UNITY AND DIVERSITY AMONG JETS IN ACTIVE GALAXIES

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1. INTRODUCTION

Jets, and more general kinds of directed flow, are increasingly seen as important aspects of the activity of galactic nuclei. Their frequent presence, on scales from parsecs to megaparsecs, in radio galaxies implicates jets in the production of radio lobes, and instances have been found of jets apparently "frustrated" and disrupted in gas-rich galactic disks. Jet-like emission is occasionally found on small scales around Seyfert nuclei, with some observations suggesting links to nuclei at yet lower levels of (radiative) activity.

Despite enormous investments of observational and theoretical effort, few of their physical properties are well-known, and most of the processes involved in their production and evolution remain obscure. Indeed, there is no firm definition of what, exactly, constitutes a "jet". The term was apparently introduced in the context of active galaxies by Baade and Minkowski (1954) to describe the feature in M87, once known as a "ray" (Curtis 1918). As several authors (e.g., Bridle 1984) have pointed out, use of "jet language" to describe elongated structures (usually as observed in the radio) can prematurely guide one's thoughts regarding energy flow, even when there is no real evidence of motion along the "jet". Indeed, the present state of understanding of jets in active galaxies is perhaps best summarized by a series of questions:

1) What (if anything) actually moves along jets? Is such a flow more like fluid or ballistic motion? Observed features might be analogous to avalanches or waterfalls.
2) How fast is this motion? Cogent arguments exist for relativistic and for non-relativistic flow, but a transition between them in most cases is difficult to envisage.
3) What relation does the observed structure bear to the pattern of mass and energy flow?
4) Do jets provide an important fraction of the energy output from at least some active nuclei? If so, on what linear scales?
5) What is the role of efficient (and so invisible) jets?
6) Do radio-quiet forms of jet activity exist? How are these related to

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"classical" radio jets?

7) Exactly how is a jet linked to the nucleus? Might we observe fossil jets after a nucleus turns off?
8) How are jets accelerated in the first place, and how do they maintain high degrees of collimation virtually independent of the local environment? These points have provoked enormous amounts of discussion in the literature, but the theoretical basis is still quite unclear.

In this review, I will discuss several of these points, with particular emphasis on some "heretical" ideas. Relatively little will be said about the systematics of recent radio observations, these having been well covered in the review by Bridle and Perley (1984) and the proceedings of the Green Bank Workshop (Bridle and Eilek 1984). However, since radio jets are the majority of suspected ejection phenomena known, some generalities arising from these observations will be discussed first.

2. WHAT ARE WE SEEING IN RADIO JETS?

The jets of radio galaxies and QSOs are in most cases clearly dominated by synchrotron radiation. Their spectral shapes and polarizations lead to consistent pictures of (local) emitting properties, including optical and IR data for a few of the brightest objects (Fig. 1). This implies the presence of electrons with an energy distribution ranging at least up to $\gamma = 10^6$ and a magnetic field which is ordered on scales at least tens of parsecs (to produce significant overall polarization). Comparison of the structure of the M87 jet in widely spaced frequency regimes (Keel 1984) suggests that the radiating particles are confined by the field structure; they are not free to stream even in one direction. The discussion of this point by Shklovskii (1984) leads to the question of whether the plasma and field distributions really resemble one another - if we see only regions where the magnetic field is high, what might be going on outside these regions? Models in which the jets carry a current (naturally easing magnetic confinement) require a backflow in unseen regions, and this might be just the beginning.

3. BULK AND LOCAL MOTIONS ALONG JETS

The high Lorentz factors associated with synchrotron radiation at the observed frequencies mean that the radiating electrons are certainly relativistic. This does not mean that the overall motion must be. In fact, in light of the preceeding discussion, it is not clear just what we would expect to see moving with what we would like to identify as the jet velocity. This is essentially the question of what the substructures seen in jets are - separate plasmoids or denser packets of ejected matter, wave phenomena within the jet, or externally imposed (e.g., magnetic) radiating regions with little direct connection to the flow. Interpretation of substructure should be approached with caution, in

