A VLBA movie of the jet launch region in M87

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Abstract. M87 has one of the largest angular size black holes known. It also has a bright jet that is well resolved across the jet near the core using high frequency VLBI. As such it is the best object to observe to study the launch region of jets where the physical sizes of structures of interest scale with the gravitational radius. Modern numerical simulations suggest that the jet formation extends over $\Delta R_s$. M87 has been observed with a resolution of about $\Delta R_s$ at 43 GHz with the VLBA every 3 weeks through 2007, and every 5 days between January and April 2008. A preliminary movie, made from the first 11 observations in 2007, shows fast ($\sim c$) and complex motions in an edge brightened structure with a wide opening angle at the base.

1. Introduction

Most compact astronomical objects are capable of producing jets. The mechanism for jet production must therefore be a generic consequence of the accretion of material onto such objects. That mechanism is not firmly established, but there has been considerable theoretical progress, especially through numerical simulation, in recent years [1, 2, 3]. It appears that magnetized material that accretes onto a compact object naturally sets up the ordered magnetic structures along which material from a disk wind or corona is accelerated and collimated. The innermost fields can also carry energy in the form of Poynting flux. The acceleration and collimation takes place over a region of up to several hundred gravitational radii. Within that region, the structure of the jet is likely to be somewhat different from what is seen on larger scales. The base of the jet may have a larger opening angle than is seen after collimation is complete. Apparent velocities should be slower where the acceleration is still occurring. And there may be distinctive collimation structures at certain characteristic size scales. Some new observational evidence for this picture has been provided by simultaneous X-ray, optical, and high-resolution radio observations of BL Lac [4]. Observations of the detailed structure and dynamics of a jet in the acceleration and collimation region could provide valuable constraints on jet models.

The compact objects that produce relativistic jets are extremely small so the resolution required to reach the region of hundreds or less gravitational radii is very high. Indeed, for objects of a few stellar masses, even nearby in the Galaxy, the required resolution is far beyond the reach of current imaging instruments. The situation is better for the far more massive black holes in the centers of galaxies. Their high mass more than makes up for the added distance. For the black hole in the center of the Galaxy, and for a few of the most massive black holes in nearby galaxies, the Schwarzschild radius ($R_s = 2GM/c^2$) is a few micro-arcseconds so the
resolution required to start to see the collimation region is a few hundred micro-arcseconds. Such resolutions can be obtained with Very Long Baseline Interferometry (VLBI) at the highest available radio frequencies. But there is an additional requirement — the object must have a jet that is bright enough in the radio to allow detailed imaging with VLBI, preferably with good cross-jet resolution. The Galactic Center source, Sgr A*, does not have a detected jet. Other nearby galaxies either don’t have bright jets, or have smaller black holes so the available resolution is inadequate. The one good exception is M87. M87 has a super-massive black hole with a mass of about $3 \times 10^9 M_\odot$ [3, 6, 7] and, as the dominant galaxy of the Virgo Cluster, has a distance of only 16 Mpc [8, 9]. For these parameters, the Schwarzschild radius of about 60 AU subtends 3.7 microarcseconds so the VLBI resolution is just adequate. M87 also has a bright radio jet with significant structure that can be imaged with high-frequency VLBI.

On sub-parsec scales, the M87 jet has a wide opening angle in the first few tenths of a milli-arcsecond (mas) after which it is much more tightly collimated and strongly edge brightened [10]. The wide opening angle suggests that the collimation region is beginning to be resolved. The jet has been the target of many VLBI observations over a range of frequencies (see [11, 12, 13, 14] and references therein for the higher frequency data). For most cases where multi-epoch, high-resolution, observations allowed the measurement of motions, speeds of significantly less than the speed of light were reported. Perhaps the best case is the recent work at 15 GHz where features are less than a few percent of the speed of light [12]. At lower resolution, farther from the core, superluminal motions of several times the speed-of-light have been seen in both the optical and radio. A clear example is the HST-1 knot at about 0.9 arcseconds from the core where a speed of 4c is seen in the radio [15] and 6c is seen in the optical [16]. A serious concern for the high-resolution observations is that, because the source is so close, sampling on time scales of a few days would be required to avoid undersampling fast motions. Such fast sampling had not been done.

