MENU FOR AN ALL-PURPOSE SOURCE MODEL

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1. INTRODUCTION

An "Observers' All-Singing, All-Dancing Dream Model" for energy transport in extragalactic sources was presented to the theorists after dinner on the third day of the Workshop. It summarized the observational constraints relating to energy transport in such a way as to promote debate about the physics of a model. It was based on what consensus I found regarding these constraints in discussions among the observers in the first three days of the meeting. These discussions included Jack Burns, John Dreher, Jean Eilek, Robert Laing, Larry Rudnick, Craig Walker, John Wardle and Peter Wilkinson, but the form the arguments take here is tinted (some may say tainted) with my own views, and none of the above should take any blame for this version's shortcomings. At the meeting, the "Observers' Dream" focused an evening of discussions in which several groups brainstormed the physics which might be implied by it.[1]

2. EVIDENCE FOR $\gamma_j \gg 1$ ON PARSEC SCALES

The evidence for Lorentz factors $\gamma_j \approx 5$ in some parsec-scale flows is drawn (in different sources) from the following smorgasbord (see also Dave De Young's review on "jet efficiency"):

(a) the superluminal knot separations in VLBI "core-jets" can be simply explained if $\gamma_j \approx 2.5$ to 10 (for $H_0 = 100$ km/s/Mpc), and if these jets are oriented within the beaming cone (whether or not this is $\approx 1/\gamma_j$ radians, see below) from the observer's line of sight,

(b) the same parameters entail Doppler boosting which accounts for the one-sidedness of the same VLBI core-jet structures,

(c) the same assumptions explain the low Compton X-ray fluxes from compact radio sources (e.g. Marscher and Broderick 1981),

(d) the small angles to the line of sight required by the relativistic-flow interpretation of the above effects are consistent with the large apparent bending observed in the jets of core-dominated sources, and with the misalignments between parsec- and kiloparsec-scale structures in these sources.

Similar assumptions (but with higher values of γ_j) would explain the excessive brightness temperatures implied by rapid low frequency variability, but the variations may also be due to interstellar scintillations (Rickett *et al.* 1984).

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1 Understandably, none of these *ad hoc* "theory groups" wished to have its midnight back-of-the-napkin "models" exposed to the daylight of these Proceedings, but the "Observers' Dream" and the rationale behind it are reproduced here in the hope that they can stimulate further discussion of the problems – Eds.

These arguments favor $\gamma_j \gg 1$ in some parsec-scale jets, and there is little evidence *against* bulk relativistic motion on this scale.[2] It is attractive to propose, as in the "unified" models, that when the line of sight lies within the beaming cone (whether or not this is larger than $1/\gamma_j$) we sample the smorgasbord of core-dominated, superluminal, etc. phenomena described above, but when it is outside the beaming cone we see only the unbeamed parts of the source. The difficulties of explaining sharp bends in relativistic jets (e.g. De Young, this Workshop) may be ameliorated if such bends are actually gradual bends in 3-D that have been amplified by projection.

If some parsec-scale emission is Doppler boosted, one might expect an inverse correlation between the relative prominence of the sub arc-second "cores" seen with connected element interferometers and the projected linear sizes of the extended emission around them – there is some evidence for this (Kapahi and Saikia 1982) in QSR samples. On the other hand, some core dominated superluminal sources have extended radio structures (e.g., Schilizzi and de Bruyn 1983) whose linear sizes would be unusually large if the entire source makes an angle $< 1/\gamma_j$ radians to the line of sight. This problem may be circumvented if the jet trajectories are curved, making the cone of directions over which superluminal motion can be observed broader than $1/\gamma_j$ however[3], so the statistics of extended source sizes around bright cores may be a weaker constraint on the parsec-scale flow parameters than the other phenomena described above. There is therefore broad agreement that:

1. The central engines can make collimated bulk relativistic ($\gamma_j \approx 5$) flows which radiate for at least a few parsecs.

3. Evidence against $\gamma_j \gg 1$ on kiloparsec scales

(a) Weak radio galaxies.

