A VLA and VLBI study of extragalactic jets: connecting the parsec and kiloparsec scales

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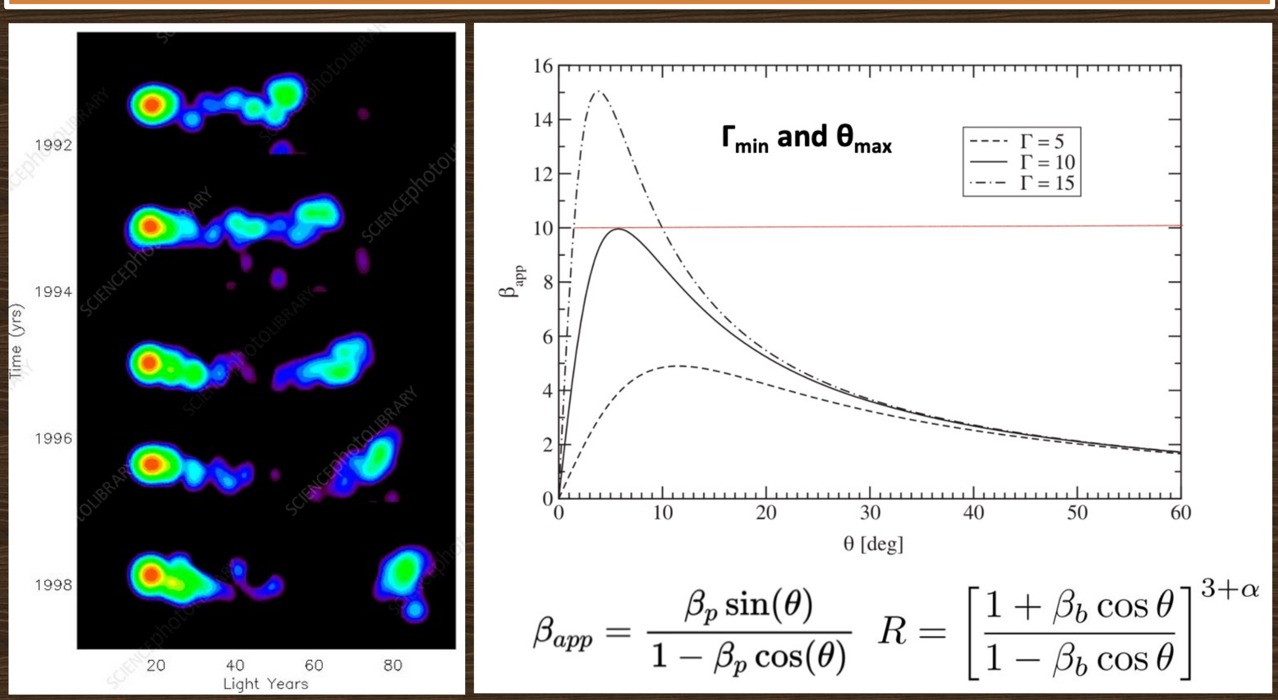
Abstract: Proper motions of extragalactic jets, primarily conducted with very long baseline interferometry (VLBI), have revealed that these jets have bulk relativistic velocities which can exceed 99.999% the speed of light (Lorentz factors up to ~80). The parsec-scale proper motions traced by VLBI observations, however, often show a flow that is still accelerating on these scales. The measurement of the full velocity profile of jets from parsec to kiloparsec scales has only been done for a handful of jets, owing to the difficulty of obtaining decades-long time baselines for comparison on the larger (kiloparsec) scales. The Very Large Array (VLA) has now been in operation for over 40 years, and the NRAO hosts a very rich archive of observations of extragalactic jets. I will present a new effort to mine the VLA archives to measure the proper motions of jet plasma on kilo-parsec scales, where I have analyzed archival VLA observations of radio galaxy 3C78 for proper motions where we detect for the first time proper motions for multiple knots with speeds of 0.1-0.4c. Although sub-luminal, we find that the maximum kiloparsec velocity (most suggestive of underlying bulk speed) is ~ 3 times higher than the maximum VLBI speed, in keeping with observations of M87 and 3C 264 which have showed that the fastest bulk speeds in these FR I jets are reached on the > 100 parsec scale, whose implications I will discuss. I will conclude with a discussion of the prospects for radio and sub-mm wavelength proper-motion studies of jets and the large catalog we intend to build using new and archival data.