Here we report on an intensive effort to study the motions in M87 at high resolution with adequate sampling. All of the observations were made using the Very Long Baseline Array (VLBA) [17] at 43 GHz. Higher resolution could have been obtained using 86 GHz or a global array, but the imaging difficulties and practical scheduling constraints make any such project far more difficult. Our project began with observations designed to determine the rates of motions in the source so that the appropriate frame rate for a movie could be specified. That was followed by observations at regular intervals from which movies can be made to study the source dynamics.

For the declination of M87 ($12^\circ$), the typical resolution of the VLBA at 43 GHz of $0.4 \times 0.2$ mas (elongated north-south which is across the jet) corresponds to 110 by 54 R_s or 0.031 by 0.015 pc. Note that distance along the jet is foreshortened if the jet is near the line-of-sight as suggested by the observation of superluminal motions. For example, in order to see motions of 6c, the angle to the line-of-sight is likely to be less than about $15^\circ$, giving foreshortening by a factor of at least 4. The maximum angle to the line-of-sight is higher for lower speeds. Other possible explanations for the observed superluminal motions might allow the overall jet to be at a larger angle to the line-of-sight, but it is unlikely that projection effects are negligible.

This contribution is very similar to a previous report by the same authors at a meeting concerned with space VLBI and the VSOP2 project [18]. The processed data available at the two meetings was the same. The publication format here allows the inclusion of color figures and an animation that are not available with the previous publication.

2. Observations
Our original effort to study the dynamics of the inner jet in M87 was based on 5 VLBA observations spaced at intervals of about a year. These were a combination of early targeted observations and observations in which M87 was used as a phase reference source for observations
of other weak sources in the Virgo Cluster. Some of the data were our own and some were from the VLBA archive. These data were reprocessed in a uniform manner and examined for indications of structural evolution [13]. The general character of the structure was consistent from epoch to epoch. But it was only possible to identify possibly related components in more than one image by using the two most closely spaced observations. If those components really were related, apparent speeds of 0.25c to 0.40c were seen. But for any higher speeds, the motions would have been so large that it would have been impossible to identify components at more than one epoch. Components moving at apparent speeds of more than the speed of light, as seen elsewhere in M87 and other sources, would not have been identified.

The images from the last 3 epochs of the archival data project showed emission on the opposite side of the “core”, or brightest feature, from the main jet. That feature was also seen in the 15 GHz observations of ref. [12] who see it extending to about 3 mas from the core. For that project, blind tests were done to confirm that the counter-feature was not an imaging artifact. There are two main options for the nature of the counter-feature. It could be the counter-jet that is expected to be there, but is likely normally hidden by Doppler boosting. Or it could be the inner jet if the location of the black hole is actually well to the east of the brightest component. The latter could be the case if the brightest feature is a shock or other structure where the jet first turns on in the radio. But the greater than 3 mas (800 R_s in projection) offset may be too large for this option. Also, although the structure of the counter-feature is not well determined, it appears to get wider with distance from the bright feature, contrary to expectations for an inner jet. If the counter-feature is the far side jet of a symmetric system, and a speed and brightness ratio can be determined, it can give strong evidence for the true speed and orientation to the line-of-sight of the jet, a possibility explored in [13].

In order to address the possible problem with under-sampling of fast motions, a project to make a fully sampled VLBA movie at 43 GHz was begun. But none of the data available at the time gave good clues of what the frame rate of the movie should be. So the first step was to do a pilot project in 2006 during which intervals of between 3 and 97 days were sampled. The images made from data taken 3 days apart looked very similar, confirming that the imaging capability of the array was adequate to look for changes that aren’t just artifacts. The structures that were seen at multiple epochs appeared to be moving at rates of between 1.5 and 2.2 mas yr^{-1} (0.4c to 0.6c). Based on this result, a proposal was made requesting observations every 3 weeks for a year.