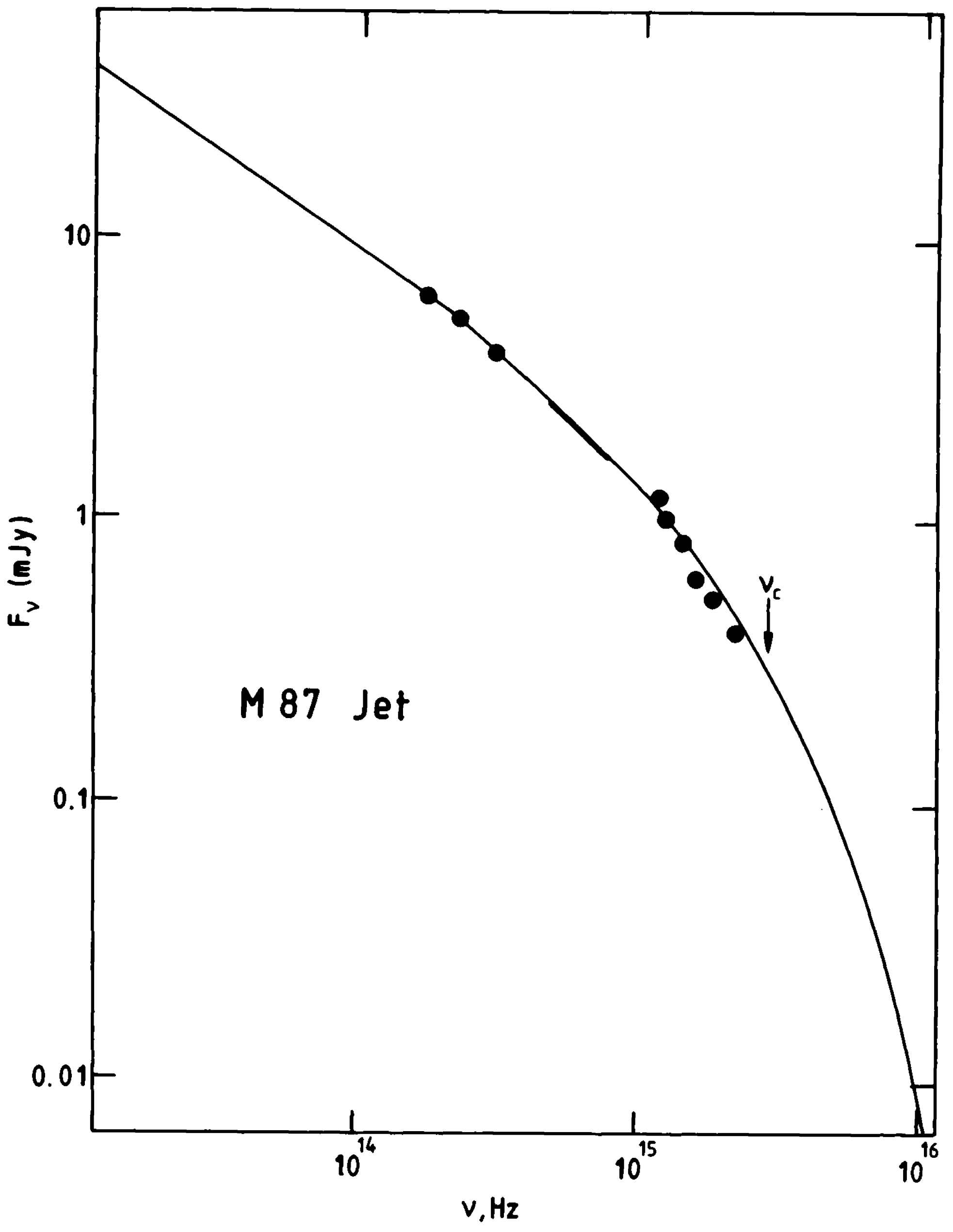

Fig. 1: Observed spectrum of the brightest part of the M87 jet (dots and thick line, from Keel 1984 and references therein), compared to the synchrotron spectrum of a truncated power-law distribution of electron energy (thin line). The critical frequency of emission from the highest-energy particles is at ν_c.

light of Roberts' (1986) simulations in which stochastic changes in flow and position angle can mimic periodic wiggles and knots.

