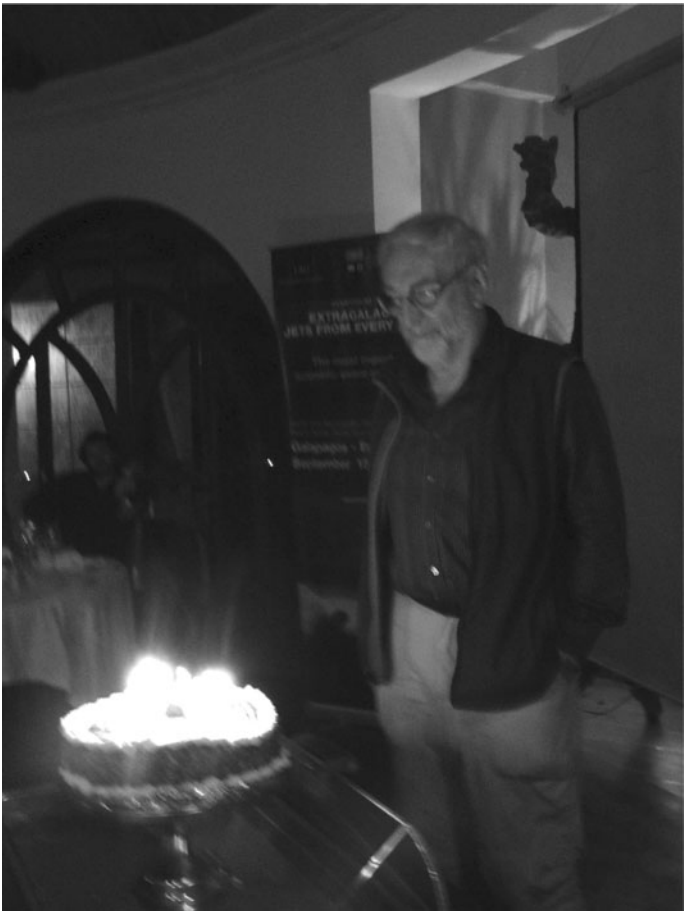
Review: Observations meet theory



Dan Harris with birthday cake at social dinner

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Extragalactic jets from every angle
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Slugs and Snails and Puppy Dog Tails: jets from an unconventional angle

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Abstract. We discuss some aspects of extragalactic jets originating from super massive black holes in the centres of active galaxies (and quasars). We start with a short review of sizes and flavors and then argue that the emission we detect across the electromagnetic spectrum does not come from the essence of the jet, but is rather a product of the jet. We go on to discuss some topics concerning synchrotron emission from jets, mainly aspects of knots. Finally we discuss the emission processes for the X-rays and describe a current experiment with LOFAR designed to test a requirement of inverse Compton models.

Keywords. radiation mechanisms: nonthermal, galaxies: jets, quasars: general, X-rays: galaxies

1. Introduction

The title comes from the nursery rhyme:

- What are little girls made of?

Sugar and Spice and Everything Nice!

- What are little boys made of?

Slugs and Snails and Puppy Dog Tails.
The third stanza would be

- What are little jets made of?

We suspect our answer would be about as informative as the answers to the other questions. After all these years and all these conferences on jets, we still don't know what jets are made of or how they work. I don't have the answers, but perhaps we can find some things that they are not!

We begin with a short review of jet sizes and flavors. Next we argue that the jet essence is not what we observe. Following that we consider some topics about synchrotron jets. Then in § 5 we describe an experiment to test one aspect of the X-ray emission process suggested for quasar jets, inverse Compton scattering on CMB photons whose energy density in the jet frame is augmented by the square of the bulk Lorentz factor of the jet.

2. A short review of jet properties

Relativistic jets have been studied for many, years, and from radio and optical polarization, we have found a natural explanation of their emission process to be synchrotron emission; e.g. Pacholczyk (1970). However, the physical parameters responsible for synchrotron emission are difficult to separate and the resulting uncertainty in the value of the magnetic field strength, B, affects estimates of the total energy, the pressure, the half-life, etc.