The movie observations began on 2007 January 27 and lasted through January 2008 as requested. The first 11 observations were reduced quickly in so that preliminary results could influence any proposal that might be made for follow-up observations that would made immediately following the movie project. Images from those 11 observations are shown in Figure 1 and are assembled into an animation that is available with the on-line version of this publication. The source maintains the same generic appearance throughout the observations, although details of the lumpy structure vary. The structure is always distinctly edge brightened, although there is emission filling in the central region. Such a structure would be consistent with a 3D system with a sheath that is observed surrounding a central spine that is dark, either because it is more relativistic and we are outside the beaming cone or because it simply is not emitting in the radio. The counter-feature is always present, although its structure varies in ways that are not yet clear. In some of the epochs, there appears to be a central spine in the main jet. The jet does not lend itself easily to a description in terms of a series of moving “components”. Some features do seem to appear in multiple images, but no very clearly defined features persist for many epochs. To improve the sensitivity to weak structures and to bring out the persistent aspects of the structure, a weighted average image was made from the first 9 epochs and is shown in Figure 2. Note that any detailed, changing structure is washed out in the average.
Figure 1. A montage of the VLBA images from the first 11 epochs the M87 movie project. The resolution (beam) is $0.43 \times 0.21$ mas elongated along position angle $-16^\circ$ as shown by the labeled cross. Each image covers a region of 8.7 by 4.6 mas. See the electronic version for an animation of this image.
Figure 2. A composite VLBA image of M87 at 43 GHz made by summing the images from the first 9 epochs of the movie project. The resolution is 0.43 × 0.21 mas elongated along position angle −16°. The image peak is 643 mJy beam$^{-1}$ and the off-source rms is 0.18 mJy beam$^{-1}$. Because this image is the sum of several images made at different times, individual features will be blurred out and the jet will appear smoother than it actually is, much like what is seen in a long-exposure photograph of moving water. If the images are examined in a static display such as the montage shown in Figure 1, the motions are not immediately apparent. But when assembled as a movie and played reasonably fast, it is clear that there is an overall fast, outward motion. It is something like watching a smoke plume that is moving in bulk, but also has rapid evolution of its internal structure. It is highly recommended to access the animation associated with this publication to experience this effect. Other animations and results are available at http://www.aoc.nrao.edu/~cwalker/M87. That website will be updated as more epochs become available.

The movie of M87 shows fast motions, motions that are significantly faster than were deduced from the pilot project. Even a re-examination of the pilot project images, knowing what was seen in the movie, fails to show significant evidence for the fast motions. It seems that a movie with many frames is needed to see the motions in the presence of the other rapid changes in structure. In order to quantify the speed in the presence of changing structure, adjacent epochs were blink compared and the changes of position of apparently related features were measured. This was done for all adjacent pairs of epochs. Such differences consistently came out to be about 0.5 mas indicating a speed of about 9 mas yr$^{-1}$ or about 2c. This is much faster than motions seen in other VLBI observations of the inner regions of this source, but those observations could not have measured such speeds because of undersampling. In fact, even the year-long movie project with 3 week intervals is undersampled because the motion is about 2.5 times the beam width per epoch.

As a result of the determination that the speed of the jet was fast enough that the movie
observations were undersampled, a proposal was made to extend the sequence with 10 additional observations at 5 day intervals. That sequence was ultimately extended to 14 observations because of problems encountered during the sequence. The reduction of those data is in progress as this is written, and the fast motions seen in the data presented here continue to be seen.

The M87 43 GHz movie project is a work in progress. More of the observations need to be reduced to finish the movies. The data were taken to allow polarization to be measured but that reduction has not yet been done. Preliminary indications suggest that polarization will only be detected on the core in the individual images. It is possible that more of the polarization structure will be determined by stacking images. The observations include short segments of phase referencing scans between M87 and M84 to allow their relative positions to be monitored. Normally it is assumed that the core position is stable and the individual epochs are aligned on that position. With these phase referencing observations, it will be possible to check for any significant variations in core position as might happen if the core is actually a shock or other structure well separated from the black hole. The relative position measurements will also be combined with results from earlier epochs, especially the one in 2001, to attempt to measure the relative proper motion of the two Virgo Cluster galaxies. Finally, our observations will be compared with observations made at other parts of the electro-magnetic spectrum to look for correlations.

