Summary: An Outsider's View

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1. Introduction

When Toni Zensus asked me to give this talk he said he wanted a review of the meeting from an "outsider"—someone without a vested interest in any model or type of observation of parsec-scale jets. I think he also feels sure that I am quite ignorant about small-scale phenomena! [The opposite is true!—Ed.] I will take his mandate literally and so I will try to reflect the view of this meeting of someone who usually looks at kiloparsec-scale phenomena, with no concessions to the logistical and technical difficulties of VLBI imaging. Because of this, I'll say a few things that may annoy some of you. But I'll make my criticisms generic and won't point a finger in any individual's direction. Between this talk and Tony Readhead's "insider's" view (page 352), we may also stoke up discussion of some of the questions that Tim Pearson asked at the start of the meeting (page 1).

2. Some Highlights

I was impressed by the quality of the best VLBI images that we saw here. They represent goals of image complexity and dynamic range that were just dreamed of for VLBI data only a few years ago. It is good to see such goals now being achieved. The "World Array" images of M 87 (Biretta and Owen, page 125) and 3C 48 (Wilkinson *et al.*, page 152) show structural complexity that rivals that seen in VLA images of much larger sources. This complexity should take away any remaining naïveté about models for parsec-scale jets! I'll come back to this later. I'll also mention later why I believe that progress in understanding these jets may depend more on future efforts like the "World Array" rather than on individual VLBI "instruments" on different continents.

The richness of the images from the VLBI polarimetry by Dave Roberts and John Wardle (page 110, page 20) was also impressive. The large percentage polarizations they are finding (especially in the BL Lac objects) imply that these observations are beginning to resolve a physically important scale in some structures. High linear polarization is

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a sign that the synthesized beam is small enough not to smear an important scale of organization too badly. For kiloparsec-scale sources, reaching the resolution at which high linear polarizations begin to appear is often the first step towards tackling the physics of the scale that is being resolved. So these observations are an encouraging preview of good things to come with the VLBA and the EVN. They are also a sign that it will be worth putting polarimeters on VLB antennas round the world. I look forward to the time when well-sampled VLBI images can be combined to make "magnetic movies" of developing features in jets, following the time evolution of their shapes and intensities in all Stokes parameters. It will be exciting to compare such "movies" with theories such as Phil Hughes's shock model (page 250).

It was good to be reminded here that perhaps not all the apparent structural changes are intrinsic to the sources (e.g., Ekers, page 333). There are clumpy media on a variety of scales both near us and near the jets, so structural monitoring programs may end up watching a "speckle" in some cases. Alan Marscher (page 236) pointed out here that some favorite VLBI targets are viewed through "busy" parts of our Galaxy. The "game" will be to distinguish speckle fluctuations reliably from intrinsic variations, in sources whose structures are more complicated than a "core-jet" or a small double. Sources whose structures change while the total intensity is constant may be especially suspect.

I was intrigued by Peter Wilkinson's (page 152) suggestion that, on top of all the usual difficulties of identifying the "core" in a VLBI image, there might be more than one "core" in 3C 380. As mergers are again a popular way to provoke or maintain activity in galaxies, it's worth asking if some of the things being merged could bring their own "engines" with them. If "merger mania" is indeed relevant to AGNs, should we occasionally see more than one active nucleus at a time? Could some of the sources with unusually disturbed small-scale structures be recent mergers, and so contain multiple engines that have not had time to coalesce yet?

Finally, among the many intriguing points in Patrick Leahy's talk (page 174) was the idea that one of the largest-scale features that we can study—the shapes of the lobes in big doubles—could tell us something about "unified models". As Patrick noted, the fainter parts of the lobes of 3CR quasars and 3CR radio galaxies have systematically different shapes. It's not clear that the galaxy lobe shapes could be projected into the quasar lobe shapes. This ingredient should be added to discussions of galaxy-quasar "unification" like those we had this morning (e.g., Murphy, page 298; Kapahi, page 304).

3. Velocities and Velocity Fields

Now to Tim Pearson's question: "Are jets relativistic to kiloparsec scales?" (page 1). The best new evidence on this point is the set of large-scale proper motions that were deduced from the VLA imaging of M 87 (the poster by John Biretta and Frazer Owen, page 125). These are difficult and important experiments, and it is good to see them turning out so well. I hope that proper motion analyses will also be done on these scales for other nearby radio galaxies, such as M 84 and Centaurus A. The large-scale jet/counterjet asymmetries remain indecisive about velocities (see Bridle, page 186). They may be interpreted either as intrinsic one-sidedness (at least of the radio dissipation from the beams) or as large-scale Doppler favoritism. The idea that jets in powerful sources may be mildly relativistic to large scales seems to have no major difficulties, however (especially if the 3CR quasar sample is somewhat biased toward the line of sight). It's just not the only way to interpret the available data.