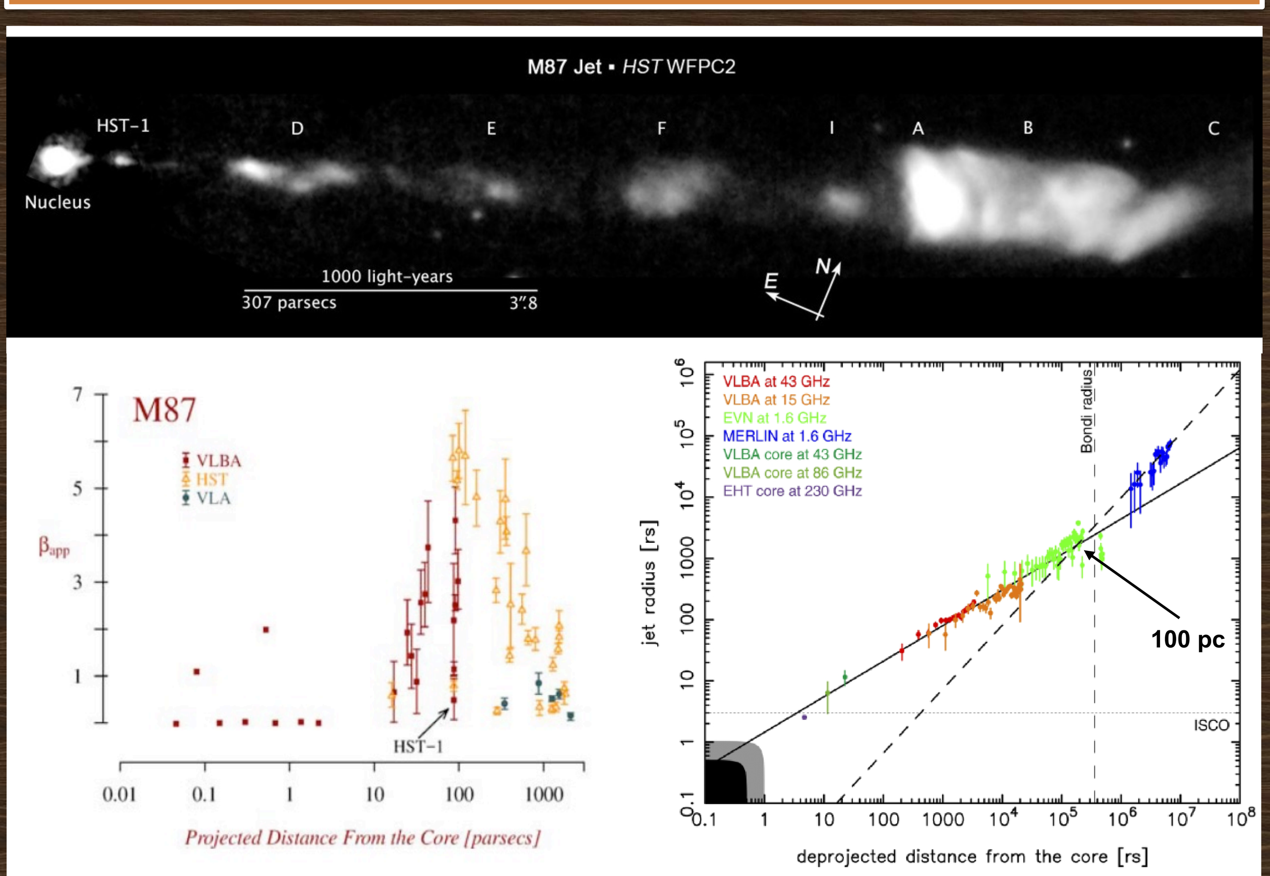
1. Proper motions of components in AGN jets



