Impact of the VLA: Physics of AGN Jets

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1 Introduction

I will begin by revisiting a VLA observation of the radio jets in NGC 315 that was made twenty years ago almost to the day. I make this my starting point partly because it gave us an early hint of how the VLA could impact the study of AGN jets, and partly because it involves (yet) another "Barry Clark story". In what follows, I will not try to summarize all of the different ways in which the VLA has added to our knowledge of AGN jets, but will focus on questions about jet velocity fields and the differences between the two primary jet "flavors", using NGC 315 as a guide.

2 NGC 315 twenty years ago

On 23 June 1978, Ed Fomalont, Mike Davis, and I were given time to observe the radio galaxy NGC 315 with the "sub-VLA" — a dozen antennas on 10.5 km of the West arm and 1.5 km of the East arm. NGC 315 is one of the "giant", *i.e.*, Mpc-scale, radio galaxies, covering almost a degree on the sky (Bridle *et al.* 1976). We had previously used the Green Bank Interferometer to show that the radio source contained a narrow, kiloparsec-scale feature next to an unresolved component in the nucleus of the elliptical galaxy. The narrow feature was aligned with a bridge of emission linking the galaxy to one lobe of the giant structure, so we thought that it might be the innermost part of an exceptionally long "radio jet". Although the largest-scale structures would be resolved out, we hoped that a long synthesis would allow us to image the narrow feature in some detail because most of its flux density could be captured whenever the short-baseline fringes aligned with it.

We were not disappointed. We got good data from most of the antennas at 4885 MHz and 1465 MHz. The bases of the jet and of a counterjet were not only detected, but also *transverse*-resolved. We could therefore measure the jet's opening angle, or spreading rate, as a function of distance from the nucleus. We also saw that to make full use of the data we needed to deconvolve the sub-VLA's sidelobe pattern from a large area of sky by 1978 standards — fully 256 × 256 pixels! We needed to make a 512 × 512 dirty image and beam to do this using the Högbom (1974) CLEAN algorithm. This was a non-trivial computation in 1978, because the CLNMAP program had to be run in the same heavily-loaded DEC-10 that handled most of the off-line computing at the VLA site. Only 128 × 128 CLEANs could be submitted to the DEC-10 routinely, so we needed Barry Clark's permission to run ours.

At this early stage of VLA work, deconvolution did not have the central role in image processing that it has today. CLEAN was still seen as a temporary stop-gap, a processing step that might not be needed when the VLA was completed. (The VLA had been designed to give sidelobe levels low enough that its "dirty" images could be used directly for science.) Despite the nuisance value of our request, Barry let us run an "over-sized" CLEAN on NGC 315 on a weekend when the DEC-10 was lightly loaded.