When viewing a radio jet, we think we see a (distorted) view of emitting volumes containing relativistic electrons and magnetic fields. The shape is distorted by projection effects and aberration; the brightness is distorted by relativistic beaming.

When viewing an X-ray image of a jet (so long as the X-rays are produced by synchrotron emission), in addition to the same attributes as the radio, we know that we are viewing acceleration regions: i.e. high energy electrons are being produced throughout the emitting volume. This follows from the very short (of order a few years; see e.g. Harris & Krawczynski (2002)) radiative life time of the $\gamma \approx 10^7$ electrons responsible for the observed X-rays (γ is the Lorentz factor of the electron).

Whereas there is little debate about the synchrotron origin of radio and optical emission for both FRI and quasar jets, there is no consensus for the X-ray emission process for jets of quasars and FRII radio galaxies. Is the observed X-ray emission synchrotron, as is the case for FRI jets, with a typical half life of a few years, or is it inverse Compton scattering of low energy electrons ($\gamma \approx 100$, whose life time would be 100,000 years or longer) with cosmic microwave background (CMB) photons?

Either we are sampling the very top end of the electron energy spectrum, N(E), or we learn about the very bottom end! Neither end is accessible by other means but unfortunately we don't know which end we are looking at! [Except of course for FRI jets where we are pretty sure that synchrotron emission dominates the X-ray as well as the radio and optical emissions Harris & Krawczynski (2002).]

Finally, it is good to remember that jets exist over a very broad range of sizes. Jets from micro quasars (observed) and from gamma ray bursts (hypothesized) are of order a parsec whereas the more powerful extragalactic jets range in size up to a mega parsec. Figure 1 provides a visual rendition of this range of lengths, although we have not attempted to deproject the examples shown.

The size and power of jets may well scale with the mass of the black hole, but I doubt that we can scale the micro physics of particle acceleration processes, be they shocks or magnetic reconnection.

3. Why the essence of jets is not what we observe

With the exception of IC/CMB X-rays from a jet with a significant bulk Lorentz factor, Γ, all the emission we observe from jets comes from 'hot' electrons (i.e. $\gamma \geqslant$ a few thousand).

We also know that some jets deliver power to locations that are a Mpc or further from the super massive black hole (SMBH) which produced the jet. So whatever agent it is that is actually responsible for transporting the energy, has to exist for at least as long as it takes to get to the end of the jet. Here we show that this agent cannot be hot electrons. This line of reasoning was first published some years ago, e.g. Harris & Krawczynski (2007).

Since hot electrons suffer inescapable IC losses from the CMB photons, we may equate the half-life for E^2 losses with the age at the end of the jet for hot electrons traveling down the jet at the speed of light.

The age at the end of jet(yrs) $= \frac{jet projected length (l.y.)}{sin(\theta) \times \Gamma}$, and the half-life is given by a simplified version of eq.(B5) of Harris & Krawczynski (2002):

$$\tau' = \frac{10^{13}}{\gamma \times [B^2 + 40(1+z)^4 \Gamma^2]} \text{ years}$$

where B is the magnetic field in μG and θ is the angle between the jet and the line of sight. So for any jet, we may associate a value of γ(max) for best guess values of θ and Γ. γ(max) gives the largest energy an electron can have and still survive its trip to the end of the jet.