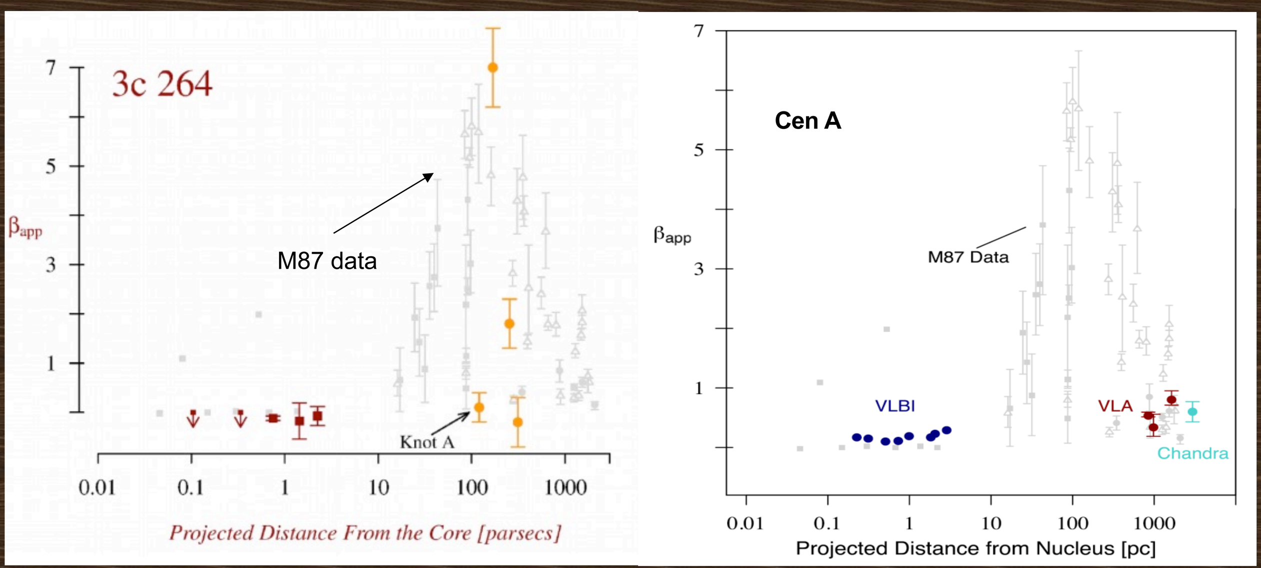
$$\beta_{app} = \frac{\beta_p \sin(\theta)}{1-\beta_p \cos(\theta)} \quad R = \left[\frac{1+\beta_b \cos\theta}{1-\beta_b\cos\theta}\right]^{3+\alpha}$$

Left: VLBI (parsec-scale) jet of 3C 279. Outermost component moving at ~5c. *Right*: Apparent speed versus angle to line-of-sight. Combination of apparent speed and jet-counterjet ratio provides model-independent constraints on jet energy content, which is influential in understanding how jets affect their environment and play a role in galaxy evolution.