The strongest evidence that at least some observed features are moving with the flow comes from VLBI "superluminal" and related sources. If the features are not some kind of wave phenomenon (in which the observed motion has the role of a phase, rather than a group, velocity), their observed speeds virtually require that jets be relativistic on parsec scales. Miley (1983) and de Waard (1986) have examined the role of the jet wall itself in supplying the illuminated screen necessary to give apparently superluminal motions under these circumstances. But, as De Young (1984) has stressed, the distortions to which large-scale jets and lobes are prone, and lack of obvious radiation from shocked regions at these locations, hardly seem compatible with high velocities. The dilemma is made even more severe by the observations of 3C293 and 3C305 (Heckman et al. 1982, van Breugel et al. 1984) which seem to show rapid disruption of powerful radio jets in gaseous disks, again suggesting relatively small specific momenta.

Perhaps more convincing evidence of relativistic motion on large scales would be direct measurement of proper motions for discrete features in a jet. In M87, probably the best case in which to search for such motions, the structures in the jet have no components small enough to be detected with current VLBI equipment (Reid et al. 1982). Repeated VLA or MERLIN observations thus seem to offer the best hope for detecting or setting important upper limits to motion of the knots, which can be done at better than the 0.1" level now (15 light-years for a distance of 20 Mpc). A time baseline of decades is then required, within which improvements in both VLBI and optical technology may well come into use.

Combined observation of 3C120 over a wide range of angular scales suggest that the superluminal blobs seen with VLBI merge smoothly into the large-scale, curved jet (Walker 1984). This object is a direct illustration of the apparent paradox posed by relativistic motion on parsec scales coupled with evidence of much slower motion on kiloparsec scales, with no hint of the side effects to be expected from decelerating the jet in between. A further question is raised by the observations of 3C345 (Biretta et al. 1983; Moore, Readhead and Baath 1983) in which the superluminal components do not start their motion at the apparent core position. A gravitational-lens effect due to the (presumedly) massive central object might be invoked, but the whole issue is quite open.

Recognition that there may not be a straightforward relation between the appearance of a jet and where the energy really goes has deep (one might say undermining) consequences. For example, if much of the flow is efficient and unseen, in a region of low magnetic field, do we really require reacceleration of the particles within the jets? Kundt (1985) has noted that a TV screen provides a local counterexample, in which radiation and acceleration are uncoupled. What we see radiating at a particular point has not necessarily been doing so all the way out.

4. JETS WE DON'T SEE AT ALL

The existence of "hot spots" in the lobes of radio galaxies is often taken as evidence for either invisible jets that are in some sense efficient, wasting little energy on radation, or for flip-flops of jets on timescales short compared to the radiating lifetime of a hot spot. The phenomenology of hot spots, jets and lobes is so complex as to be of little help here; in addition to classical Cyg A hot spots in lobes, single hot spots are seen, either at the end of a radio jet or (rarely, as in 3C200 and PKS0521-36) on the opposite side from a jet.

The observations,even if arbitrarily good, can thus provide only a lower limit to the number of active galaxies with jets. There are some nearby galaxies in which it appears that the effects of jets are much more obvious than jets themselves. The type 2 Seyfert NGC 5929 shows a pair of radio sources, each associated with a distinct emission-line region, on either side of the kinematical center of the galaxy, which is itself the locus of a weak broad-line region (Keel 1985, Whittle et al. 1986). The twin narrow-line regions may be fed by (yet-unobserved) jets from the nucleus. An optical emission and radio knot in NGC 2655 (Fig. 2) may be a one-sided version (Keel and Hummel 1986). Some form of unseen energy transport seems required to explain the kinematics of gas near the nucleus of M51 (Ford et al. 1985; Goad and Gallagher 1985).

Aside from suggesting a possibly common class of objects with rather dim but important jets, these may point our attention to jet smaller scales. How much of the commotion deep inside galactic nuclei involves jets? Norman and Miley (1984) have considered both kinetic energy and radiation from small-scale (radio-loud) jets in accounting for the various emission regions deduced from spectroscopic studies. Certainly in many luminous radio galaxies and QSOs with VLBI jets, the energy content of these is so high that a significant impact on the surrounding gas seems inevitable.