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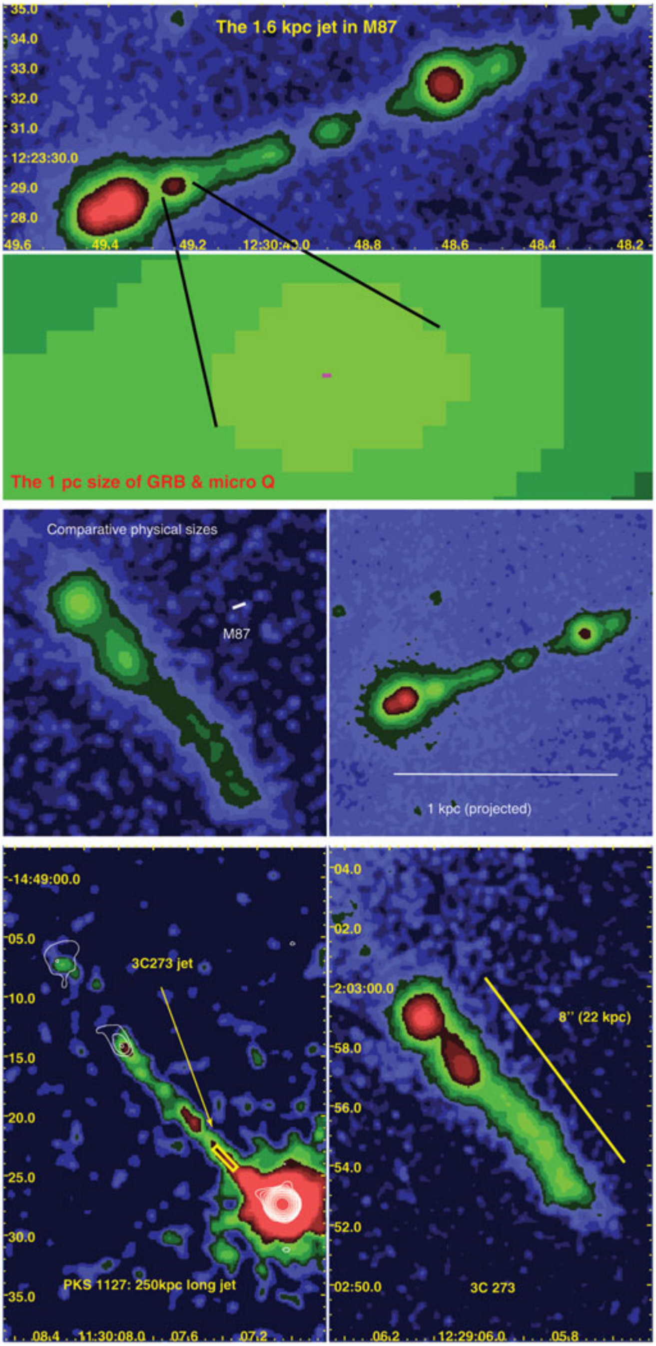

Figure 1. Comparative sizes of jets. The top panel shows an X-ray image of the M87 jet which, in projection is about 1.5 kpc long. The next panel shows how insignificant a pc scale jet (represented by the small blip at the center of the magnified view of knot D) from a gamma ray burst or a micro quasar would be. The next panel compares the M87 jet to that of the quasar 3C273: the entire M87 jet is smaller than the resolution element for Chandra when observing 3C273. In the bottom panel we show how the entire jet from 3C273 would appear if at the distance of PKS1127 (z=1.18).

Table 1. A few results for γ(max)

JET	**Length** (arcsec)	**Scale** (kpc/")	**d** (kpc)	θ	Γ	**z**	γ**(max)**
3C273	22	2.7	60	20	3	0.1583	82,378
				5	10		6,300
4C19.44	28.5	7.2	205	10	8	0.72	927
PKS0637	17	6.9	117	5	10	0.651	770
PKS1127	28	8.3	232	20	3	1.18	1668

Notes: d is the projected length of the jet in kpc; θ is the angle between the line of sight and the jet; Γ is the bulk Lorentz factor of the jet; z is the redshift of the source.

$$\gamma(\max) = \frac{10^{13} sin(\theta)}{40 \times length(l.y.)(1+z)^4 \; \Gamma}, \text{ or}$$

$$\gamma(\max) = \frac{7.67 \; 10^7 sin(\theta)}{d(kpc) \; \Gamma \; (1+z)^4}$$

where we have ignored the synchrotron losses, leaving only the IC losses which are inescapable. In Table 1 we give some representative values.

