ_{SSA}∼1 surface (Fig. 2).

■The upstream 'end' of the jet can be specified by measuring frequency dependence of the core-shift

→ This site should be the immediate vicinity of the central engine

■VLBI astrometry achieves the position accuracy of tens of microarcseconds (μas).

→ This angular scale corresponds to below **10 R_s** for M87

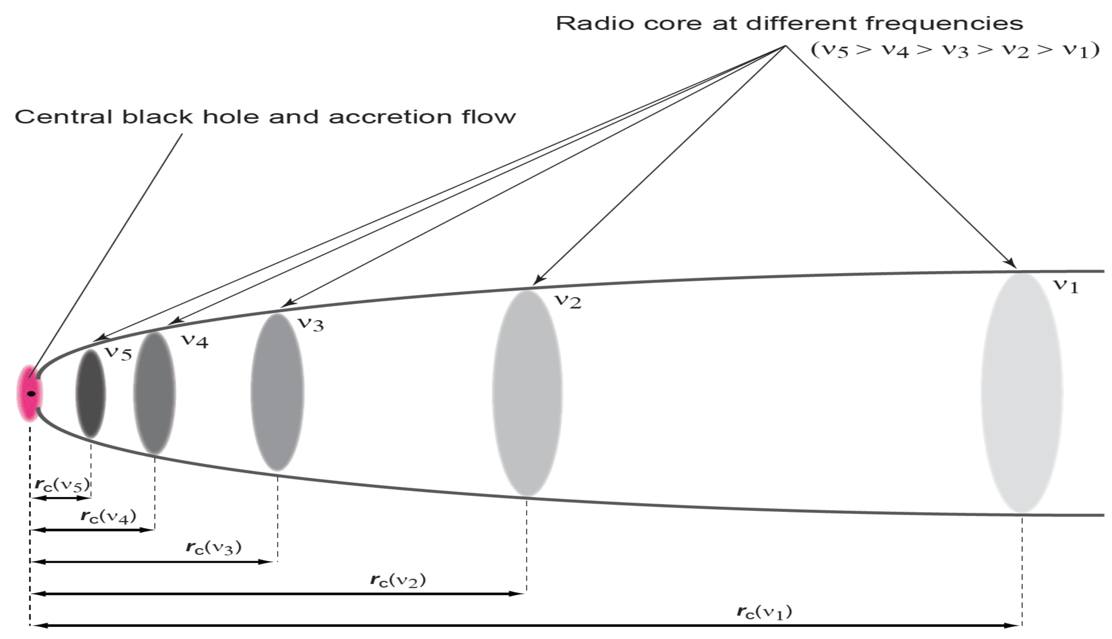

Fig.2 Diagram illustrating the core-shift of a jet . Optical depth for SSA (τ_{SSA}) is a function of the electron number density N_e, the magnetic field B and the observing frequency ν. Since τ_{SSA} decreases with increasing frequency, the separation between the central engine and a radio core at a given ν satisfies $r_c(\nu) \propto \nu^{-\alpha}$ ($\alpha > 0$) when the radial profiles of N_e and B in the jet show power law dependences.

Observations

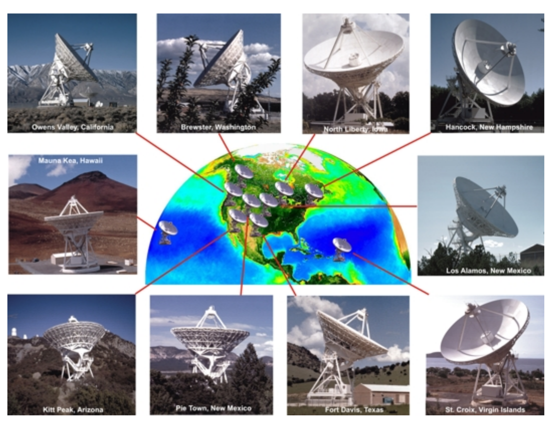

Fig.3 VLBA (http://www.vlba.nrao.edu/)

- ■ Very-Long-Baseline-Array (VLBA)
- ■ Apr/8, 18/ 2010
- ■ 2 times 12 hours
- ■ Simultaneous observations at 2, 5, 8, 15, 22, and 43 GHz
- ■Astrometry relative to the nearby position reference source M84 (1.5°separated). Since M84 also has its own core-shift in the north, we extracted the east-west contributions of the core-shift of M87 jet.

Results (Hada et al. Nature 2011)

✸The core-shift of M87 is clearly detected (Fig. 4), demonstrating that the core of M87 is τ_{SSA}∼1 surface, not the standing shock feature.

✸Based on the trend of the core-shift, the significant shift is less likely at higher than 43GHz, indicating that the central engine resides in the immediate vicinity of the 43GHz core.