I have two comments about velocity fields in jets. The flow velocities must change in magnitude and direction along most jets (if they have anything like the internal dynamics that was discussed here). So is there much point in doing statistical tests based on single values of γ? I am puzzled that this is still reputable, if the jets can't have single-valued uni-directional velocities and still contain many of the features that we see. On the other side of this coin, the best VLBI images are reaching the point where it may be possible to measure the two-dimensional velocity fields across nearby jets. It will be good to break the barrier of one proper motion value per epoch per feature! This will add the structure of a pattern velocity field to our constraints on jet physics.

4. Undersampling Problems

Temporal Undersampling and Proper Motions

I was disappointed that we didn't get to see the Space Shuttle take off, because rocket exhausts sometimes demonstrate a few interesting properties of jets.† Fortunately, some of these properties were mentioned here by Alan Marscher (page 236), and by Phil Hardee (page 266) when he showed us his numerical models. Real, time-variable jets are not restricted to patterns that are outward-moving, or standing, shocks. They may also contain in-going patterns. When a rocket engine is throttled up and down, you may see shock patterns near the outlet set themselves up, stand around for a while and then go back in again. The flow in

† A special break during the meeting was held, but NASA delayed the start by a day! Ed.

these exhausts is always outward, but the patterns can move inward when the engine thrust decreases. It may therefore be significant if we don't see occasional in-going patterns in parsec-scale jets, given that their central engines also vary. A lack of in-going features may tell us something about the flow physics, or about biases in how we "visualize" the flows via their synchrotron emission. (Maybe these are constant-thrust engines, or ones whose output of relativistic particles and fields changes when they are throttled back. Maybe we also have some of the physics wrong!)

As an "outsider" to VLBI imaging, I would therefore like a little more reassurance that in-going or even stationary features are not legislated against when VLBI observers interpret their data. The proper motion data are badly under-sampled in some cases. Everyone complains privately about that! You'd all like to get time on the Network more frequently. You all hope that the VLBA will improve the situation by letting you watch the interesting sources more often. So, despite Marshall Cohen's protest every time I raise this point, I'd like to be more convinced that you're not biased against claiming stationary or in-going features when you interpret your data. I'd like to see more diagrams of feature separations against time, showing what range of models can be fitted or excluded. Is a particular range of outward velocities now being favored "for consistency"? I saw examples at this meeting where I didn't understand why nothing was said about possible stationary or in-going features.

(u, v)-Plane Undersampling and "the First Spurious Feature"

The potential ambiguity in proper motions comes from temporal undersampling. Undersampling in the (u, v) plane is also still a big problem. It is especially hard to assess the uncertainties in images when the sources are complex and the (u, v) plane is sparsely sampled. It's not always clear how VLBI observers identify the mysterious quantity that was sometimes referred to here as the "first spurious feature", i.e., the brightest thing in your data that you don't believe. I hope the "first spurious feature" isn't just the first one that is an embarrassment to a favored physical model! It's worrying when nothing is said about a peak, with several contours around it, that is off at a large angle to the jet, while fainter peaks that are near the jet axis get attention. Also, if there's something on the counterjet side that doesn't look anything like the main jet you can say: "It can't be a calibration error so it may be real". But if it does look like the main jet, or it's very close to the "core", you can say: "Maybe it's a calibration error". This makes it hard to assess some statements about the presence or lack of parsec-scale counterjets, and their asymmetries with respect to the main jets.

This is not, of course, a problem that is unique to VLBI—it's hard to assess the errors in images from any synthesis telescope. The problem doesn't go away when you have 27 antennas! We should really assign errors to our deconvolved, self-calibrated images on a pixel-by-pixel basis. But we can't do that with the algorithms and computers that are available now. I would like to encourage people who think about estimating errors in synthesis images to search for ways to identify that "first spurious feature" objectively—it should not depend on the observer's favorite astrophysical model.

In that context, I'll ask why we never see a "dirty beam" display any more. We are often reminded that the uncertainties in an image are a function of radius away from the brightest thing in it. They are also a function of azimuth around the brightest thing, and there is information about both dependencies in the dirty beam shape. I wonder if VLBI observers stopped looking at the dirty beam because it can be so horrible! When assessing VLA images, we often compare questionable features with the dirty beam shape. If we're asking if some odd-looking feature is part of the source or an artifact that we ought to ignore, it matters whether or not it lies smack dab on a big hump in the dirty beam! So it's not a bad idea still to look at the data this way!