Except for IC/CMB X-rays, *all* the radiation we get from jets comes from $\gamma > 1000$ electrons which are not the carrier of jet power. So when we view a synchrotron jet in radio, optical, and/or X-rays, we are *not* seeing the basic jet, we are seeing a product of the jet: a location where jet energy is transferred to a radiating plasma.

There are not that many options remaining for the agent that carries jet power:

- Poynting Flux
- Protons: hot or cold
- Cold pairs

There is a large body of literature on this subject and we will not attempt to discuss that here, but it seems clear that what we see in radio, optical, and X-rays are emitting volumes produced by the jet: we don't actually see the jet.

4. Some topics on synchrotron jets

If the radiation we detect is not the jet, then what are knots? We regard knots as regions where acceleration is favored, as in Lovelace's analogy of a load on a transmission line, Lovelace & Kronberg (2013).

4.1. *Offsets and progressions*

These terms are used to describe common, but not universal attributes when comparing images of jets at different wave bands, but with similar angular resolutions. Examples are given in Harris & Krawczynski (2006): what is often observed is that some knots seem to have their peak brightness move downstream with increasing wavelength ("Offsets"). Although we first thought this might be caused by the different energy loss rate for electrons in the various frequency bands, because offsets have been found for a large range of scale sizes, we favor a spectral explanation. "Progressions" is a term used to describe a changing intensity moving downstream. In the case of 3C273, profiles down the jet show that the X-ray emission is strongly peaked closest to the quasar whereas the radio emission peaks at the jet termination, e.g. see fig. 12 of Harris & Krawczynski (2007). If such a jet were observed with a single resolution element, it is clear that there would be a sizable offset.

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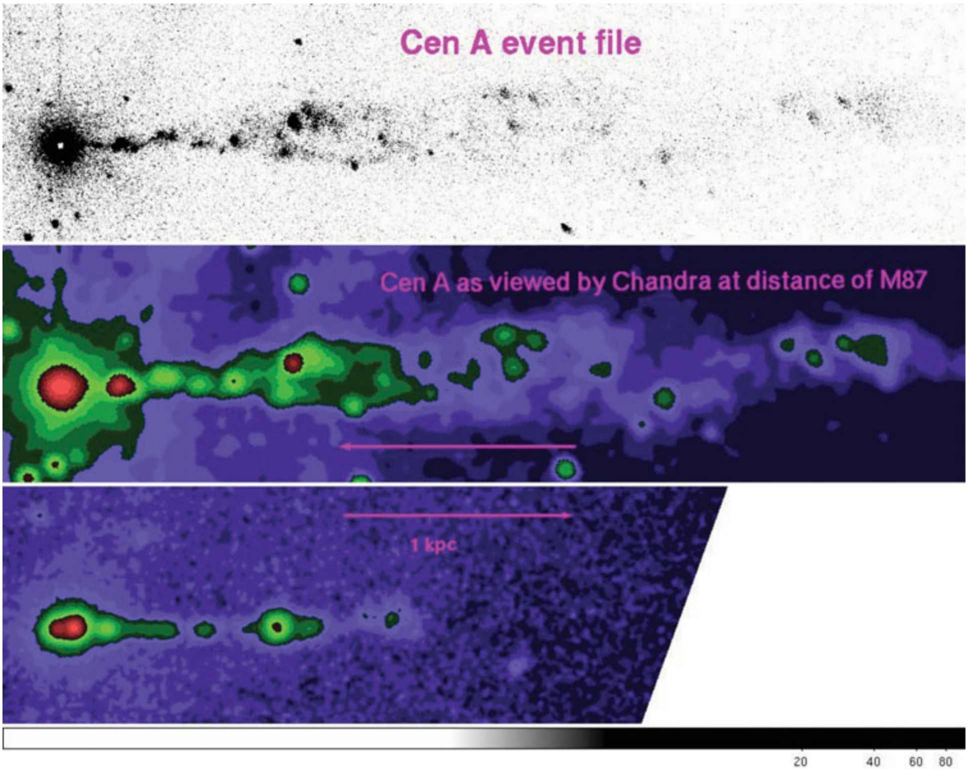