✸The weighted least square fitting was made with the power law $r(\nu) \propto \nu^{-\alpha}$. **We found that the core-shift converges to (41±12)μas east side of the 43GHz core (equivalent to the projected distance of 6±2 R_s)**

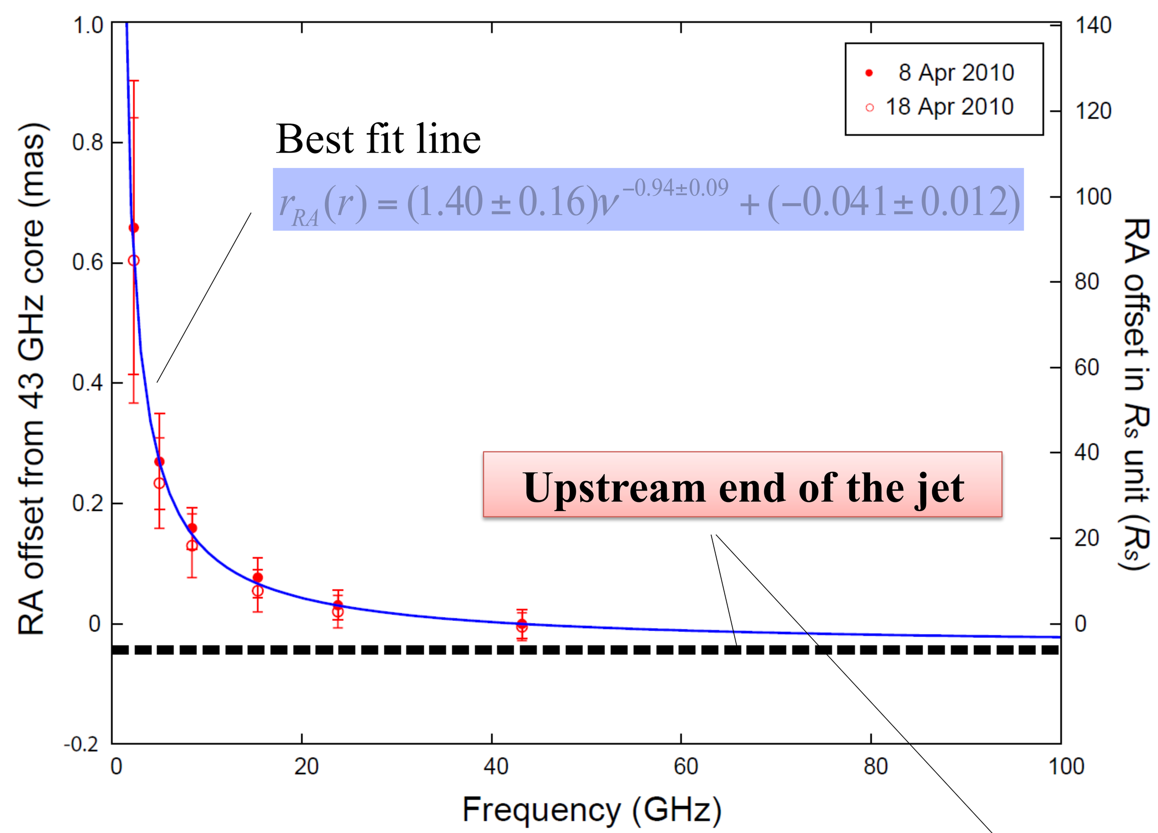

Fig.4 Measured core positions of M87 as a function of frequency (in R.A. direction).

✸The measured frequency dependence ∼ν^{-1} is consistent with the conical shape jet with the radial profiles of the magnetic field and the electron density as r^{-1} and r^{-2} (Konigl 1981). Then the dashed line in Fig.4 corresponds to the 'vertex' of the cone. If the jet of M87 starts up with a wider opening angle than the core near the origin, the location of the central engine is likely to be even a bit closer to the 43GHz core than the dashed line.