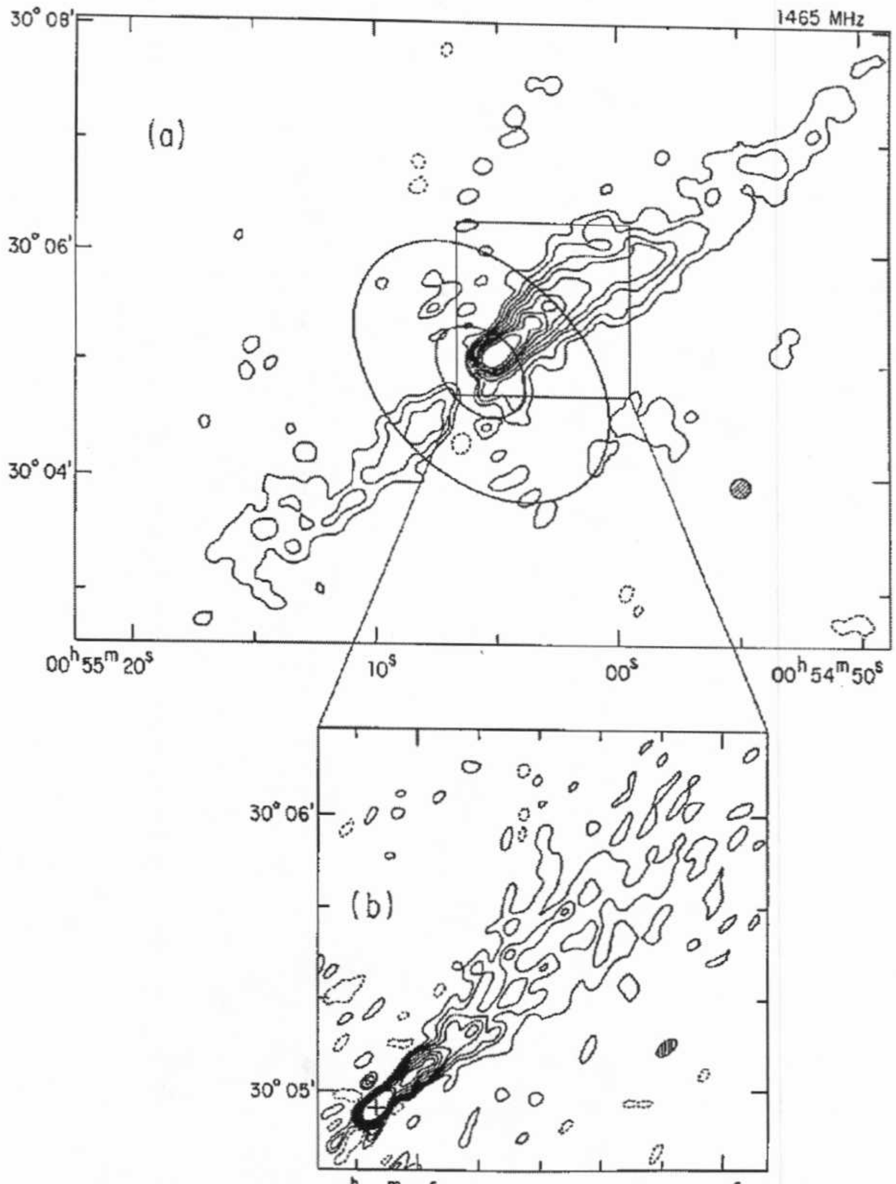

Figure 1: The upper panel shows the 1465 MHz contour plot of NGC 315 at 11″ resolution; an unresolved nuclear source was subtracted. The ellipses show the size and orientation of the overexposed core and outer envelope of the galaxy on the red-sensitive *National Geographic Society – Palomar Observatory Sky Survey* print. The inset shows the VLA data at 2.5″ resolution. (From Bridle *et al.* 1979.)

Our 1465-MHz data traced the jet and counterjet for a few tens of kiloparsecs away from the nucleus (see Figure 1). The key result was that the structure of these jets changes with distance from the nucleus in several ways. The jet ridge lines "wiggle", the brighter jet clearly spreads at a variable rate, and its degree of linear polarization increases outwards. This was evidence for *ongoing* changes in the jets' collimation and internal structures, including the magnetic field configuration, on scales that were easily resolvable by the VLA. VLA observations of such jets might therefore be able to provide important clues to the physics of jet propagation on kiloparsec (and greater) scales in galactic environments.

The clientele for CLEANing "large" fields of view ballooned as more extended sources were studied with the sub-VLA. But the DEC-10 could not handle the growing demand for the Högbom CLEAN. Fortunately, Barry turned this computing problem into a wonderful opportunity, and gave us the "Clark CLEAN" (Clark 1980).

To move some of the deconvolution load out of the DEC-10, Barry coded a CLEAN for a PDP 11/70 and FPS 120B Array Processor that were later to become part of the spectral-line "pipeline" system. The FPS 120B had three control panel lights: one for power, one showing data transfer activity, and one showing array processor activity — actual computation. Barry says that watching these lights showed him that his first CLEAN code spent too little time doing the computations. Most of the time instead went into shuffling data in and out of the AP memory. The more efficient algorithm that he developed to keep the "AP activity" light lit up saved our bacon in the early 1980's. Without it, the practice of feeding CLEAN models back into self-calibration, which was the route to high image fidelity, would have been slow to develop. Barry's efficient AP microcode later went around the world as part of AIPS, and the "computation" light stayed lit up on the AP's of thankful VLA users for years thereafter.

Our early look at NGC 315 with the sub-VLA previewed some features of FR I jets which may still be central to understanding differences between jet propagation in FR I and FR II sources; but it may have advanced the field more by being one of the early projects that got Barry Clark thinking about an efficient CLEAN algorithm.