The sensitivity of Doppler boosting to $v_j \sin i$ (where v_j is the flow velocity and i is the angle of the flow out of the plane of the sky) argues against $v_j \approx c$ in the C–shaped jets in "narrow head-tail" sources. If these are bent by the ram pressure of the IGM, v_j changes direction along them by angles approaching 90°. If $v_j \approx c$, they would (a) have large side-to-side asymmetries and (b) change brightness noticeably as they bend, unless the flows are nearly all very close to the plane of the sky, which is highly improbable. This says (e.g. Chris O'Dea, this Workshop):

2. The velocities in head-tail flows are nonrelativistic.

Studies of some elliptical or S0 radio galaxies with dust lanes also show that one-sidedness at the bases of their two-sided jets is not due to Doppler favoritism – three of the one-sided jet bases in seven such galaxies studied by Robert Laing (this Workshop) are on the *receding* side (if the flow goes *out*, not *in*!), and three others lie too close to the plane of the sky for their brightness asymmetry to be due to Doppler boosting. These

[2] Although 3C147 has a complex, two-sided parsec-scale structure (Preuss *et al.* 1984), this is not yet a problem for the bulk relativistic flow model of small jets – a *small* number of apparently two-sided core-jets could arise in the 3C sample as a result of bending relativistic flows across the line of sight.

[3] Scheuer (1984) has proposed an example of such a situation, where the flows follow diverging curves, rather than straight lines. The refractive shock models described by Lind and Blandford (this Workshop, and *M.N.*, in press) give one physical basis for bent trajectories. The Doppler boosting cone may also be broadened by such effects.

data and the brightness asymmetries of some head-tail sources (e.g. 3C129) suggest that (at least in sources with total 1.4 GHz powers $P_{tot}^{1.4} < 10^{24}$ W/Hz) :

3. Some brightness asymmetries in kiloparsec-scale jets are not due to Doppler boosting.

This should make us distrust one-sidedness *alone* as evidence for bulk relativistic motion on any scale, or in sources of any power. Whatever makes non-Doppler asymmetries on kiloparsec scales in weak sources may operate elsewhere too ! Also, as there is no "Compton catastrophe" for weak radio cores, we should attempt to measure proper motions in them. If none proves to be superluminal, there would be no evidence for bulk relativistic motion in *any* weak radio galaxy jets, large or small.

(b) Powerful radio galaxies and QSRs.

The flow parameters in the jets in weak and strong sources could however be significantly different, as the jets in the weaker sources have significantly different properties from those in more powerful sources (Bridle 1984 and this Workshop). The jets in powerful sources are narrow, blobby, and tend to make hot spots, while those in the weak sources are wider, smoother, and fade away without making hot spots. The first list is more characteristic of hypersonic flows, with little entrainment and lots of internal reflecting shocks, punching their way out to classical "working surfaces". The second list is more characteristic of mildly supersonic flows, entraining ambient gas and decelerating, perhaps turning into buoyant plumes (e.g., Geoff Bicknell, this Workshop). It would therefore be attractive if the central engine made high Mach number, narrow flows in powerful sources, and lower Mach number, wide flows in weak sources.

The correlation of jet magnetic orientation with luminosity (Bridle 1984) may also be explained if the mean flow *velocity* increases with source power. The parallel magnetic field components in powerful jets must be maintained efficiently along them against $1/R_j^2$ dilution, as these jets are $B_{||}$ dominated over most of their length (except perhaps at very bright knots, where oblique fields may occur). In weak sources, $B_{||}$ need not be maintained so efficiently, as their jets generally become $B_{\perp}$-dominated, except perhaps at their edges and at bends. If $B_{||}$ maintenance is linked to shear at the edges of a jet, we need a deep, strong velocity shear around straight powerful jets but a shallow, weak shear around straight weak ones. Velocity estimates based on assuming steady energy supply to the lobes and thrust balance between jets and the brighter lobe features (e.g., Bridle and Perley 1984) also suggest that v_j increases with P_{tot}.

These ideas taken together suggest that:

4. Mean flow velocities and Mach numbers both increase with increased power output from the central engine.

But does v_j approach c in the kiloparsec-scale jets in the most powerful "classical double" sources ? The evidence on this point is ambiguous.

