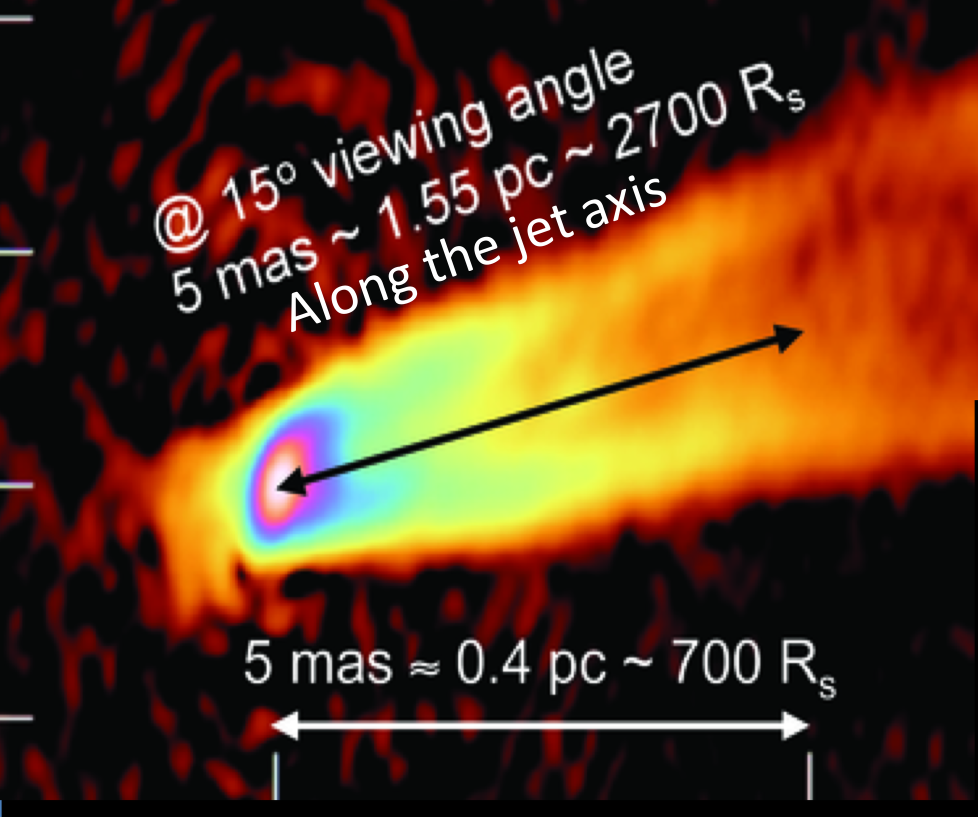
THE STRUCTURE AND DYNAMICS OF THE INNER PARSEC OF THE M87 JET

R. C. Walker (NRAO), P. E. Hardee (U. Alabama), F. Davies (MPIA), W. Junor (LANL), C. Ly (GSFC), F. Mertens (MPIfR), A. Lobanov (MPIfR)