Frequency Undersampling and Future Prospects

Another domain in which VLBI data are obviously still undersampled is the observing frequency. Models were described at this meeting that could say something about the expected spectral evolution of features in jets. But the data can't test these predictions even if the source is well resolved, because only one frequency at a time comes out of these Herculean efforts to make images. The point I want to stress is this: some of the interesting physics can be tackled only by making images in which the frequency is varied without varying the resolution. This is important if you go looking for foreground gas screens by their free-free absorption or their Faraday depth, or if you want to measure spectral variations in resolved jets as they evolve. It's especially important in polarimetry to measure Faraday rotations and depolarization at fixed angular resolution, not with a beam that gets bigger at the lower frequencies.

Unfortunately, there isn't yet, and won't be soon, a single VLBI "instrument" whose pattern of baseline lengths can be scaled in wavelengths when the observing frequency is changed. To get such physically useful frequency agility in VLBI takes different "instruments" (i.e., combinations of different antennas) at each observing frequency. The "scaled configurations" of the VLA give us a powerful tool that VLB arrays will have to emulate if they are to get at the detailed physics of small-scale jets. No one dense array, however well it covers the (u, v) plane at one frequency, will answer all the questions. The full cooperative effort of a "World Array" will be needed. It will therefore be crucial to maintain compatibility between the next generations of VLBI "instruments" on different continents.

Our best (and maybe our last?) chance to explore jet dynamics in detail with radio telescopes will come when we can couple velocity field data with multi-epoch polarimetry and radiometry over a wide range of frequencies at constant angular resolution. If radio data can't answer our questions then, they may never do so! But the data shown at this meeting suggest that the 1990s will be a good decade for this field.

5. Language

I'll end with three comments about terminology. The first is minor, but the other two involve subtle dangers. The language that we use to describe our data is important, because over the long term it can subtly bias the range of physical processes that we think about.

Simulation: I think numerical jet modelers shouldn't use the word "simulation". If you say are "simulating" something, then at least in English that means you are actively trying to deceive someone! "Numerical modeling" is a much better term.

Component: There's a long history behind the use of the word "component" in extragalactic radio astronomy and we all fall into using it. But there is a physical prejudice that comes with this word. It conjures up a view of a wrapped lump of matter—a bullet, rather than something that may equally well be a collective feature or pattern in a flow. The word "component" came into use at a time when discrete events were a popular model for extragalactic sources. In those days, the data were sparse in all domains except Hour Angle, and the best that could be done with them was to fit a few Gaussians—a "component model". So I agree with Ron Ekers's remark that the term "component" should be dropped now that the subject has "grown up".

Core: Ron Ekers also pointed out that it's presumptuous to use the word "core" without knowing (in more than one case, that is) how the alleged "core" moves in an external reference frame. In the light-echo model that he described (page 333), the most compact feature moves in a different direction from the others because it isn't the opaque base of the main jet as the standard picture assumes. It's more like the tip of the counterjet in the "born-again jet" picture. But whatever your favorite model now, the word "core" is a leftover from a model that was discarded a decade ago: it was originally supposed to be a stationary nucleus—the engine, not part of the exhaust! Perhaps it's time for a new word altogether.

I want to add to this a purely observational issue: what are the minimal criteria for nominating a "component" as the "core"? I'm glad that the subject has moved away from assuming that the brightest feature on the image is the "core"; some phony two-sided jets went away at that point! This meeting brought out some dangers of nominating flat-spectrum features as "cores", particularly at low frequencies if foreground absorption isn't negligible. Lack of polarization is also a dangerous criterion at low resolution. Perhaps the only good criterion is a clear demonstration of compactness, i.e., that the "core" is a significant constriction in half-width of the image, at least across the jet axis. For some features that were nominated here as cores, I wonder if compactness was demonstrated well enough to be sure that the right feature was identified.

Well, having tossed my "outsider's" bricks and not having been lynched yet, I will quit while I am ahead, and hand over to the "insider".

6. Discussion

Question: What about the word "jet"?

Bridle: Well, you know what I think about that word! [Laughter]. We still have little right to call the thin kiloparsec-scale features "jets". They might be static cocoons around the real thing, for example. At least in VLBI you have found some direct evidence for outflows—the patterns do actually change! But I think the word "jet" is here to stay! I just hope we can keep minimal criteria—elongation and brightness contrast—for calling part of a source the "jet". But as imaging of the kiloparsec scales has improved, the case for most "jets" based on how long and thin they are and how well they stand out against the lobes has also improved. This may be a place where our intuitions led us to jump in the right direction.