Some bent one-sided large-scale jets in powerful sources (e.g. 4C49.22, 4C32.69) have smooth brightness variations which are inconsistent with changing Doppler boosts in high-γ_j flows *if they bend because they are confined or deflected.* Such jets might instead be ballistic, their shapes arising from wobble (precession ?) of the primary collimator; $\mathbf{v_j}$ would not then follow the bends but the wiggle pattern would move outwards as a whole, so that changes in $v_j \sin i$ and in the Doppler boost could still be small. We need to assess whether such jets are indeed ballistic in order to assess whether their brightness distributions argue against $v_j \approx c$. John Wardle showed us evidence that $B_{||}$ is enhanced at the outer edges of the bends in the jet in 4C32.69; this is a phenomenon seen in the jets of lower power sources, where it is attributed to real bending of the flow and to shearing of the field at the outer edges of the bends. If this interpretation is correct, the smooth brightness variation in the jet in 4C32.69 argues that its one-sidedness is not due to Doppler boosting; this may be a useful way to attack this question for other long one-sided jets.

In some radio galaxies, such as 3C277.3, bright, low-velocity extranuclear optical emission line features share the asymmetries of adjacent one-sided radio continuum jets. This requires non-Doppler interpretations of the radio jet asymmetry, as the emission lines cannot be Doppler boosted. Larry Rudnick (this Workshop) has extended this argument to the powerful QSR 0812+02, which has a one-sided optical emission line feature on the same side as its one-sided radio jet. These correlations between radio continuum and optical emission line asymmetries hint that the non-Doppler asymmetries of jets in weaker radio galaxies may indeed extend to more powerful sources.

If the brightness asymmetries in the long one-sided jets in powerful sources are due to the Doppler boost, these jets must be longer in 3-D than they appear in projection. Without detections of the counterjets, it is difficult to assess how seriously this argues against the Doppler boost as the prime cause of these jet asymmetries. We have learned that our statistics of 3CR and 4C QSR source sizes come from samples with significant numbers of one-sided jets – if some kiloparsec-scale flows are even mildly relativistic, the reference samples of lobe-dominated QSRs may be biased away from the plane of the sky to some extent, making us underestimate the intrinsic sizes. Nonetheless, it will embarrass the Doppler boost interpretation if large numbers of very one-sided jets continue to be found in samples of the *most extended* QSR radio sources, as reported here by John Wardle and by Frazer Owen. Even so, energy balance in the lobes and thrust balance at the hot spots may require *mildly* relativistic ($\beta \approx 0.5$) jets in the most powerful sources (e.g. John Dreher, this Workshop). We must carefully distinguish recessed hot spots, which may be oblique shocks in continuing flows, from genuine "beam caps" when making these calculations, however. We also need to know how to recognize, and discount, overpressures at shocks near the ends of hypersonic jets when making the thrust balance calculations for powerful sources.

Overall, it seems likely that:

5. The jets which radiate on kiloparsec scales are generally nonrelativistic, or at most mildly relativistic, flows. There is no clear evidence for flows with $\gamma_j \approx 5$ on kiloparsec scales.

4. PARSEC - KILOPARSEC CORRELATIONS

(a) Core - jet detectability.

With resolving powers ≥ 0.1 arcsec, core and jet detectabilities appear coupled. Jets are detected more often in sources with prominent cores (see the papers by Jack Burns and myself earlier in these Proceedings), and there are very few, possibly no[4],

[4] Robert Laing's evidence that the "core" of 3C351 may be a one-sided jet is my reason for equivocating

known coreless ("disembodied") large-scale jets. Either both the cores and the jets are about equally Doppler boosted, or the luminosities of intrinsically one-sided jets are coupled to those of the cores. This requires that:

6. A significant fraction of the core luminosity in most sources is no more strongly beamed than is the large-scale jet luminosity.

(b) Sidedness.

The correlation between the brightness asymmetries of resolved parsec-scale scale and kiloparsec-scale emission in the same source hands model builders their worst dilemma, so the evidence is worth relating again in some detail.