Figure 2. Cen A as it would appear to Chandra if it were at a distance of 16 Mpc. The top panel is the actual Chandra event file (full resolution). The middle panel has been smoothed to emulate the physical resolution of M87 if Cen A were at the same distance. The bottom panel is a lightly smoothed Chandra map of M87. As one can easily see, most Cen A knots comparable to those of the M87 jet are actually comprised of multiple smaller bits.

4.2. *The Cen A experiment*

We devised the Cen A experiment to demonstrate that jet knots are likely to consist of smaller bits of emission regions; i.e. the filling factor of features we observe are most likely significantly smaller than unity. This is demonstrated in Fig. 2.

Thus we conclude that what appear to be unique knots on M87 scales are in fact regions containing multiple emission bits. From the work of Goodger *et al.* (2010), some of the bits are detected at both radio and X-rays while others only in one or the other band. If there were any coherence in the grouping of emission bits, we could well find offsets (see Fig. 3).

4.3. *Update on the M87 Jet*

Although our concerted monitoring program ended in 2009, we have managed to continue coverage with 2 observations per year for the last 3 years. The nucleus continues to flicker. HST-1 continues to decay. The latest available light curves are shown in Fig. 4.

What about the other knots?

With A. Paggi, A. Chen, & F. Massaro, we have reanalyzed the Chandra M87 data for long term variability. By reprocessing all the Chandra exposures with 0.4s frame time (2000 to 2014), we have added together all the data for each observing season (Nov to Aug) and produced flux maps in 3 energy bands for each season. Although this