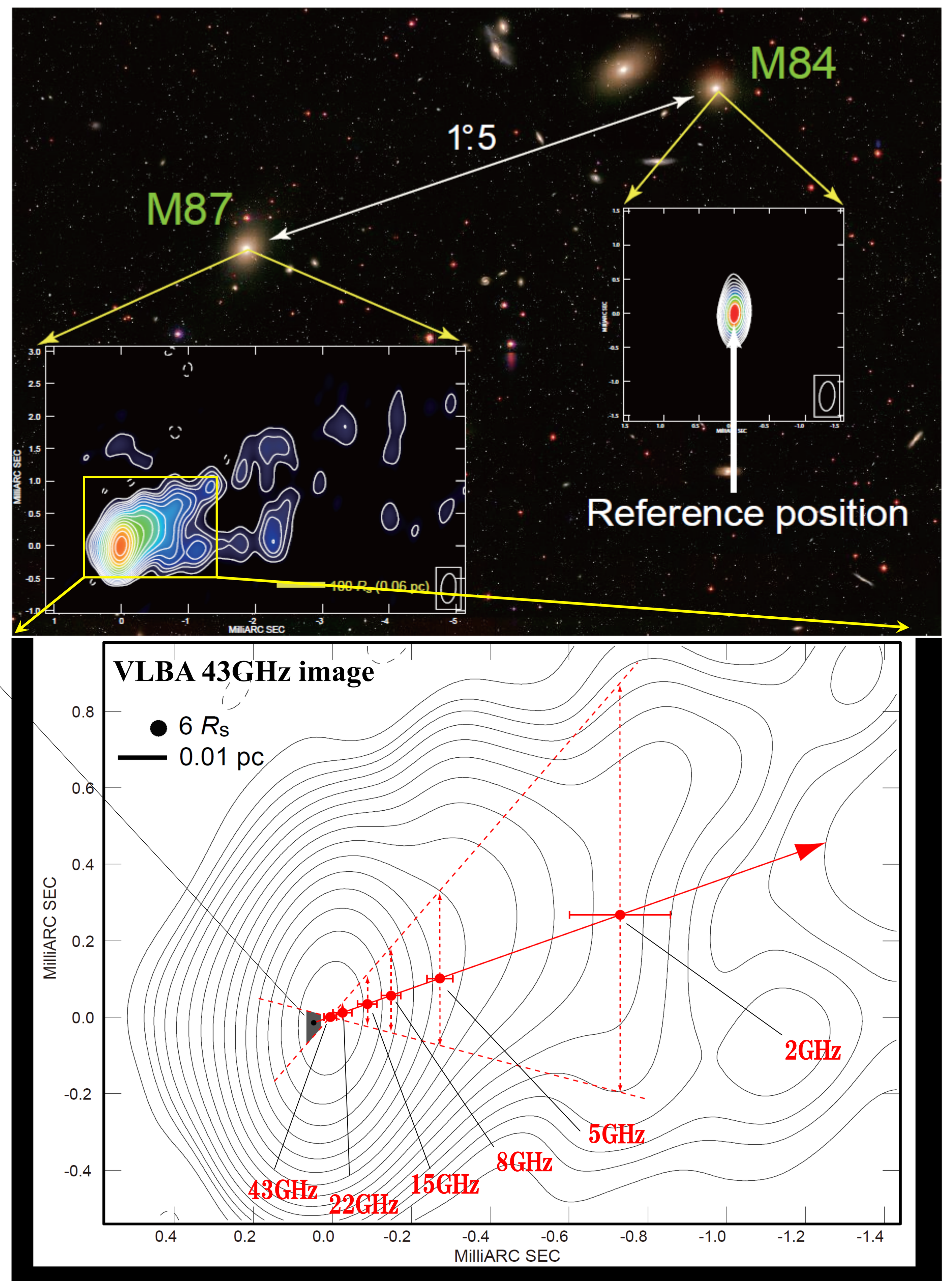

Fig.6 Schematic picture of this work. (Upper panel) Radio core position of M87 at each frequency was measured with respect to the core of M84. (Lower panel) The upstream end of the jet corresponding to the dashed line in Fig.4 is overlaid on the 43-GHz image as the shaded area. Each red point indicates the measured core position at each frequency. Tow broken red lines represent the maximum uncertainty range of the core-shift direction. The synthesized beam is 0.22mas×0.46mas at a position angle of -5°

Discussion

■The de-projected separation between the central engine and 43GHz core results in 14-23R_s(0.007-0.01pc) or smaller if the jet opens up faster (in the case of the viewing angle 15-25°)

■**Much smaller separation than the case of blazars such as BL Lac and PKS 1510-089, for which the central engines are on the order of $10^{4\text{-}6}R_s$ offset from the emission region (Marscher et al. 2008,2010).**

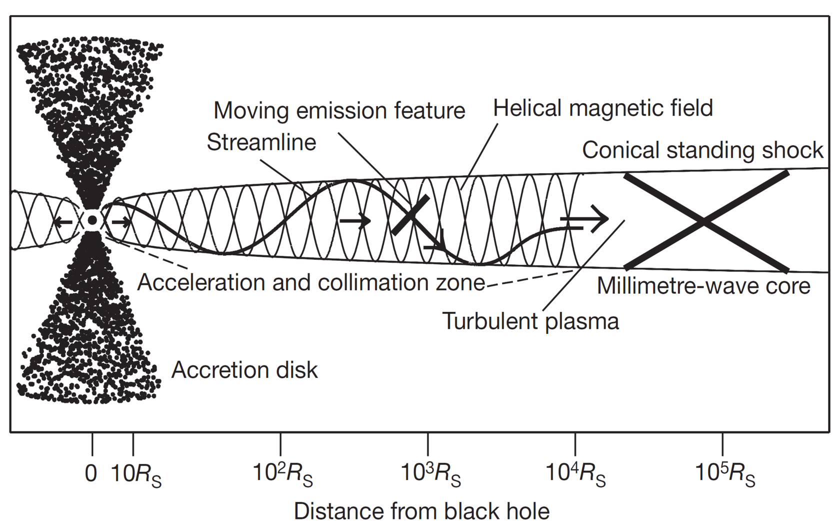

Fig.5 Model of the inner jet of the BL Lac proposed by Marscher et al. 2008

■ This significant discrepancy could be due to the detailed internal structure such as faster spine surrounded by the slower outer layer. Based on this scenario, the core of a blazar is dominated by the spine part propagating further down the jet. In contrast, the core of a radio galaxy, whose jet axis is offset from the observer, originates in the layer part closer to the black hole.