Of 20 sources in the Bridle and Perley (1984, BP) list with both parsec-scale jets (or jetlike elongations) and kiloparsec-scale jets, five exhibit superluminal expansion (3C120, 3C179, 3C273, 3C279, 3C345 – Cohen and Unwin 1984). In all five, one-sided kiloparsec- and parsec-scale jets start out *on the same side* of the unresolved core. Fifteen other sources in the BP list have jets on both scales, but the proper motions on the parsec scales are either unknown or small. In 12 of the 15 (NGC315, 3C78, 3C84, 0957+56, 3C111, M87, Cen A, NGC6251, 3C371, 3C405, 3C418 and 3C454.3) the brighter large-scale jet is on the same side as a small-scale one-sided jet. The other three are 3C147 (complex small-scale structure), M84 (no closure-phase VLBI map, so its sidedness is unknown), and 3C309.1 (complex large-scale structure, though Peter Wilkinson's results suggest that it fits the trend of the other 12). The fact that the one-sided small-scale jet points "towards" the brighter of the large-scale jets in at least 17 of these 20 sources argues that the prime cause of the jet brightness asymmetry is the same on both scales. Three possibilities may be envisaged: (a) both large and small scale jets are the approaching sides of two-sided (symmetric) bulk relativistic flows, (b) both arise from symmetric two-sided flows whose dissipation of flow energy to synchrotron radiation is greater on one side than on the other, (c) both arise from intrinsically one-sided flows.

Option (b) may be hard to arrange; what physics could maintain a purely dissipative asymmetry over a $10^5 : 1$ range of linear scales, and make its range increase with the power output of the central engine ? Constraints (**1**), (**5**) and (**6**) complicate option (a) if we place all the required ingredients in every source and rely on variations in geometrical aspect to dictate which features dominate the observed radiation. This approach would require a *two-component* ($\gamma_j \approx 5$ and $\gamma_j \approx 1$) flow on parsec scales, the latter persisting to kiloparsec scales and producing the pc-kpc sidedness correlation. This option becomes less attractive as higher fractions of one-sided jets show up in powerful sources (unless the beaming/boosting cones are much wider than $1/\gamma_j$).

Option (c) has no problem with the statistics of large-scale one-sidedness – but if the asymmetric flows were nonrelativistic, or only mildly relativistic, on *both* kiloparsec and parsec scales it would not explain superluminal motions, weak X-ray emission from bright cores, rapid variability etc. in that fraction of the sources which is favorably oriented towards the observer. We can resolve this difficulty if:

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here; other jetted sources with "steep-spectrum cores" could enter this category if no flat spectrum compact component is found in their "core".

7. The engines normally eject material asymmetrically, with both relativistic ($\gamma_j \approx 5$) and nonrelativistic components of the flow on the same side at the same time.

This permits sources in which the flows are sufficiently close to the line of sight to exhibit bulk relativistic effects on parsec scales, but produces the *correlation* between parsec- and kiloparsec-scale sidedness via the *intrinsic* asymmetry. It can be criticised as "having our cake and eating it", but may be physically reasonable if the relativistic flow has a nonrelativistic sheath, or boundary layer. It can be distinguished from other alternatives statistically if the intrinsic asymmetry is too large to be overcome often by boosting. It allows many one-sided jets in big sources, but predicts that only a *small* fraction of the cores in sources with one-sided large-scale jets will show superluminal motions – half of the relativistic flows will be receding from us, and only a subset of the approaching ones will be oriented so as to exhibit superluminal motion. The superluminal motions should always be on the same side as the large-scale jet. Note that the sources with very prominent cores may be those in which emission from the nonrelativistic core component has been augmented by a Doppler-boosted relativistic component, so the statistics of superluminal motion in bright-core sources do not test the above prediction. Because it postulates a nonrelativistic component in the core, hypothesis (**7**) can satisfy constraint (**6**) and also pass Scheuer's (1984) "core detectability" test.

5. Old stuff – Large-scale symmetries

The size and brightness symmetries of the large-scale double structures both require that these structures are unbeamed, and that energy is transported to both sides of most sources within the typical time scale τ_{lobes} for radiative decay of the emission from the lobes. (τ_{lobes} is $\geq \tau_{syn}$, the local synchrotron decay time, the inequality depending on the physics of particle transport and reacceleration within the lobes). Energy transport from the nucleus need not be continuous, however, and *some* sources show detailed "avoidance" behavior in their brightest regions, suggesting that it is not (Rudnick and Edgar 1984; also see Ensman and Ulvestad 1984). The basic requirement is thus:

8. Energy transport is equalised on the two sides of most sources on time scales $< \tau_{lobes}$.

6. Constraints on Flip-Flop Models

Constraints (**7**) and (**8**) together nudge us in the direction of "flip-flop", or at least very asymmetric, outflow models (Willis *et al.* 1978; Wiita and Siah 1981; Robson 1981; Linfield 1982; Saikia and Wiita 1982; Rudnick 1982 and this Workshop; Icke 1983; Lonsdale and Morison 1983; Rudnick and Edgar 1984), and impose constraints on the *mean* time scale τ_{flip} for reversing the asymmetry at the central engine:

9. The asymmetry of the large-scale flow must reverse on a typical time scale τ_{flip}, where $\tau_{flip} < \tau_{jet} < \tau_{lobe}$ in the low power sources, but $\tau_{jet} < \tau_{flip} < \tau_{lobe}$ in the powerful sources.

Here τ_{jet} is the typical time scale for decay of the emission from the jet(s) in a given source – it will generally be the energy transport time scale d_j/v_j for a jet feature distant d_j from the core, but could be the local synchrotron decay time scale if this is $< d_j/v_j$ and there is no particle reacceleration. The constraints in (**9**) are required if flip-flop models are to produce two-sided jets and two-sided lobes in the weak sources, but one-sided jets and two-sided lobes in the more powerful sources. Loosely speaking, they call for rapidly flipping asymmetric ejection in the weak sources and slowly flipping asymmetric ejection in the powerful ones. τ_{flip} need not be interpreted strictly as the constant period of an oscillation – it is sufficient that it represent the *mean* time between the flow from the central engine favoring one side over the other. "Pieces of jets" (Larry Rudnick, this Workshop) could be cases where the ejection is intermittent, or flips sides, on a time scale $< d_{lobe}/v_j$. The flip-flop model readily accommodates both "avoidance" behavior and "pieces of jets", but apparently smooth two-sided jets (as in the symmetric parts of 3C31 or M84) are harder to explain, unless $v_j \tau_{flip}$ is below the linear resolution of present maps. This may be possible if the flows in weak radio galaxies are decelerating due to entrainment, but seems somewhat contrived. It might be simpler if the model could provide for the average asymmetry of the flow to decrease with decreasing luminosity of the central engine.

7. Constraints from Hot Spots

Hot spots can occur on both sides, on one side only, or on neither side, of double sources – the hot spots are prominent in powerful sources and absent in weak ones. The absence of hot spots in weak sources can be interpreted as a low-Mach number effect, as in §3, but there is also an important correlation in powerful sources with strong cores (BP; Robert Laing, this Workshop) – in many of these, one hot spot has significantly higher surface brightness and flatter spectrum than any other, and this is usually the jetted hot spot if a jet is visible. (This is the main *systematic* difference between the radio structures on the jetted and unjetted sides of strong-core doubles). In powerful radio galaxies, or powerful sources with weak cores (these definitions are almost equivalent), the hot spot brightnesses are generally more equal and the jet and hot spot symmetries are less clearly related – the jets are also much harder to detect. The enhanced brightness of the jetted hot spots in strong-core doubles could be due either to intrinsic asymmetries or to the hot spots having mildly relativistic motions, but the brighter hot spots in such sources are not systematically further from the cores, as expected in naive (steady, collinear) relativistic outflow models.

A model with intrinsically asymmetric outflow can accommodate these constraints if $\tau_{flip} > \tau_{hotspot}$ in most QSRs but $\tau_{flip} < \tau_{hotspot}$ in most powerful radio galaxies. Cyg A exemplifies the powerful radio galaxy case – it has a relatively weak core, strong symmetric hot spots and a weak jet; these properties fit mildly relativistic symmetric flows easier than intrinsically asymmetric flows. The brightness fluctuations of the main jet in Cyg A may fit an *intermittent* ejection model, but the brightness symmetry of its hot spots would be explained more convincingly in an *alternating* ejection model if there was clear evidence for similar "pieces of the counterjet" among the filaments and wisps in its South-following lobe[5].

[5] Whether such evidence existed already was debated at the Workshop, based on VLA images of Cyg A employing various contrast- and gradient-enhancement techniques. The brightness, location, shape and continuity of the Cyg A counterjet, if one exists, are so important that I reserve assessment of them until the experimental evidence becomes clearer.