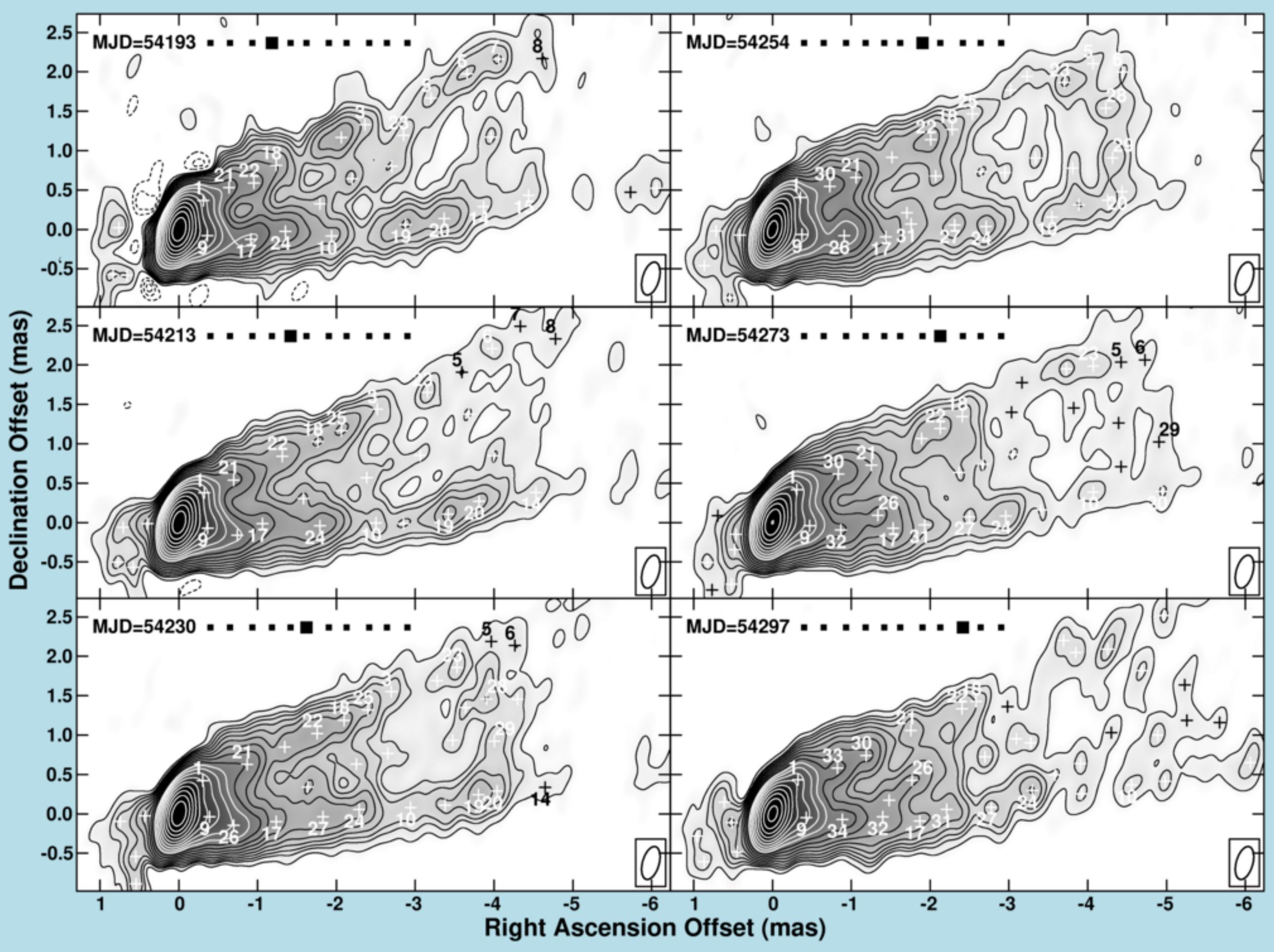


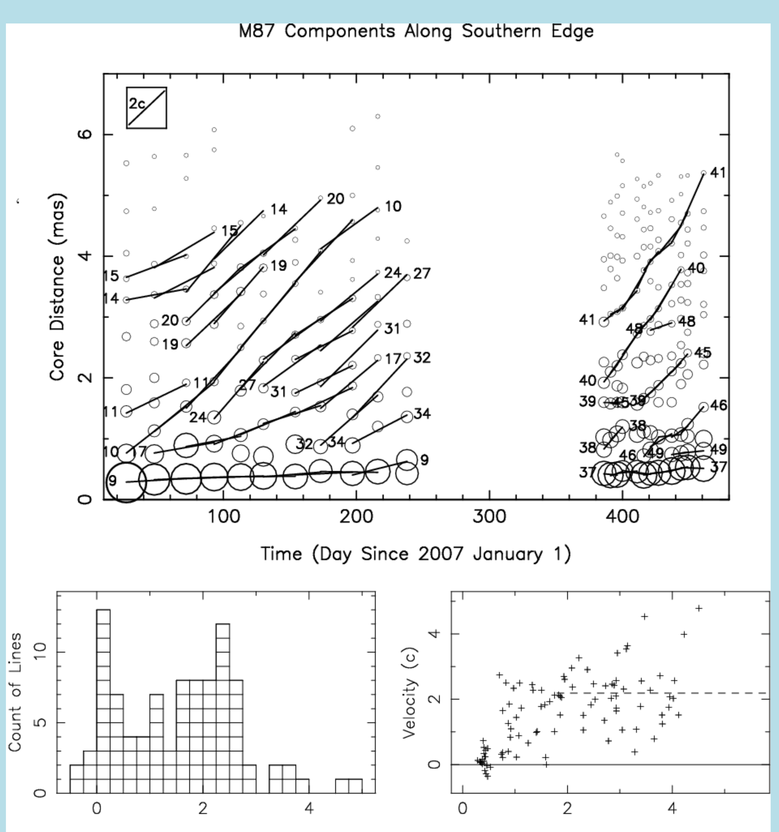
Beam 0.43 x 0.21 mas ~ 56 x 28 R_s

Abstract: M87 is both relatively nearby and has a very massive black hole. It also has a jet that is bright enough to allow detailed VLBI observations. This combination makes it the best target for attempts to study the jet base and launch region observationally.