2. Jet acceleration at 100 pc scales

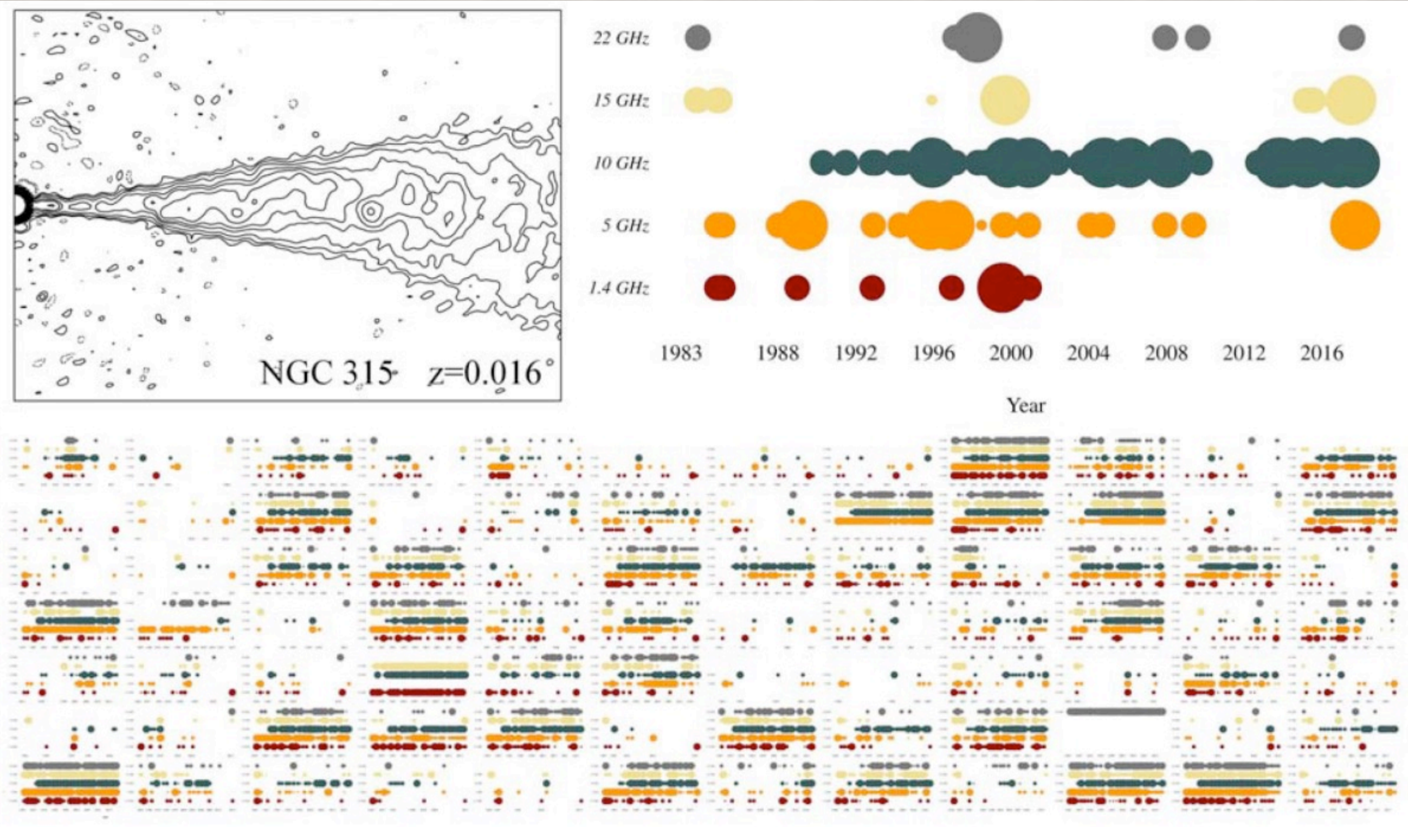


Left: Evidence of acceleration to superluminal speeds in the kpc-scale jet of M87. *Right*: Jet profile becomes steeper (changes from conic to parabolic) at HST-I, hence believed to be the site of a recollimation shock.