5. RADIO-QUIET JETS

Considering invisible or shrouded jets also leads one to examine jets that are visible in one domain (usually optical) but not in the radio as expected for canonical synchrotron jets. The four jets of NGC1097 are the best example known so far. Ten years after the discovery of the first (Wolstencroft and Zealey 1975), they are as much of a puzzle as ever. Considerable observational effort (required by their very low surface brightnesses, near B = 27 per square arcsec) has been expended in several attempts to specify the jets' radiation mechanism, and what, if any, relation they have to the history of the nucleus. Many of these results have been negative: searches for radio or X-ray emission (Wolstencroft et al. 1983; Wolstencroft, Tully and Perley 1984) detected neither; additionally no strong emission lines are present in the

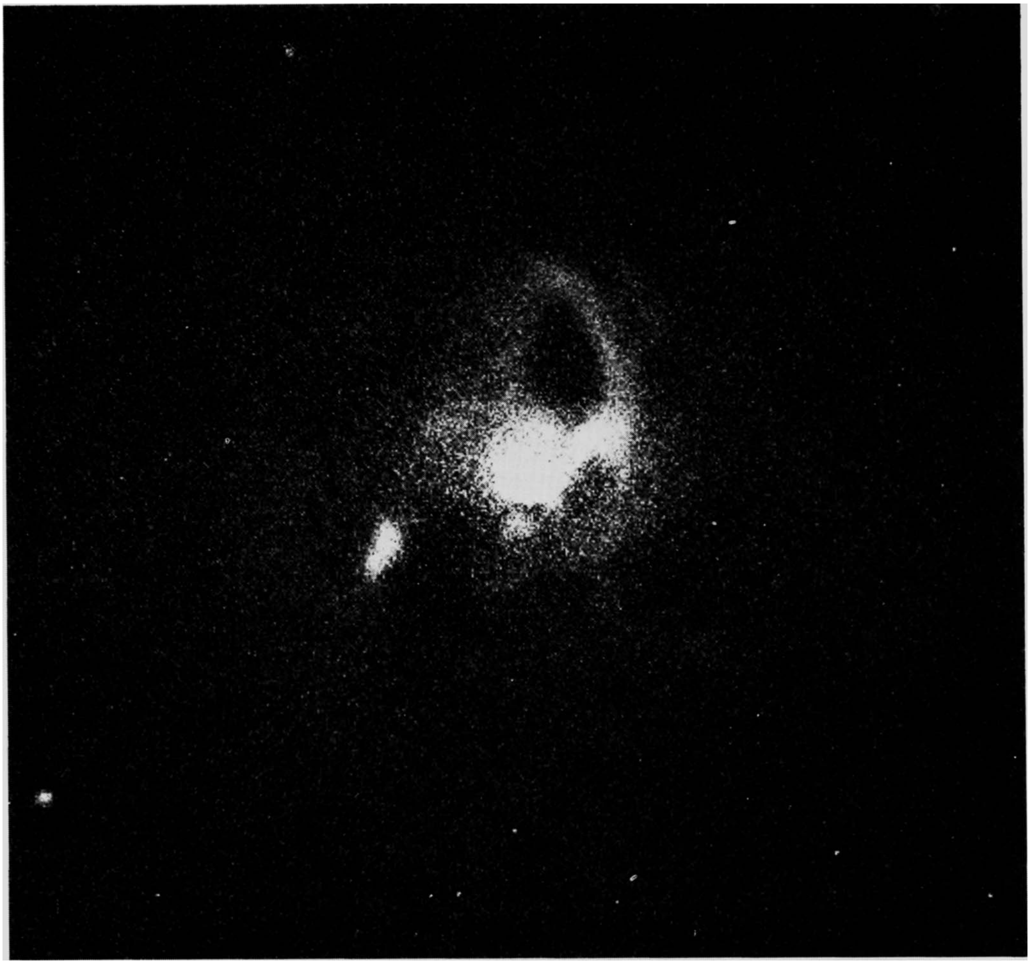

Fig. 2: Hα+[N II] image, after continuum subtraction, of the nucleus of NGC 2655 (KPNO 2.1-m with TI CCD, 100" square). The detached emission region to the southwest (lower left) coincides with a radio source, and may be the working surface of a very faint jet.