Figure 2 shows the radio jets and the galaxy in modern dress, superposing a 4885 MHz VLA multi-configuration image of the radio jets on the red-sensitive image of NGC 315 from the *Digitized National Geographic Society – Palomar Observatory Sky Survey.*

3 AGN jets before 1978

Use of the term "jet" in extragalactic astronomy dates back to Baade & Minkowski (1954), who described an optical feature in M 87 as "a unique peculiarity known for a long time ... a straight jet extending from the nucleus in p.a. 290°, bluer than the nebula itself ... several strong condensations". This feature was first recorded by Curtis (1918), as "a curious straight ray apparently connected with the nucleus by a thin line of matter". Its linear polarization at optical wavelengths (Baade 1956) provided early evidence for synchrotron emission from extragalactic radio sources.

The existence of radio emission from AGN jets was also known for many years before the VLA went into operation.

The first sign of radio emission from a "jet" had come via Schmidt's (1963) identification of "a star of about thirteenth magnitude and a faint wisp or jet" near the accurate positions of the radio components of 3C 273 (Hazard *et al.* 1963). Schmidt's identification of radio component 'B' with the "star" marks the start of the quasar industry. His identification of component 'A' with the tip of the "faint wisp or jet" likewise marks the start of a radio jet industry that developed much more slowly. Six years passed before Hogg *et al.* (1969) showed that a compact extranuclear radio component in 3C 274 coincided with the brightest knot in M 87's optical jet (thus providing evidence for radio emission *from*, rather than just *around*, that optical feature).