Romney: In the early days, proper motions had to be superluminal or you couldn't detect them at all. And in the early days, they were also observed in the (u, v) plane. One of the alternative explanations that was advanced was the "Christmas tree" model. It seems to me that this model was taken fairly seriously, to the extent that people looked and tried to convince themselves whether it was possible. At the time, it was not. So I would say that your point is well taken that we should probably go back and reexamine this bit of dogma. But the dogma is not based purely on wishful thinking, it's based on an earlier examination of the data.

Readhead: In a number of objects we do have a nice sampling. In sources like 3C 345, there is just no way that they could be moving backwards.

Bridle: But I don't think one object should be allowed to define an entire...

Readhead: I said in a number of objects; not all the superluminal sources have that kind of quality in their data.

Bridle: Yes, but if you discriminate against stationary features when the data are poor, I would say that this is wrong!

Readhead: We don't insist on not having any stationary components. We see them in 3C 345, and then we see accelerations. You are right, we have to be careful, but it's not as if this is not being looked at carefully.

Clark: With respect to your stationary components, I would like to ask a question that is probably too naïve to have a useful answer...

Bridle: No question that Barry asks is too naïve!

Clark: Are stationary components Doppler-boosted?

Readhead: The idea that stationary components were Doppler boosted was one of the ways to get over the fact that they seemed to have about the same flux density as the moving components. That was the first embarrassment with the model where things were going in opposite directions. One of the motivations for the light-echo models was the fact that all components were about the same brightness. Then it was found that the sources were one-sided jets morphologically, so you could explain the core as a region where the material was moving towards you relativistically just like the moving components. This overcame the problem of why there was no three orders of magnitude difference in brightness that was so difficult to explain before. So the answer is yes, the interior of a stationary component is moving relativistically.

Clark: And what is the relation of the gamma that boosts it to the actual speed of the jet?

Readhead: One to one. The idea is that the cores are the places where the jets become optically thick. It's just the surface that the jet material is moving through.

Clark: But the shock is a change in speed, and which of the speeds are you talking about?

Readhead: That's a good question, but it's a sort of second order one.

Ekers: Alan Marscher (page 236) pointed out that the place where the jet is optically thick might either be coming or going. I am having a little trouble seeing how your whole house of cards hangs together; you used to find it to be stationary. But that was not my main point. Alan, I realized as you were talking that you kept saying "you should do this".

I felt embarrassed when I noticed I was doing it myself. Now especially as we are in this building, we have a chance to be one community of people studying these objects instead of VLBA people and VLA people. Putting those together is I believe where many of the answers will come from.

Bridle: I agree. I was asked to wear an "outsider's hat" here, remember!

Owen: I had a comment about "backwards and forwards" motions. From my perspective, it seems that early on there was an attempt to look at whether these things were moving in or out, and you found some very good examples where they were really moving out. But some of the arguments that Phil Hardee has made (page 266), for example, predict that if phase effects are important you might see a minority of sources where things move in. You don't expect it to be the rule, and you pretty much convinced us that most of them are moving out. But maybe we should see some moving in. So you should look really carefully—it would be very exciting if someone reported the first case where you actually have a convincing motion inward...

Readhead: We reported such cases in 1983. Unfortunately, they went away. But still, we will keep trying!

Leahy: Another point is that moving and stationary components are not mutually exclusive. If you watch those things, you can see a semi-stationary feature to which the blobs flow, and brighten as they go through it, and decay as they go out. Now, it would be interesting (I have not seen it done very much) to ask if in a well-tracked source like 3C 345 the brightness of the blobs track each other. It happens in SS433. That would tell us that a shock can be pseudo-stationary. The jet fluctuates as it flows round, but there may still be some particular distance at which a standing shock typically forms.

Wilkinson: 3C 309.1 (Kus, page 161) may be such an example where the bright front is stationary, and there is at least a hint that we can see the material flowing through and past it. That may well be a case where that is actually happening. It shows you can begin to ask those questions and hope to get an answer.

Marr (to Bridle): You were so successful in promoting the word "jet" [laughter] that I wonder if when telling us not to use the word "component" you would like to promote another word, maybe "feature" —something that doesn't imply a physical object?

Bridle: I'd like to think about that! "Feature" covers the case of a pattern that moves differently from the flow. Actually, I didn't promote the word "jet"! That started in the mid-seventies in Cambridge and Leiden, before I was involved.

Ekers: Yes, but you are the one who gave the definition!