optical. The optical and near-IR colors of at least one of the jets (Carter, Allen and Malin 1984); Keel, in preparation) suggest starlight as the radiation mechanism; further, this requires the least ejected mass among the processes still allowed by the data. The number of jets, even though one bends abruptly by 90°, suggest very strongly that we are dealing here with matter ejected from the nucleus, or illuminated by some stimulus from the nucleus. Thus, we are forced to consider the possibility that some galaxies can eject 10^7 solar masses in a form which, after 10^8 years, can end up in stars.

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It remains unclear how many objects with ejection of this kind might be found. The low surface brightness of the features in NGC1097 has meant until recently that such objects could only be found accidentally, during deep studies of individual galaxies. The SRC(J) sky survey can show structures at these levels, so that this survey (and the northern IIIa-J survey in progress with the Palomar Schmidt) should allow reasonable searches for more such objects. A search from the SRC survey, taking due account of the many things that can mimic the appearance of jets (Keel 1985), has already turned up about 15 confirmed jet-like features at least comparable to those around NGC 1097, though none of the new ones is as extensive or multiple. To this extent, there does seem to be a class of galaxies showing optical, but not radio, evidence for collimated ejection of matter from the nuclei. The relations between them and more conventional radio galaxies will be important to uncover.

6. JETS AND WIDE-ANGLE OUTFLOW FROM ACTIVE NUCLEI

Tied to the exact "narrowness" we require of a "jet" is the relationship of highly collimated features to the broader outflow now inferred to proceed from many galactic nuclei. Are such flows distinct phenomena, or failed jets that were not well collimated?

The existence of wide, more or less conical distribution of outflowing matter has usually been deduced from gas kinematics measured in optical emission lines. In NGC 1365 (Phillips et al. 1983), NGC 5506 (Wilson, Baldwin, and Ulvestad 1985), NGC 7582 (Morris et al. 1985) and Fairall 427 (Wilson and Baldwin 1986) the velocity pattern in high-ionization lines is best modelled as roughly biconical outflow, with one lobe often obscured by dust in or near the galactic plane. The expansion velocities are modest, of order 300 km/s.

The major unknown in relating these flows to other manifestations of nuclear activity is whether they are more closely related to winds or to jets. It may be that jets are a very special case of collimated winds (as in models where collimation proceeds via a thick accretion torus), but the mechanisms for generating a wind are general enough that both winds and jets may be expected in some objects (Schiano 1985). Energetic winds may not actually require an active nucleus for their production; intense star formation seems to have produced hot flows detected in X-rays around the nuclei of NGC 253 and NGC 5236 (Fabbiano and Trinchieri 1984; Trinchieri, Fabbiano, and Palumbo 1985), and several very powerful starbursts found by IRAS show M82-like sets of emission filaments that may be modelled in a similar way (Heckman, Armus, and Miley 1986).

7. INTERACTION OF JETS AND THEIR ENVIRONMENTS

There are several observable effects of jets' interactions with the gaseous environment, which can in principle probe both the jets'

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surroundings and the properties of the jets themselves. On large (kiloparsec) scales, we might expect to see effects of mass entrainment and shocks of various kinds as the jet strikes clouds essentially at rest in the host galaxy's interstellar medium. These will in turn produce emission-line or star-forming regions, and decollimate or deflect the jet. In the latter case, the clouds' existence is so far only inferred; although a hot cloud is perhaps the cleanest way yet discussed to produce discrete bends in radio sources (e.g. Eilek et al. 1984), there is yet no direct evidence of such clouds despite careful optical searches (O'Dea, Owen, and Keel 1986). Emission-line clouds do appear at bends in the southern jet of Coma A (van Breugel et al. 1985a), but a synchrotron continuum is produced locally in these regions, complicating the analysis. Their data do suggest that a massive ($> 2 \times 10^6$ $M_\odot$) cloud has been struck and accelerated by a radio jet, which is itself defected and widens rapidly past the collision site. Some of the Hα filaments associated with the NE jet of Centaurus A also appear to be of this kind (Fig. 3).