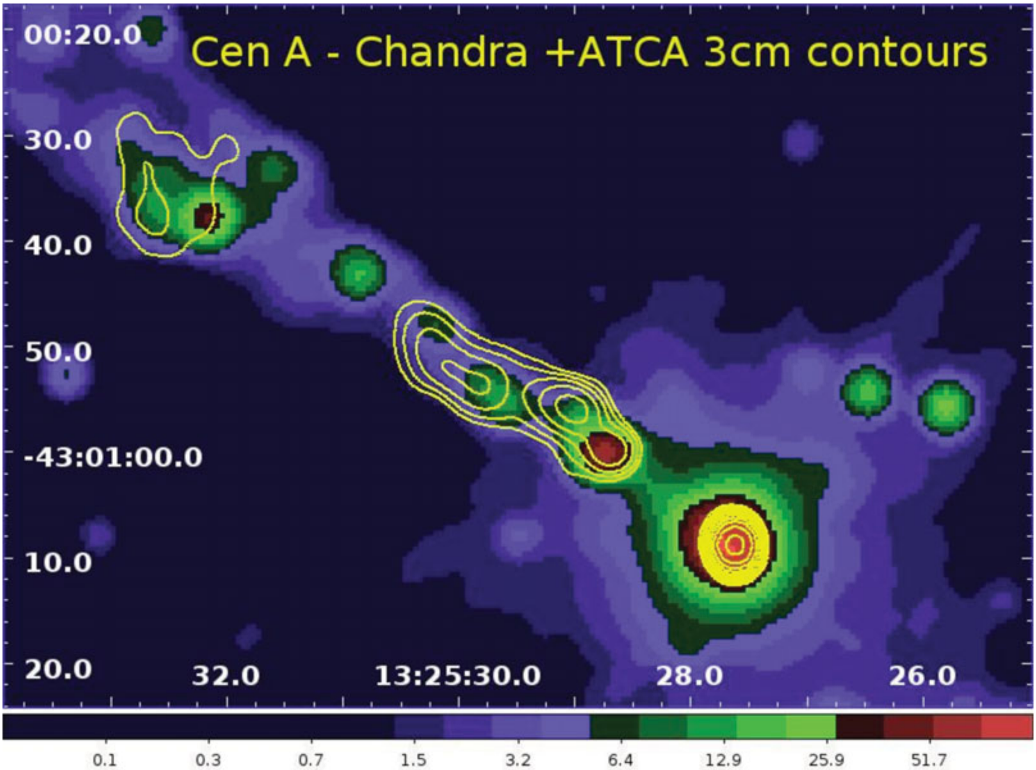

Figure 3. Cen A as it would appear to Chandra if it were at a distance of 16 Mpc. The contours come from a smoothed 3cm ATCA map. The image is from Chandra. Both the feature in the center of the image and that to the upper left demonstrate aspects of offsets.

work is still in progress, our preliminary results include the following. The spectrum of HST-1 is harder during the rise of the massive flare of 2005 than during the decay. There is a 2 year segment during which the hard flux of HST-1 decays faster than the medium flux, which decays faster than the soft flux. The observed rates are consistent with synchrotron losses in a field of 1 to 10 mG, a value similar to that derived earlier for a different time segment (Harris *et al.* (2009)). Knot D is slowly increasing. Knot A is slowly fading.

5. Quasar jets and the X-ray emission process

As mentioned earlier, we are still uncertain as to the emission process responsible for the X-ray jets of high power sources such as quasars and FRII radio galaxies. Is there a separate synchrotron component distinct from that responsible for the radio and optical emission? Or is it IC/CMB emission from a jet with significant (e.g. $\Gamma \approx 10$) bulk velocity on kpc scales?

How can we make progress on evaluating the IC/CMB model? Is Γ large enough? Is it valid to use the radio spectral index, α_r, to extrapolate the spectrum to low frequencies (low electron energies)?

A few years ago Uchiyama *et al.* (2006) used IRAC data to argue that the optical part of the spectrum for some knots in 3C273 seemed to connect smoothly to the X-ray power

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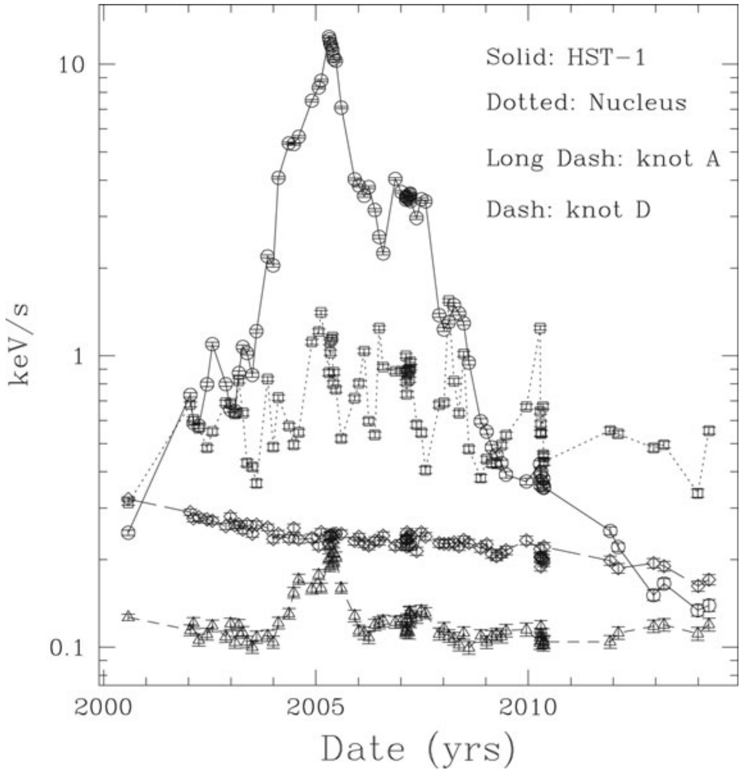

Figure 4. X-ray light curves for the 4 brightest features in M87: the nucleus, HST-1, knot D and knot A. The excursions of knot D and the nucleus around 2005 are artifacts caused by severe pileup in HST-1. The intensities have not been corrected for the changing effective area of the ACIS detectors.

law, i.e. it was not part of the radio spectrum. Since the optical emission was polarized, these authors suggested that the X-rays came from synchrotron, not IC/CMB emission.

