THE RELATIVE PROPER MOTION OF THE VIRGO CLUSTER GALAXIES M87 AND M84

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M87 43 GHz Project

• Primary goal to study jet dynamics in M87
• M87 has a $6 \times 10^9$ solar mass black hole
• In Virgo Cluster at 16.7 Mpc.
• VLBA 43 GHz resolution reaches $\sim 30 \, R_s$
• Goal: Constrain jet launch models
• Each epoch included 18-40 scans on M84 for phase referencing between it and M87 – separation 1.5 deg
• Since March 2008, geodetic segments included for atmospheric calibration
THE VLBA 43 GHz M87/M84 OBSERVATIONS

• 2001: Rapid phase referencing to image M84 (too fast).
• 2004: M84 long track imaging. Occasional M87 scan.
• 2007: 18 Observations at 3 week intervals for movie.
  – Undersampled. Not all processing finished.
• 2008: 14 Observations at 5 day intervals in early 2008
  – Major flare seen coinciding with a TeV flare.
• 2009-2015: Prepared to respond to TeV or γ-ray trigger
  – 1 or 2 background observations each year
  – Triggered 5 additional observations in 2010 but no flare
• Since 2007 there have been 15-40 M84 scans per epoch
M87 STRUCTURE OVERVIEW

1 kpc scale

Distance: 16.7 Mpc (Mei 2007; Bird 2010)
**MORPHOLOGY**

**M87**
43 GHz VLBA

Edge brightened:
Suggests emission is from the surface or sheath

Wide base: Collimation region

Counterjet: Real – in all images. Seen by others.
Fades fast: Beaming + Acceleration?

Average of 23 images
VLBA 2007, 2008, 43 GHz
Before upgrade; 256 Mbps
Average smooths changing features – like time exposure of a waterfall

1 mas = 0.08 pc = 140 $R_s$
Resolution: 0.43x0.21 mas
KINEMATICS: VLBA 43 GHz M87 MOVIE

Beam
0.43x0.21 mas
0.2mas
= 0.016pc
= 28R_s
1mas/yr = 0.25c

Motions about
0.5 mas per 21 days - ~ 2c

“Smoke plume”
VLBA 43 GHz
Jan 12, 2013
New 2 Gbps system

Beam $0.215 \times 0.158 \text{ mas}$
$\cong 30 \times 22 \, R_s$
Uniform weight plus 30% superresolution in N-S direction.

Shows wide base
Details quite disturbed
Structure symmetric between jet and counterjet
Slightly shorter on counterjet side as might be expected
IS RADIO CORE AT THE BLACK HOLE?

- Some blazars appear to have large offsets ($\sim 10^5 R_s$) (cf BLLac - Marscher)
- M87 is weaker and probably at a higher angle to the line-of-sight, with less beaming
- Astrometry during a 2008 flare showed limited position change of about 50 $\mu$as or about 7 $R_s$ (Unlikely if far down jet).
- Hada et al. (2011) showed the expected opacity effect for jet expanding from core – estimate offset 14-23 $R_s$
M84=NGC4374=3C272.1

Classical FR I – Distance 18.5 Mpc


Compact core about 50 mJy at 43 GHz

Jets nearly perpendicular to M87 jet 1.49° from M87.
ASTROMETRIC CALIBRATION

- **Ionsosphere** corrections with global GPS models (TECOR)
- **UT and pole position** corrections with updated EOP file.
- **Atmospheric delay** corrections based on fringe rate until March 2008 (“rate DELZN”).
- **Atmospheric delay** and clock corrections based geodetic segments after March 2008 (based on delay DELZN).
- **M87 position**: Gaussian fit to peak (JMFIT)
- **M84 position**: Fit to phase referenced UV data (UVFIT)
- **Offsets from average** position for obtained for each epoch for each source
- **Final offset** is the M84 offset minus the M87 offset.
- **Errors** estimated from scatter of 2007 (rate DELZN) and 2010 (delay DELZN) data
M84 – M87
Relative Positions vs Time

- Top along PA 39° Bottom along PA -51°
- Fit result:
  - $8.18 \pm 0.94 \, \mu\text{as/yr} = 717 \pm 82 \, \text{km/s at M84}$
  - $648 \pm 74 \, \text{km/s at M87}$
- First 6 points in 2008 (flare) not included in fit or plot
M84 – M87
Relative
Positions

All points shown
Deviant southeast
points are during flare.
Not used in fit.

Ellipse is beam.
Dashed line is fitted
motion.