Star-forming regions triggered by jets allow some firm conclusions, because at least timescales and rough physical conditions needed for this are known. The optical filaments associated with the NE jet of Centaurus A (Blanco et al. 1975) contain blue supergiants and H II regions indicates a timescale of a few times 10^6 years for complete dissipation - either this is a very transient phase in evolution of the source, or replenishment takes place through compression of presently unseen low-density gas (Graham and Price 1981).

A more spectacular example of jet-induced star formation has been identified by van Breugel et al. (1985b) and Brodie, Bowyer, and McCarthy (1985) - PKS 0123-016A and Minkowski's object. Extensive and intense star formation is seen at the point where the jet of PKS 0123-016A loses collimation and intensity, and becomes depolarized. Van Breugel et al. suggest that this is the result of a jet impinging on a gas-rich irregular galaxy, shocking many of its interstellar clouds into collapse. They are able to estimate a jet velocity of a few thousand km/s at the contact with the clouds - important because of the total lack of direct measurements of velocity in large jets.

8. JETS AND NUCLEI

This is perhaps the most fundamental area in the study of jets in active galaxies. What does the existence of a jet tell us about the central engine, and about its immediate vicinity? It is widely believed that accretion disks define allowed directions of ejection, and perhaps play a role in collimating the jets as well. Clues to the physics here might be found by examining the occurrence of jets among active nuclei whose properties span the observational classifications (Seyfert nuclei, radio galaxies, QSOs...) and seeking any relationships between jets and nuclear properties.

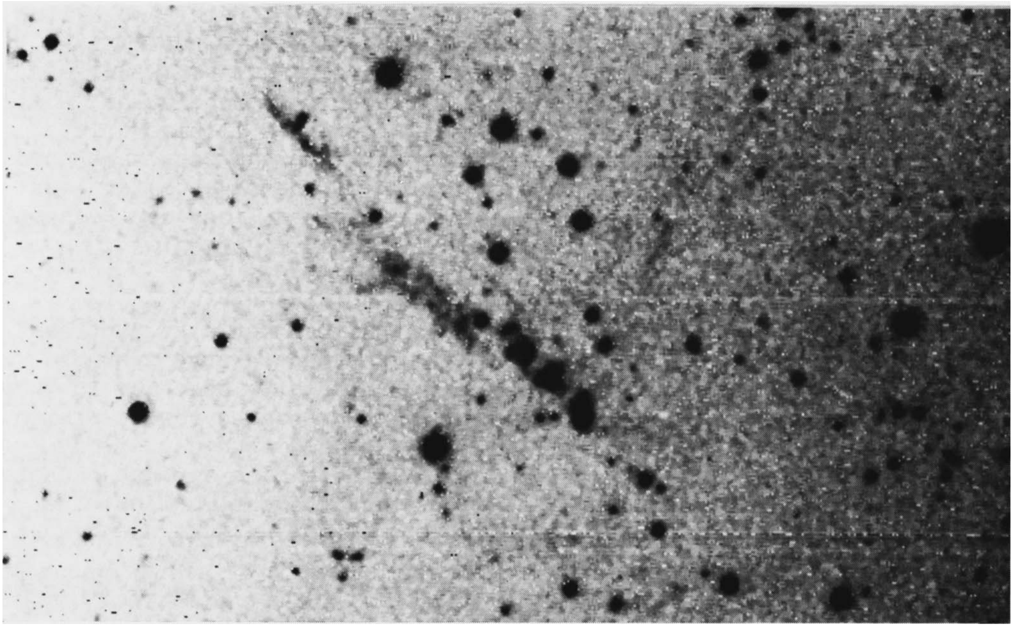

Fig. 3: Hα image of optical filaments in the NE jet of Centaurus A (CTIO 1.5-m with RCA CCD; field 3!2 x 4!6). The bright emission regions lie near the edge of the radio jet; weak filaments cross the jet and might be entrained matter.