More recently, Meyer & Georganopoulos (2014) use Fermi data for 3C273 during a low state to argue that that the total gamma ray emission was less than that expected from the IC/CMB model of the jet, again concluding that the X-ray emission from this jet is not dominated by IC/CMB emission.

Another approach is to use new low frequency radio telescopes to see if the extrapolations required by IC/CMB models are valid. LOFAR in the Netherlands is now capable of arc sec resolution when the international stations are added to the Dutch array. We have begun such a test with an observation of the quasar 4C19.44 (z=0.72). Fig. 5 shows the radio spectra for 6 knots along the jet as well as the expected sensitivities of the high band (HBA) and low band (LBA) arrays of LOFAR.

A map at 165 MHz with FWHM 0.9″ is shown in Fig. 6. This map comes from 1/16 of the total data obtained with the HBA. Eventually we will have better sensitivity and additional maps at several frequencies ranging down to 120 MHz.

From the preliminary map at 165 MHz, we have measured flux densities for the regions used for the VLA data and at this stage we see no striking signs of major spectral changes. There is no evidence for spectral breaks near γ=2000 which might be expected from some acceleration processes such as shock acceleration.

In a paper in preparation (Harris, Oonk, Moldon *et al.*), we will include a section on how well we can associate an observed frequency with the energy of the electrons