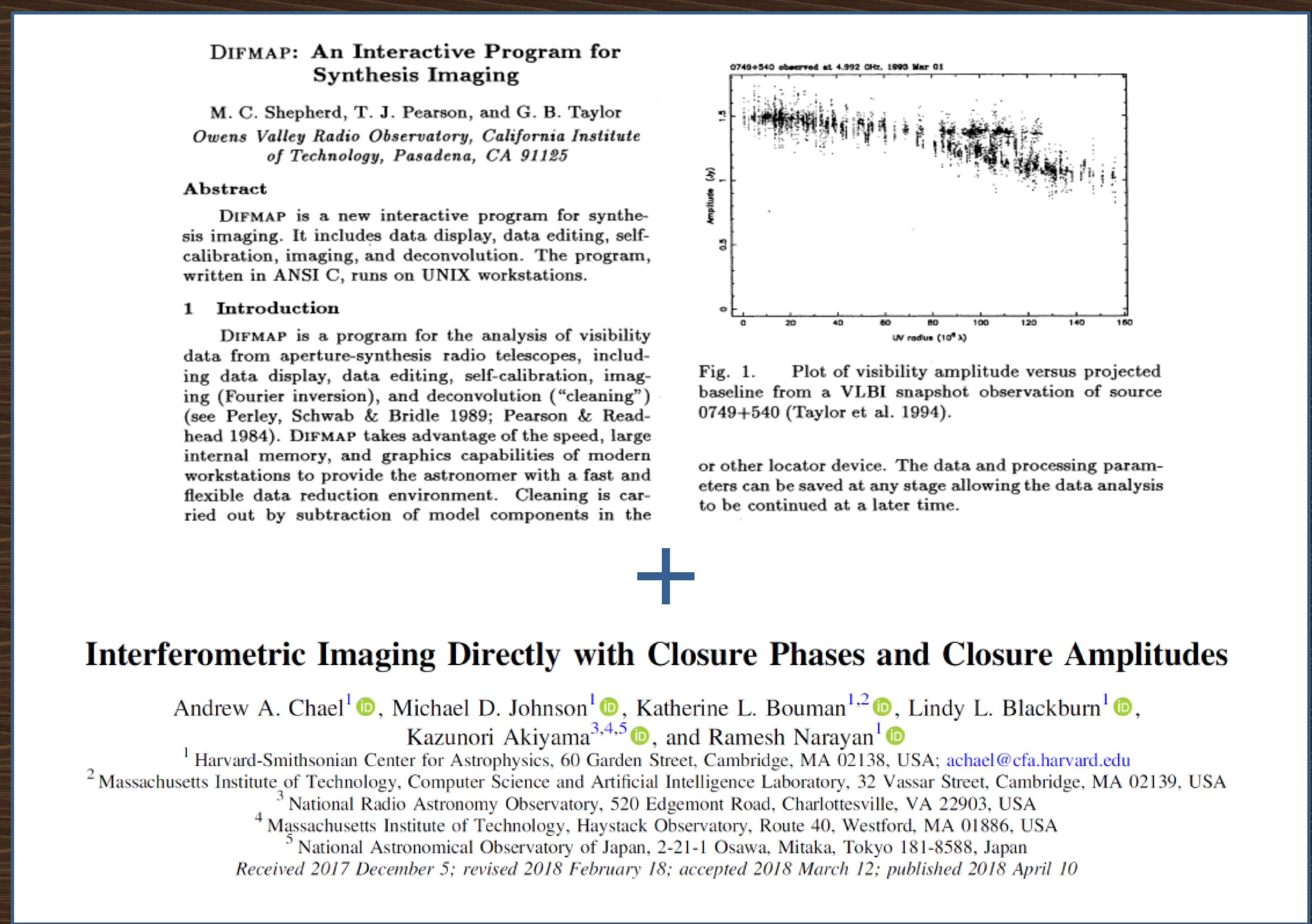
Kpc-scale proper motion measurements are extremely rare in AGN jets, which includes only 3C 264, Cen A, M84 and 3C 273 (upper limit only). 3C 264 and Cen A show evidence of acceleration on the kpc-scales.
Left: Jet of quasar 3C 264 showing acceleration to superluminal speeds at >100 parsecs. *Right*: Jet of radio galaxy Centaurus A with less pronounced acceleration at kpc-scales. The data for M87 has been plotted as watermark for reference.