We now have roughly annual observations with the VLBA at 43 GHz between 1999 and 2016, observations every 3 weeks during 2007, and observations every 5 days for a bit over 2 months in 2008. The jet has a wide opening angle base and is edge brightened right to the core. A counterjet, reflecting the structure of the jet, is seen, but drops rapidly in brightness with core distance. The jet structure is rapidly changing, making simple identification of long lasting components difficult. But a movie made from the 2007 data makes it very clear visually that there is rapid motion of the jet structures.

Various methods used to quantify the velocities show that apparent velocities between zero and about 2.5c are present, with evidence for acceleration near the core. The faster motions and acceleration are consistent, in a beaming model, with the brightness drop of the counterjet. In addition to motions along the jet, the roughly annual observations show that the whole jet moves side-to-side somewhat.



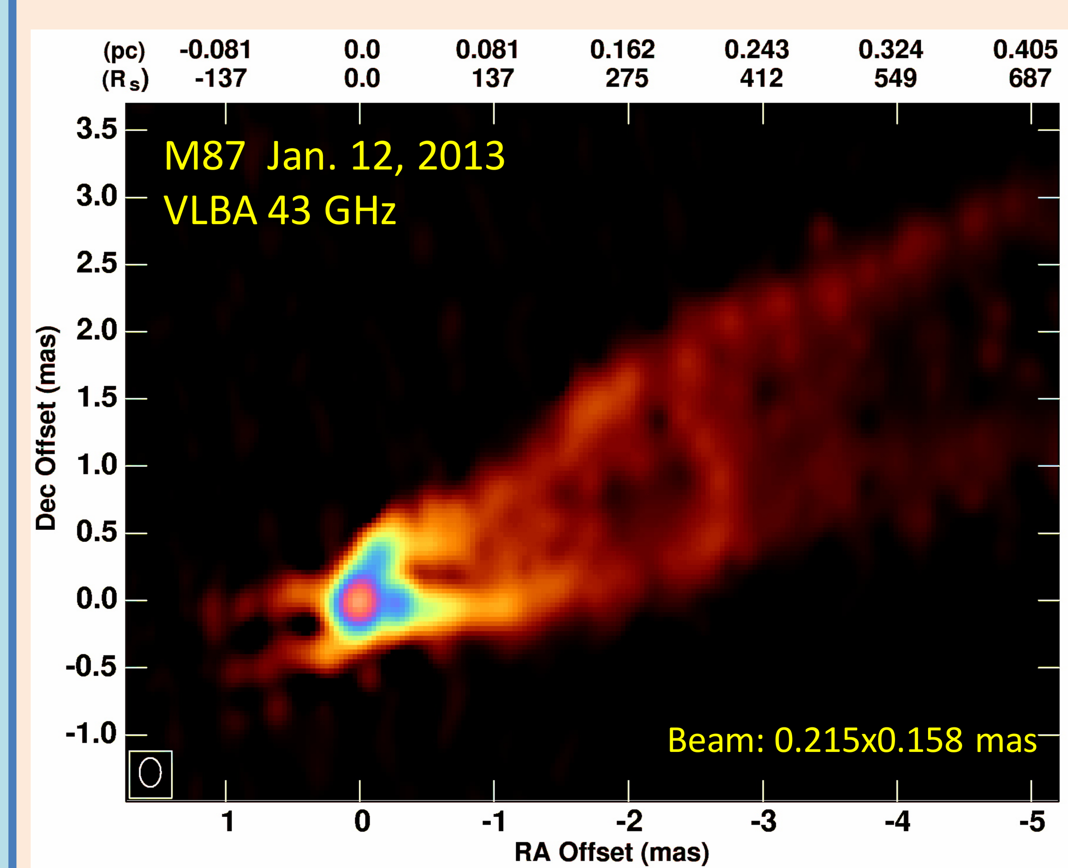


Jet Speed

See the 2007 movie at link above for the best visual impression of motion.

Classical method: Follow components in 2007 & 2008 data. Six sample images are shown above (of 23) with marked components. Crosses mark local maxima (by eye). Numbers mark traceable components determined by eye. Plot shows core distance for components on southern ridge. Speeds are from 3 point line fits for numbered components. Histogram of fit speeds has peaks near 0 and ~2.5c. Velocity vs distance plot suggests acceleration in the inner 2 mas.