Scale is 100 μas =
0.0081 pc = 1670 au
NEW FEATURE AT CORE

A: Average of 2007 images
B: April 5 2008 image
C-F: 2008 difference images
   The 2007 average subtracted

During a significant flare
   Core brightened
   New feature
   TeV flare (at end of talk)

New feature speed ~0.4 c
   Significantly slower than
   The jet further out

Suggests the jet is still
   accelerating at 100 Rs
M84 – M87 Relative Position During 2008 Flare

- Top PA 108°
  - If motion is in M87, shows along jet.
- Indicates centroid of core displaced along jet at start of flare.
- Centroid returns to normal position (fit line) as component separates.

M84 – M87 Relative Position vs Time

PA 108.0 Offset (µas)

PA 18.0 Offset (µas)

Date (year)

Nov. 6, 2015
Other Information on M84 motion

  - XMM_Newton data with others
  - Stripping plume to south – roughly consistent with our data.

- Literature search still needed.
SUMMARY

- Relative proper motion detected between M84 and M87
  - $8.18 \pm 0.94 \mu\text{as/yr}$
  - $717 \pm 82$ km/s at M84
  - Position angle 39°
- Sky separation $1.49° = 0.434\text{Mpc}$ at M87
- Radial distance separation based on surface brightness fluctuation method: $18.5-16.7 = 1.8\text{ Mpc}$
- Systemic velocities M87: 1284 km/s
  M84: 1017 km/s
  Diff: 267 km/s (NED)
- Virgo Cluster radial velocity dispersion: 699 km/s.
WHY M87?

- **THE BEST SOURCE FOR IMAGING A JET BASE**

  - Large angular size black hole
    - Nearby: 16.7 Mpc (Virgo Cluster: Mei 2007; Bird 2010)
      - 1mas = 0.081 pc = 16700 au; 1 c = 3.8 mas/yr
    - Massive: 6.2 X 10^9 M☉ (Gebhardt et all. 2011 scaled for distance)
      - Caution – the mass is controversial
    - Scale: R_s = 7.2 μas = 120 au (R_s = 2GM/c^2 = 2R_g)
      - VLBA 43 GHz resolution; 210 X 430 μas ≈ 30 X 60 R_s

- **Bright jet** with complex observable structure
  - 43 GHz Peak ~0.7 Jy – can self-calibrate VLBI data
  - Resolved transversely very near core – uncommon for VLBI jets
  - Easy to observe with northern hemisphere instruments

- Well studied at all wavelengths from radio to TeV
- Other candidates have no jet (SgrA*) or smaller black hole (CenA)
M87 in Jan. 2013

CHANGE IN JET ENVELOPE

- Blink comparison of 2007/8 average and 2013
- Significant changes in overall jet structure and position
  - Hardee looking at implications for stability
  - We will investigate further with nearly annual observations since 1999

1 mas = 0.08 pc = 140 R_s
KINEMATICS: VLBI SUBLUMINAL MOTION MEASUREMENTS

- Many VLBI observations show slow motions
  - VLBA < 0.1c (Biretta & Junor 1995; Junor & Biretta 1995)
  - VSOP No motions (Dodson et al 2006)
  - VLBI 1.6 GHz 0.28c (Reid et al 1989)
  - VLBA 43 GHz 0.25-0.40c (Ly et al 2007)

- Perhaps best case is 15 GHz monitoring (Kovalev et al. 2007)
  - A few percent of the speed of light
  - Sampling interval 5±3 months

- Slow material or is it patterns, perhaps from instabilities?
KINEMATICS: SUPERLUMINAL MOTIONS

- VLA Typical 0.5 c, but up to 2.5c (Biretta et al 1995)
- HST-1 Optical with HST (Biretta et al 1999)
  - Knot at 0.9” (70pc projected) Speeds ~5-6 c
- HST-1 VLBA 20cm (Cheung et al 2007; Giroletti et al. 2012)
  - Downstream component speeds 2.5 - 4.5 c.
  - Feature near core slow
  - HST-1 Plausible site for TEV emission
- EVN Possible acceleration from 160 mas to HST1 (Asada et al)
- HST1 superluminal motions suggest a fast core
TeV FLARES

- Location of TeV emission not known
- TeV and 43 GHz VLBI flares at same time in 2008 - suggests TeV in core
- But no 43 GHz with 2010 TeV flare
- Possible activity at HST1
  - Giroletti et al 2012 A&A
  - Weak core flare? Hada et al 2012