3. Goal: To create a Catalogue of kpc-scale motions in jets from Active galactic Nuclei using Very-large-Array Studies (**CAgNVAS**)



Highlight of the richness of the VLA archive for observations of ~100 kpc-scale jets from active galactic nuclei, which we will analyze to measure proper motions. Inlet shows VLA archival data (larger circle implies higher sensitivity) per frequency through years of operation of the VLA. The large time-baseline (>40 years) is perfectly tailored for accurate studies of motion on larger scales, which would not have been otherwise possible a decade or two ago.

4. **DIFMAP 3.0**
or how I learned to stop worrying about calibration errors and love proper motions



DIFMAP: An Interactive Program for Synthesis Imaging

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Abstract

DIFMAP is a new interactive program for synthesis imaging. It includes data display, data editing, self-calibration, imaging, and deconvolution. The program, written in ANSI C, runs on UNIX workstations.

1 Introduction

DIFMAP is a program for the analysis of visibility data from aperture-synthesis radio telescopes, including data display, data editing, self-calibration, imaging (Fourier inversion), and deconvolution ("cleaning") (see Perley, Schwab & Bridle 1989; Pearson & Readhead 1984). DIFMAP takes advantage of the speed, large internal memory, and graphics capabilities of modern workstations to provide the astronomer with a fast and flexible data reduction environment. Cleaning is carried out by subtraction of model components in the

Fig. 1. Plot of visibility amplitude versus projected baseline from a VLBI snapshot observation of source 0749+540 (Taylor et al. 1994).

or other locator device. The data and processing parameters can be saved at any stage allowing the data analysis to be continued at a later time.

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Interferometric Imaging Directly with Closure Phases and Closure Amplitudes