The best way to appreciate the dynamics of M87 is to look at the movies. They cannot be shown here, but are available at: http://www.aoc.nrao.edu/~cwalker/M87

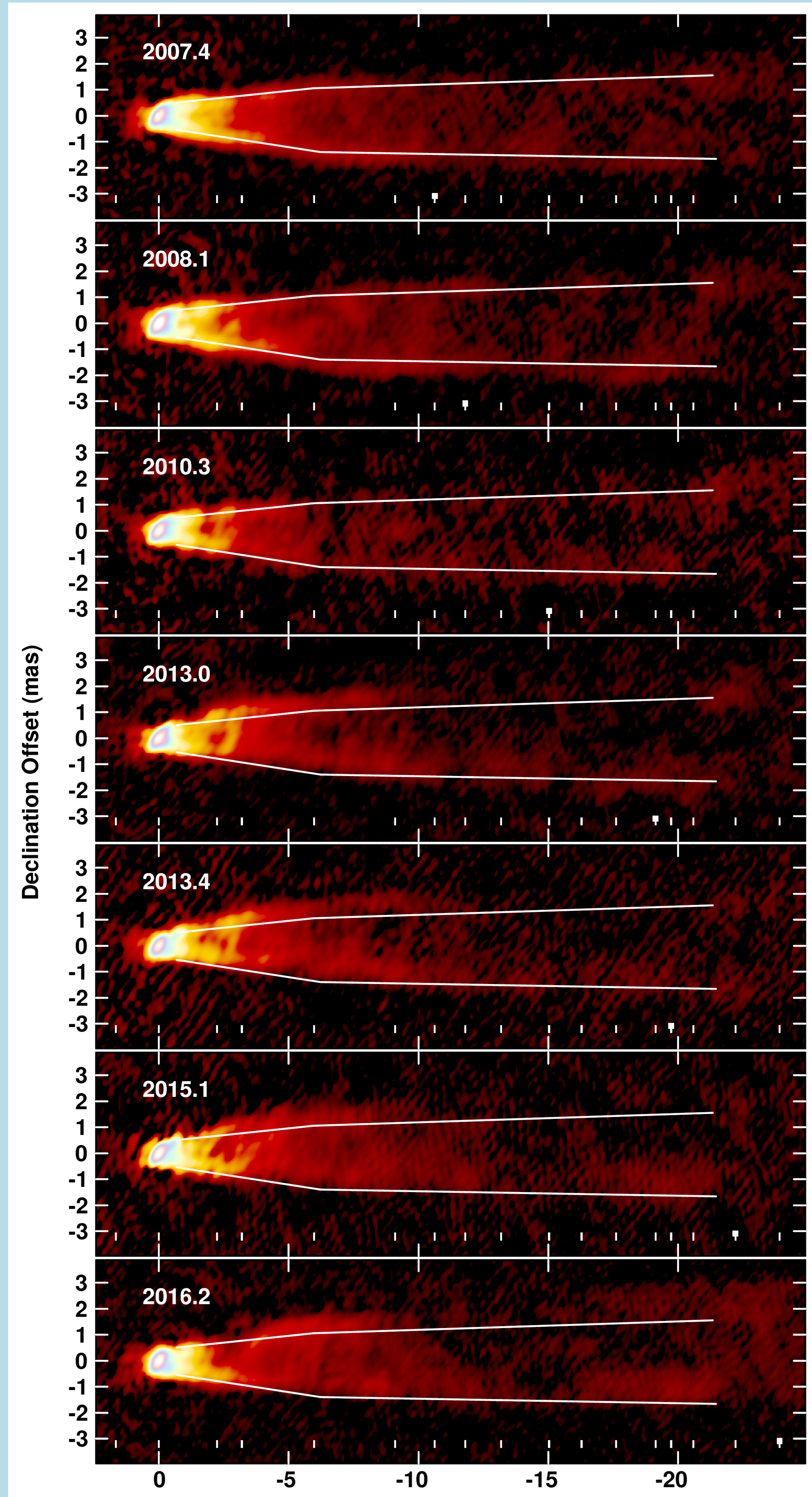


Counterjet & Inner Jet

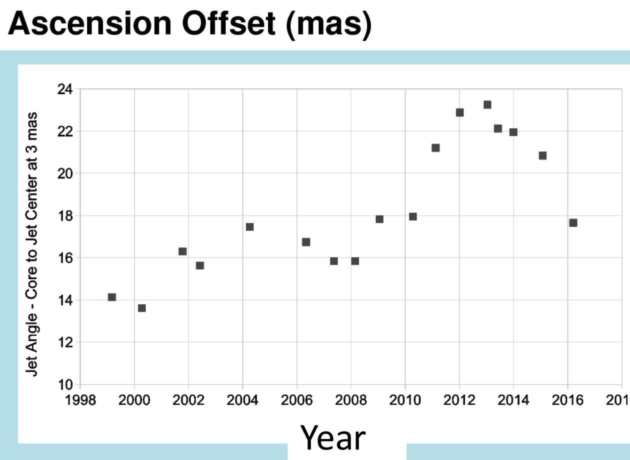
High resolution image made with uniform weighting and 30% superresolution in the N-S direction. Beam ≅ 30 x 22 R_s The shape is symmetric between the jet and the counterjet. Rapid counterjet brightness decay suggests acceleration.

Envelope Motion

Roughly annual observations for 17 years show that the jet moves sideways. The images below are a selection of the best annual images. Those from 2010 and before are stacks while the rest are based on wide-band data. They show a northward shift between 2007/8 and 2013 followed by a return toward the south. The lower plot shows the position angle from the core to the jet midpoint at 3 mas, showing this effect and hinting at a ~9 year cycle time. Such side-to side motions are likely the result of instabilities and are seen in some simulations (cf. Tchekhovskoy 2011, MNRAS, 418).