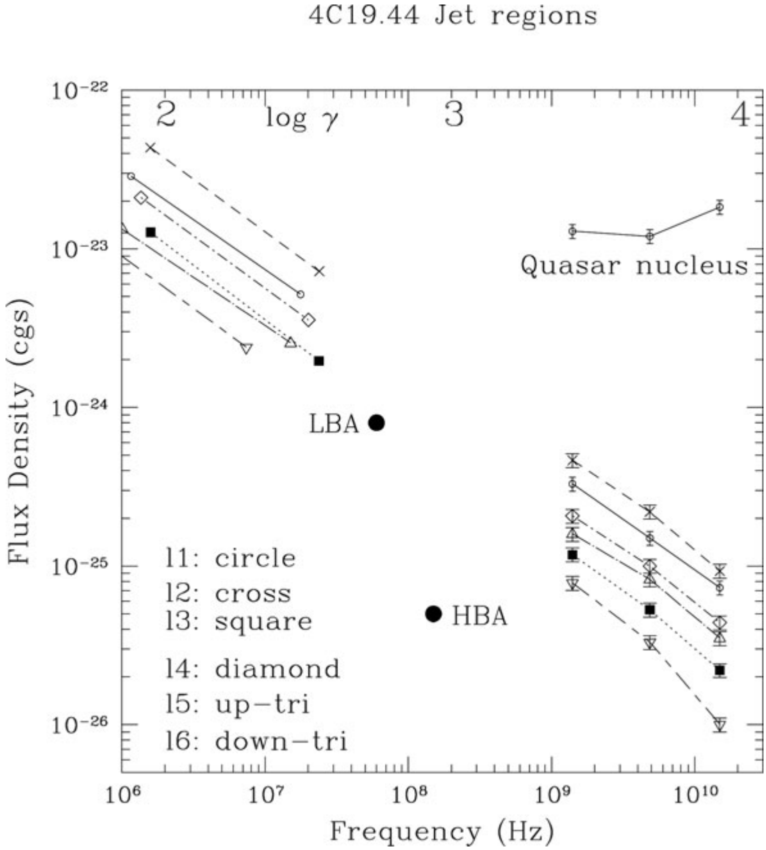

Figure 5. Radio spectra for knots in the jet of 4C19.44. Jet regions are labeled consecutively with distance from the nucleus. Region 1 is 4″ from the nucleus and region 6 lies at 16.7″. The spectra to the right come from VLA observations (10% error bars are assigned); the quasar nucleus is also shown. The spectral segments to the left define synchrotron emission which would come from the electrons responsible for the observed X-ray band (0.4-6keV) if the beaming model for IC/CMB were the origin of the X-rays. Along the top border we have indicated the correspondence between electron energy and frequency (for magnetic field strengths a bit less than 100 μG, approximately the minimum equipartition field). The two large filled circles indicate LOFAR 5σ sensitivity limits for an 8 hour observation. The smaller value corresponds to the High Band Array for a single sub band whereas the larger value is for the Low Band Array, but with a bandwidth of 2 MHz. Note that the HBA samples $\log\gamma \leqslant 3$.

responsible for that frequency. Our conclusion is that if we calculate the equipartition field on the basis of the critical parameters that minimize the resulting field strength, then using that field will give the maximum value for the electron energy, and our ignorance of such parameters as the filling factor and the contribution from relativistic protons is unlikely to mean that we over estimate the energy by more than a factor of ten i.e. our assigned energies might eventually be found to be smaller, but never any larger.

Acknowledgements

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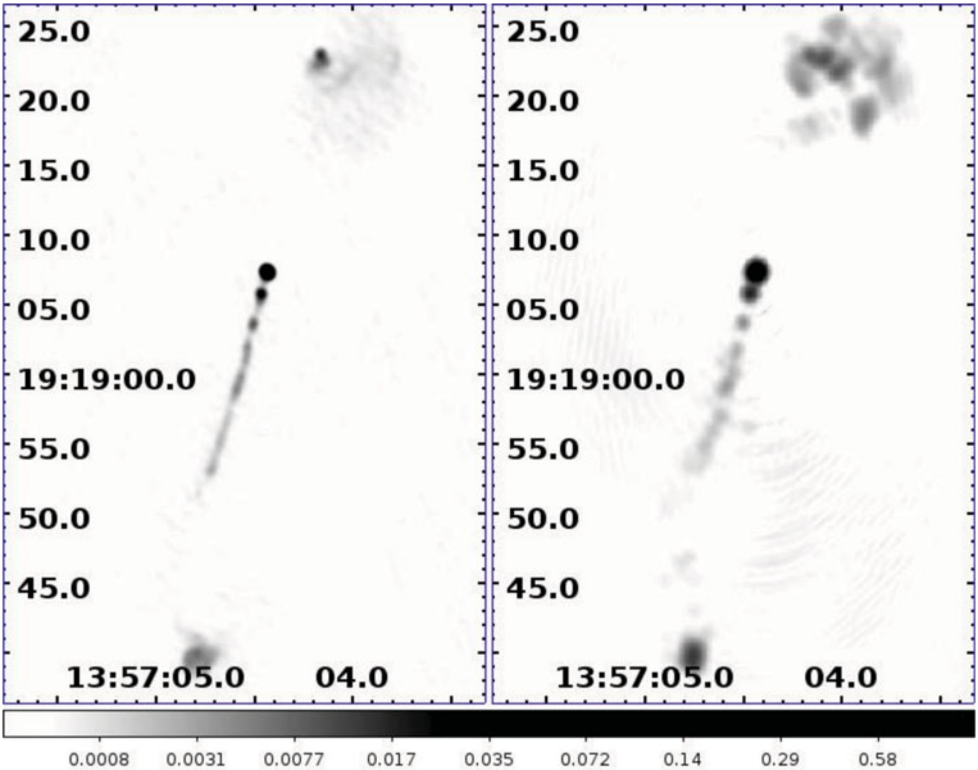

Figure 6. Radio maps of the quasar 4C19.44. The left panel is a 5 GHz VLA image (S. Jorstad, private communication) and the right panel is a preliminary LOFAR map at 165 MHz.

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