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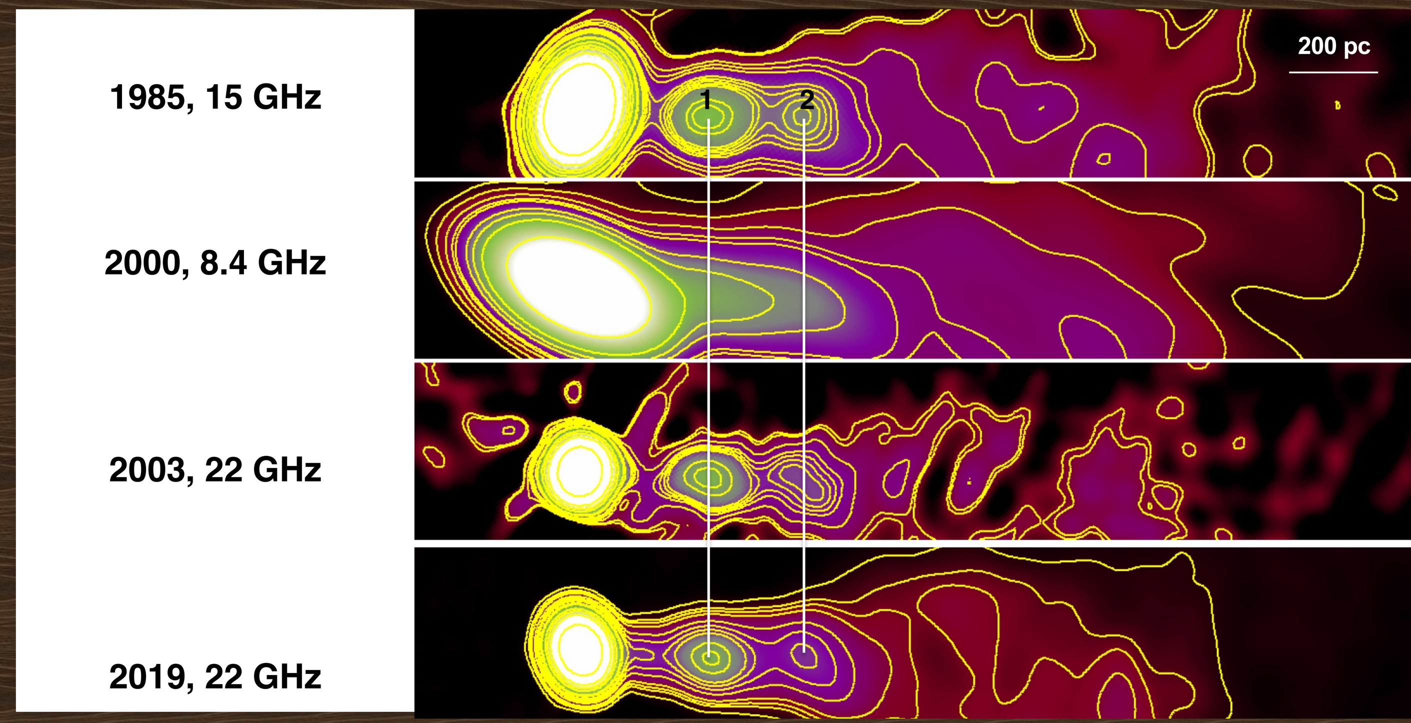
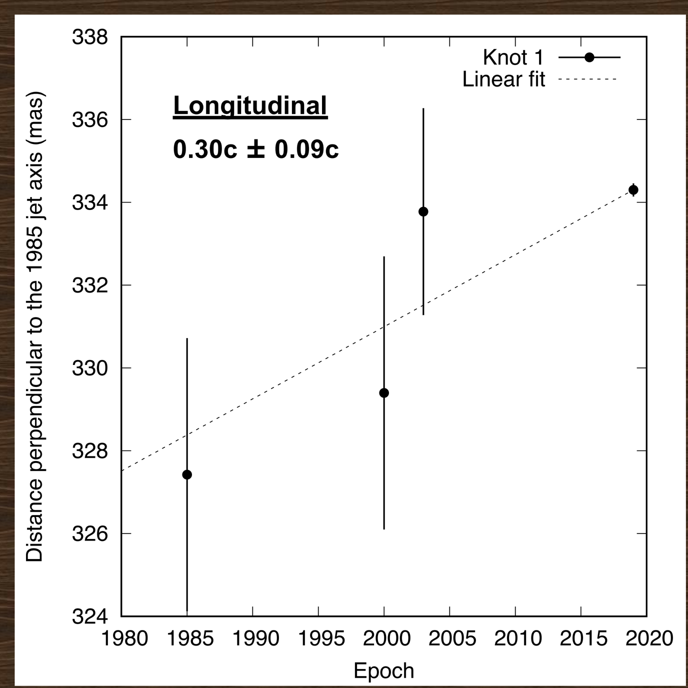
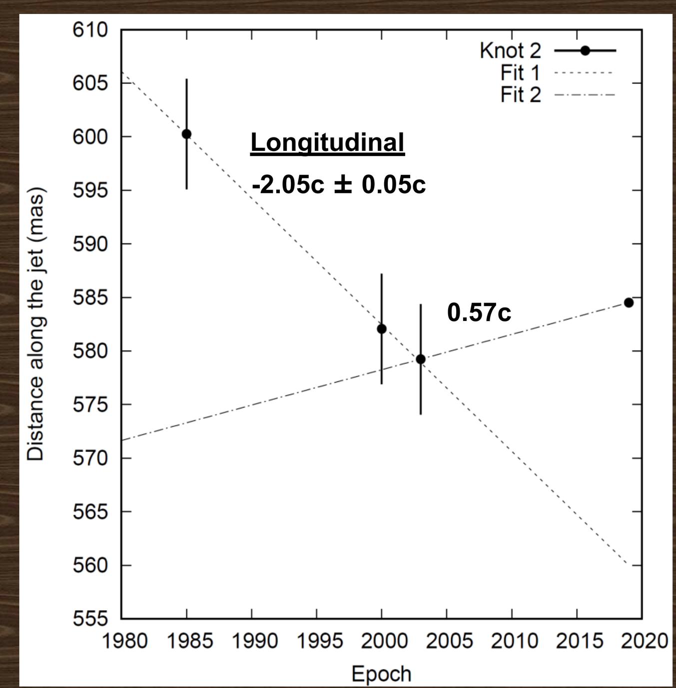
Model-fitting in the Fourier plane using DIFMAP is usually done for VLBI data to measure proper motions and change in source structure. The latest version of DIFMAP (v2.5k, May '21) only fits the complex visibility using a local optimization algorithm. Since motions are often slow on the larger scales and the VLA archival data are not always ideal, I included closure quantity (amplitude and phase) fitting inside DIFMAP using a global optimization algorithm (simulated annealing), which is robust to calibration-related errors and choice of initial model parameters. I will publish this new version of DIFMAP as **DIFMAP 3.0.**