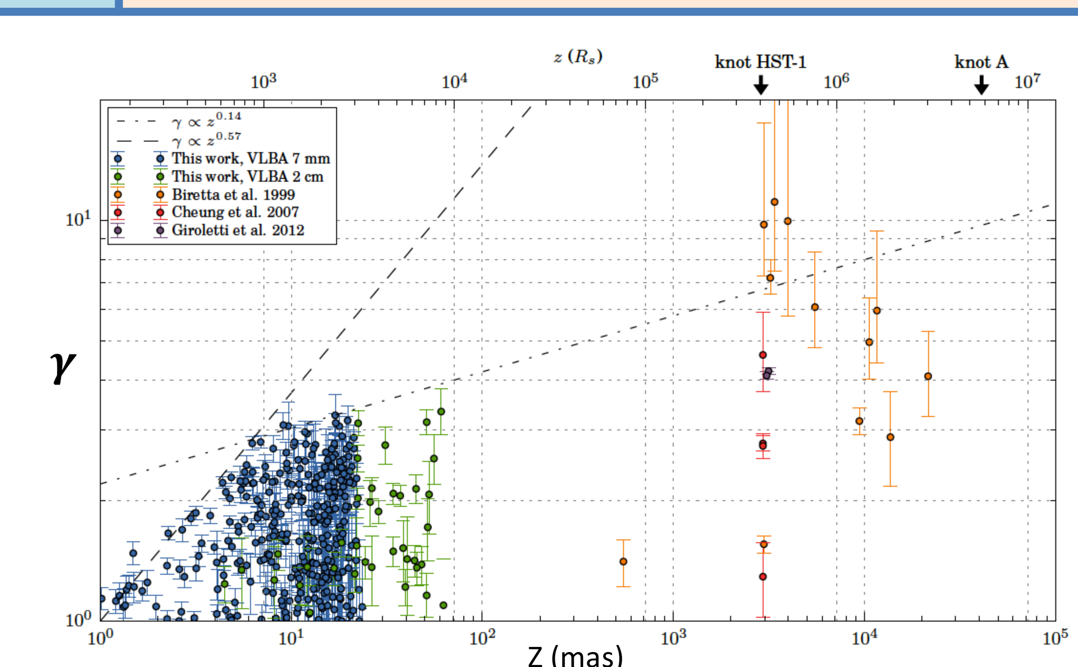


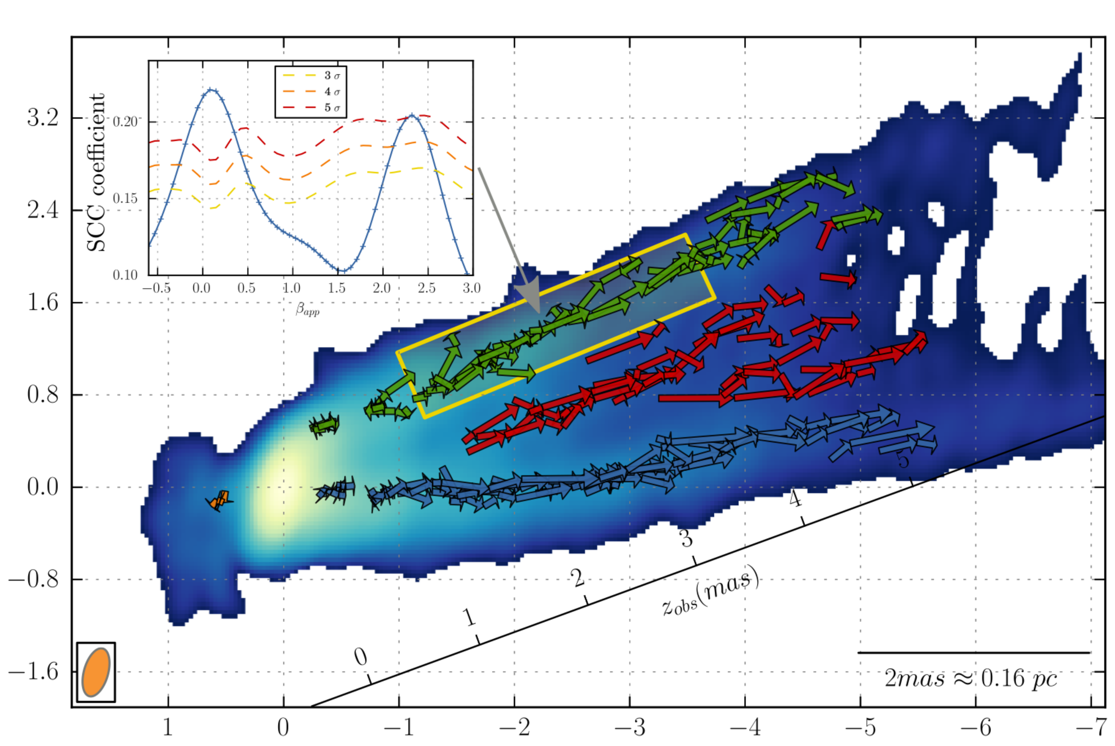
Position angle from core to jet center at 3 mas, 1999 to 2016 showing a possible oscillation.



Jet Speed, Stratification, and Acceleration

Method: WISE analysis (Wavelet-based Image Segmentation and Evaluation: Mertens and Lobanov 2015 A&A 574, A67). The 11 images at 43 GHz from 2007 were analyzed along with a few 15 GHz images from the MOJAVE project. For full M87 results and analysis, see Mertens, Lobanov, Walker, and Hardee, 2016, A&A, submitted. This work is based on Florent Merten's Thesis.



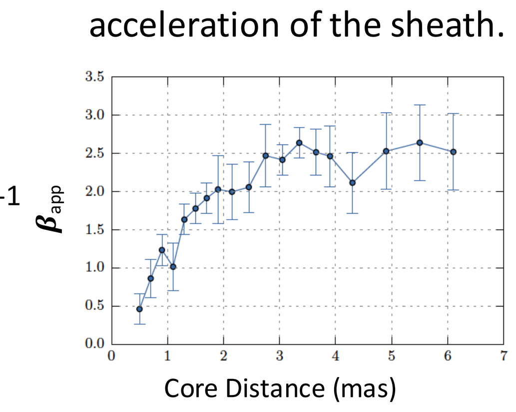


The plot above shows the WISE velocity field at 43 GHz and the two-peaked velocity distribution for the north ridge. The middle and south ridges show similar distributions.

Results from WISE analysis

- Viewing angle ~18° obtained from counterjet, jet rotation, and modeling of acceleration (3 methods)
- The jet collimation profile is parabolic ($r \propto z^{0.58}$)
- Multiple velocities and the edge brightened jet structure suggest stratification across jet with:
  - A slow instability pattern or outer wind (~0.4c)
  - A faster sheath (~2.5c)
  - An unseen, faster spine (perhaps ~6c)
- Acceleration region measured (sheath)
- N-S velocity difference suggests rotation Ω~10^{-6} s^{-1}
  - Suggests disk launch location at r_0 ~ 5 R_s
  - But BZ not excluded.
- MHD and Wind models produce good fits to the data. See Mertens et al, submitted.

Plots of the apparent velocity vs core distance. Above shows WISE results in the context of others over the full jet. Below emphasizes the acceleration of the sheath.



Most of these data will appear in Walker, Hardee, Davies, Ly, and Junor, 2016, in preparation.

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.