3. Conclusions

Preliminary results from a VLBA movie with fast sampling and a resolution of about 60 $R_\bullet$ of the inner jet in M87 show a fast moving and rapidly evolving structure. The overall structure, including a wide opening angle at the core, a strongly edge brightened jet, and the presence of a weak feature opposite the core from the main jet, is consistent throughout the period of the observations. But the jet is not smooth and the movie shows that the features contributing to this lack of smoothness are rapidly evolving and are moving outward from the core at a speed of near 2c. This is in contrast to the far slower speeds measured by others in this source [12] near the core but on slightly larger scales than observed here. But this speed is slower than speeds seen near HST-1 and other regions far from the core. The previous high resolution observations would not have been sensitive to the fast motions seen here because of undersampling.

The fast motions seen here and the slower motions seen by others are not necessarily inconsistent. In fact, the fast motions seen in HST-1 are for components adjacent to another component that is basically stationary [16, 15]. This situation can happen if some “components” are actual density enhancements or other structures that are moving with the jet material and other “components” are shocks or instabilities through which the material travels, but that have their own, presumably slow, pattern speed. They could even be simple geometric effects, such as helical patterns, along which the jet travels and which give enhanced emission where the amount of material along the line-of-sight is enhanced by projection effects.

The feature on the side of the core away from the main jet continues to be present in all images. But its dynamics are still not clear. It is most likely the counter-jet, perhaps seen close to the core because it is slower and less strongly beamed there. But the possibility that it is the inner jet and the black hole is offset from the “core” has not been fully excluded. A measurement of the direction of motion in this feature would help determine its nature and might be possible once all the epochs from this project are reduced. Otherwise, very deep imaging to show the structure over larger scales may be required.

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References
[1] Hawley J F and Krolik J H 2006 Ap. J. 641 103
[2] McKinney J C 2006 MNRAS 368 1561
[3] Mizuno Y, Nishikawa K I, Koide S, Hardee P and Fishman G J 2006 Proc. of Sci. PoS(MQW6)045
[4] Marscher A P, Jorstad S G, D’Arcangelo F D, Smith P S, Williams G G, Larionov V M, Oh H, Olmstead A R, Aller M F, Aller H D, McHardy I M, Lähteenmäki A, Tornikoski M, Valtaoja E, Hagen-Thorn V A, Kopatskaya E N, Gear W K, Tosti G, Kurtanidze O, Nikolashvili M, Sigua L, Miller H R and Ryle W T 2008 Nature 452 966–969
[5] Harms R J, Ford H C, Tsvetanov Z I, Hartig G F, Dressel L L, Kriss G A, Bohlin R, Davidson A F, Margon B and Kochhar A K 1994 Ap. J. 435 L35–L38
[6] Macchetto F, Marconi A, Axon D J, Capetti A, Sparks W and Crane P 1997 Ap. J. 489 579
[7] Marconi A, Axon D J, Macchetto F D, Capetti A, Sparks W B and Crane P 1997 MNRAS 289 L21
[8] Whitmore B C, Sparks W B, Lucas R A, Macchetto F D and Biretta J A 1995 Ap. J. 454 L73
[9] Tony J L, Dressler A, Blakeslee J P, Ajhar E A, Fletcher A B, Luppino G A, Metzger M R and Moore C B 2001 Ap. J. 546 681
[10] Junor W, Biretta J A and Livio M 1999 Nature 401 891
[11] Dodson R, Edwards P G and Hirabayashi H 2006 PASJ 58 243
[12] Kovalev Y Y, Lister M L, Homan D C and Kellermann K I 2007 Ap. J. 668 L27
[13] Ly C, Walker R C and Junor W 2007 Ap. J. 660 200
[14] Krichbaum T P, Lee S S, Lobanov A P, Marscher A P and Gurwell M A 2008 Astronomical Society of the Pacific Conference Series (Astronomical Society of the Pacific Conference Series vol 386) ed T A Rector and D S De Young p 186
[15] Cheung C C, Harris D E and Stawarz L 2007 Ap. J. 663 L65
[16] Biretta J A, Sparks W B and Macchetto F 1999 Ap. J. 520 621
[17] Napier P J, Bagri D S, Clark B G, Rogers A E E, Romney J D, Thompson A R and Walker R C 1994 Proc. IEEE 82 658
[18] Walker R C, Ly C, Junor W and Hardee P E 2008 Astronomical Society of the Pacific Conference Series ed Y Hagiwara, et al (Preprint arXiv:0803.1837)