8. The Stuff the "Dream" is made of

The "Observers' Dream" is thus a central engine that can produce intrinsically asymmetric, relativistic *and* nonrelativistic flows whose velocity, Mach number, flipping time scale, and perhaps asymmetry, all increase with total power output. To meet constraint (6), the nonrelativistic (unbeamed) flow should begin on sub-parsec scales in most sources. Whether there need be a relativistic flow on *any* scale in intrinsically weak sources depends on whether superluminal motions are found in those with weak large-scale structure[6]. The $\gamma_j \approx 5$ component specified in (7) could be an "optional extra" if superluminal motions and rapid variability prove to be sufficiently rare in complete samples selected by the flux density in their large scale structures.

Conversely, it is not (yet) essential that highly relativistic flow persists beyond ~ 10 pc in any of the sources which *do* show evidence for it closer to the nucleus, but detection of superluminal motions at greater distances could extend the range required. The modelers are free to specify the fate of this component of the flow far from the core, providing it "poops out" sufficiently that its radiation rarely dominates the large-scale emission; the *radio* data do not yet tell us clearly where or even whether it is decelerated to nonrelativistic velocities.

9. Problems for the Observers

(1) Find secure, direct constraints on the flow velocities, particularly in the one-sided, powerful jets.

(2) Find out *how* one-sided these jets really are by hunting for their counterjets. This will be easiest in sources with bright enough small-scale structure to permit self calibration, but which are not too core-dominated. I hope that improvements in image processing, and long VLA syntheses, will show us the counterjets in some powerful sources – this would tell us (a) by how much the asymmetries of these sources exceed the non-Doppler asymmetries at the bases of the jets in weaker sources, and (b) how bad the inclination-related problems are for these sources if their asymmetries are interpreted using the standard relativistic flow models. Such observations could also tell us more about how well the radiation is suppressed in the initial "gaps" in jets, and between "pieces of jets" further from the cores; this would help us to assess whether we are dealing with actual flip-flops, or variable asymmetry, or variable jet velocity.

(3) Use VLB arrays to study the cores in complete samples of sources with (a) one-sided and (b) two-sided, large-scale jets. How often does superluminal motion occur in each of these groups ? Do their parsec scale properties differ – is there any evidence, other than jet sidedness, for relativistic flow on parsec scales in weak sources with two-sided jets ? How often does superluminal motion occur on the large-scale jetted side of sources with one-sided jets ? Are there convincing cases of two-sided jets on parsec scales, or of a one-sided parsec-scale jet opposing a one-sided kiloparsec-scale jet ?

(4) Do we violate Faraday rotation constraints if we ask that the relativistic parsec-scale flows are surrounded by nonrelativistic flows going in the same direction ? This requires polarimetry of the superluminal components – the maps John Wardle showed

[6] 3C120 shows that this *can* happen, and the core dominated BL Lac objects with weak, edge darkened large-scale structure may be the best places to search for superluminal motions to test this point.

us here prove there is polarized signal to look at, so VLBI referees should be encouraged to allocate the time !

10. Problems for the Theorists

(1) How difficult is it to brake a relativistic jet between the parsec and kiloparsec scales without converting much of its energy into heat ? Must a jet be transonic to slow down quietly (Begelman 1982; Scheuer 1983) ? (If quiet braking is possible, the nonrelativistic or mildly relativistic flow required on kiloparsec scales in powerful sources may derive its energy and momentum fluxes by degrading an initially relativistic flow).

(2) How would a spine of "radio-quiet" relativistic flow affect the observable properties of a sheath of "radio-loud" nonrelativistic flow on kiloparsec scales ? Could it be bent without becoming visible in ways which conflict with jet data ? Could it provide ongoing particle acceleration far from the core ?

(3) Can a flip-flop jet production mechanism be made, which switches its asymmetry on time scales *long* compared with those of outflow from the primary collimator, but *short* compared with those of radiative decay in the jets of weak sources and the lobes and hot spots of strong ones ? Can the switching time, flow velocity, initial Mach number (and perhaps asymmetry) be made to increase with outflow power ?

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