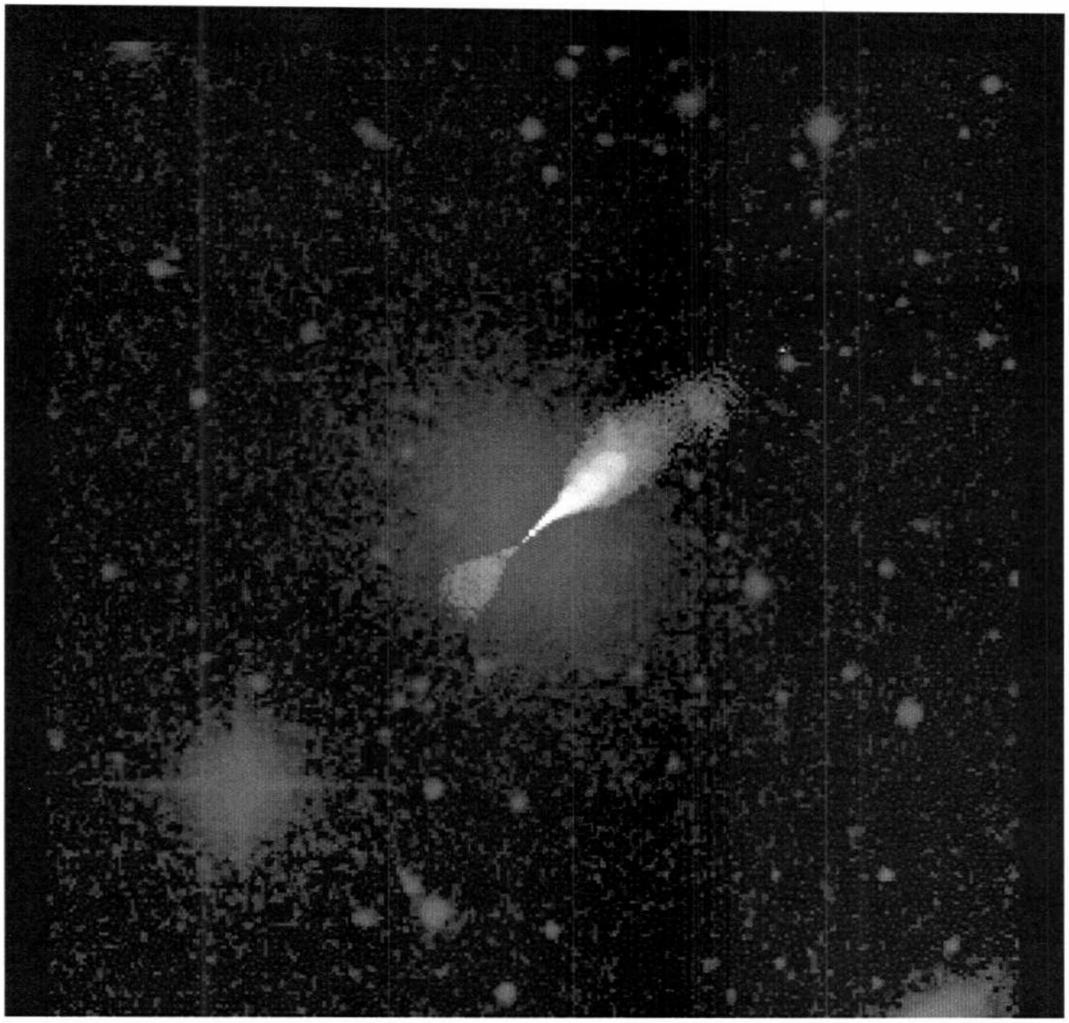

Figure 2: A modern VLA image of NGC 315 at 2″ resolution superposed on an image of the galaxy from the E plate of the *Digitized National Geographic Society – Palomar Observatory Sky Survey.*

The next evidence for radio jets came from observations made at Cambridge. Northover (1973) found a "narrow jet of emission linking the galactic nucleus to one of the extended regions" in the low-power plume-like radio source 3C 66B, and suggested that this implied a continuous resupply of energy from the nucleus to the extended source (in compact sub-components that he interpreted as buoyant "bubbles"). Hargrave & Ryle (1974) used high-resolution imaging of Cygnus A's hot spots and spectral-aging analysis to argue for "continuous replenishment of energetic electrons within the two main compact components", favoring models with "continuing ejection of beams of energetic particles or low frequency waves from the nucleus of the galaxy". The first *direct* evidence for a radio jet in a powerful "classical double" source came when Turland (1975) detected the abbreviated jet in the radio galaxy 3C 219. A spectacularly long and narrow one-sided jet was found in the giant radio galaxy NGC 6251 by Waggett *et al.* (1977).

Radio jets were also recognized in WSRT images of several radio galaxies at about this time: van Breugel & Miley (1977) reported jets in B0844+319 and 3C 129, and gave retrospective evidence for jets in several other galaxies, including 3C 449 (Högbom & Carlsson 1974) and 3C 83.1 (Miley *et al.* 1975).

4 The VLA and large scale features of jets

The VLA greatly accelerated the study of radio jets, for several reasons. It had the sensitivity to detect weak jets with short observations, the dynamic range to do so in the presence of bright unresolved emission in the galactic nuclei, and the angular resolution to separate the jets convincingly from surrounding extended structures. It also allowed polarization imaging with good sensitivity and resolution, and this revealed key details of the jets' magnetic configurations.

VLA observations quickly provided examples of jets in all types of radio-loud AGN. The detection of radio emission from, or at least closely associated with, the presumed pathways of energy transport in continuous-outflow models cemented the case for these models[1]. Furthermore, numerous correlations between the properties of the jets and other attributes of the radio sources became apparent. These included:

- **Correlations between jet properties and the Fanaroff-Riley structure classes:** The plume-like, low-luminosity, Fanaroff-Riley Class I sources (Fanaroff & Riley 1974) have two-sided, rapidly spreading and prominent jets (*e.g.*, Figure 3). The "classical double", higher-luminosity, FR II sources have one-sided, narrowly-collimated jets that are more prominent in quasars than in radio galaxies (Bridle & Perley 1984).

- **Correlations between kiloparsec and parsec scales:** The brighter kiloparsec-scale (VLA) jet is always a plausible extension of the brighter parsec-scale (VLB) jet. The kiloparsec-scale jets are also well aligned with the parsec-scale jets in the FR I sources (Giovannini *et al.* 1995; Venturi *et al.* 1994, 1995), as exemplified by NGC 315 in Figure 4, and in lobe-dominated FR II sources. The *angular* relationships are more complex in core-dominated sources whose jets appear more bent, but even in these sources the brighter large-scale jet is usually a plausible continuation of the brighter small-scale jet.

- **Correlations between jet sidedness and depolarization asymmetry:** In sources whose jets differ greatly in brightness, the brighter jet is on the side of the source that depo-

[1]The models had their roots in early papers by Morrison (1969), who outlined a pulsar-like model for an AGN emitting a continuous relativistic beam, and by Rees (1971), who suggested that the sources were powered by low-frequency electromagnetic beams. Longair *et al.* (1973) argued for an energy transport time scale "comparable with the age of the source" and Scheuer (1974) explored the dynamics of radio sources powered by relativistic beams. Blandford & Rees (1974) suggested a "twin-exhaust" collimation mechanism for relativistic plasma flows (on 100-pc scales).