5. Test case: proper motions in the VLA jet of optically-detected radio galaxy 3C 78





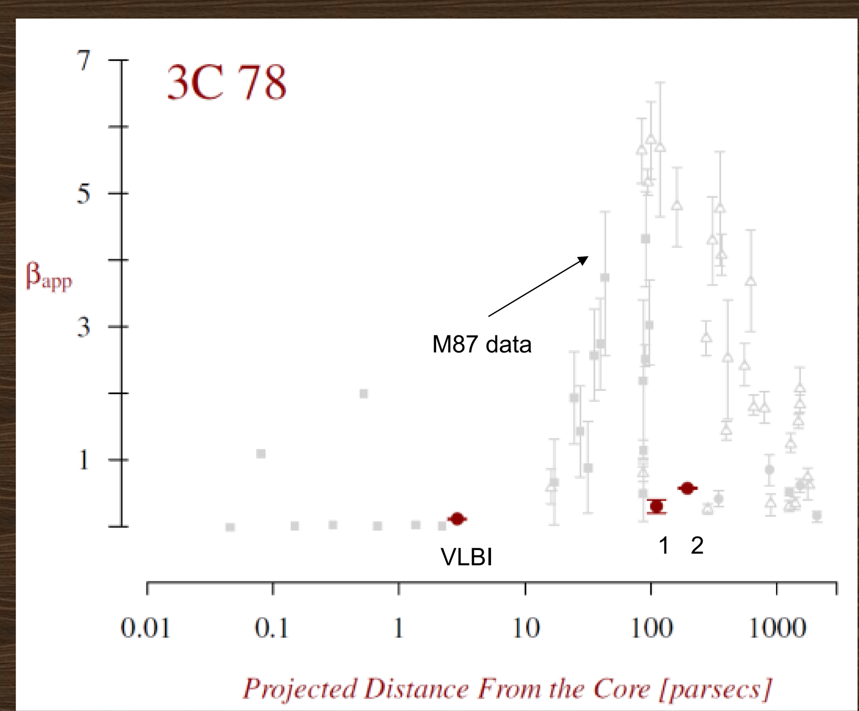


Left: Knot 1 exhibiting subluminal motion away from core, at ~0.30c. *Right*: Knot 2 initially moving upstream *superluminally*, before moving downstream eventually; indicates multiple components/stationary shock(s) (e.g., HST-I in M87, Meyer+13, Harvey+ in prep.). Average motion is ~0.57c.
The average transverse motion for Knots 1 and 2 are ~0.14c and consistent with zero respectively (not shown here).

6. Evidence of jet acceleration at >100 pc scales

The observed VLA speeds (0.30c, 0.57c) are > 3-5 times that in the VLBI (0.11c, Lister et al. 13), implying the jet is still accelerating at the >100 pc scales.

According to the standard model of jet acceleration, does it then imply that the jet is Poynting-dominated until 500 parsecs (e.g., Komissarov et al. 07)?



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