Only the sketchiest results are possible yet, even for classical radio jets. It does seem to be the case that no jets are seen without fairly strong flat-spectrum core sources, but it is not clear whether the data allow the optical continuum luminosities of these cores to scale simply with the radio luminosity. Most nuclei among samples of galaxies selected purely on the basis of integrated radio flux show optical emission idicative of only weak activity, as for example in LINERs (Antonucci 1984b). It has often been assumed that a high level of activity, as shown by the radiation output of the central source, is a prerequisite for producing powerful jets. However, models do exist in which the presence of an accretion disk an magnetic field around a black hole of large angular momentum can lead to expulsion of material along the disk axis, independent of the rate at which accretion across the event horizon is occurring. This is a form of the "Penrose mechnism" for extracting energy from a rotating black hole (e.g. Penrose 1969). Its viability in the context of active nuclei has been investigated recently by Wagh, Dhurandar and Dadhich (1985) and by Chakrabarti (1985); the process seems to be feasible if large-scale, changing fields are present. Such an origin is at least consistent with large magnetic-energy content inferred in synchrotron jets.

Important evidence that indicate a direct link between accretion disks and jet production comes from the comparison of position angles of optical polarization and radio structure. It now appears that quasars (Stockman, Angel, and Miley 1979), Seyfert nuclei (Antonucci and Miller 1985), and radio galaxies (Antonucci 1984a) may fall into two classes, in which these angles tend to be parallel or perpendicular. There is a tendency for narrow-line objects to have the angles perpendicular, while they are systematically parallel in broad-line objects. A plausible interpretation is that much of the optical continuum has been scattered off the disk, which is thick (a torus) in narrow-line objects (so less of the innermost region normally giving rise to broad lines can be seen) or thin (in objects with a readily observable broad-line region).

One problem in addressing the relation between jets and nuclei is that of choosing an appropriate indicator of nuclear activity. Optical continuum and emission lines may be weak or obscured in some systems with a strong radio core, while such a core, unless its spectrum is very flat, could be confused with emission from jets on parsec scales (which can be as strong as the true core, from various VLBI studies). X-ray luminosity might be less confused, but present data here are not capable of enough resolution to separate the nucleus and its environment. The best that can be done now is to say that an active core must be present in some cases (flat-spectrum radio core, rapid optical or X-ray variability), but not to rule out such activity in many objects. This is obviously a rather unsatisfactory state of affairs.

9. CONCLUSIONS

I cannot resist closing with the familiar refrain of "more and better observations are clearly needed". Despite the considerable observational and theoretical effort already expended on extragalactic jets, our understanding of these structures has only the most rudimentary physical basis. In particular, there are strong needs to have

1) reliable velocity information for at least one synchrotron jet
2) knowledge of the environments of jets within galaxies
3) a clear indication of the nature of radio-quiet jets
4) kinematic studies sufficient to indicate whether intermediate-cone angle ejection is found in active nuclei.

These items are at present difficult observational tasks, and will remain difficult (but perhaps tractable) in the foreseeable future. However, their results will be crucial in understanding the physics of nuclear ejection and its relationship to the central energy source. As one of the most characteristic features of active nuclei, jets almost certainly hold important keys to our understanding of active nuclei.

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DISCUSSION

SULENTIC: You show numerous examples of galaxies with and without jet-like features. The general impression gained is of collimated and explosive outflows from galactic nuclei. Several objects in this general class (e.g. N 4736, M 51 and N 4319) show LINER spectra (particularly [NII]/H$\alpha \geq 1$). This suggests that a fourth class is needed in Dr. Heckman's list of LINER mechanisms IV - Shock excitation by explosive events originating in galactic nuclei.

BOCHKAREV: Is there any correlation between LINER phenomenon and presence of jets? To what type of LINERs does this correlation apply (according to Heckman's classification)? And what percentage of nuclei (or LINERS) have optical jets?

KEEL: The statistics available are very poor and in no sense complete, especially as to the fraction of nuclei of any kind with jets. It is clear, however, that galaxies with luminous radio sources (and jets) can have LINER nuclei. NGC 1097 is also a LINER; these could be "classical" LINERs in Heckman's classification.

ANTONUCCI: Several comments: 1) Your reasoning requires the assumptions that the jets are intrinsically two sided. 2) Schilizzi and de Bruyn took several short cuts in the comparison of the projected linear sizes of superluminal to ordinary radiosources. They compared low-extended power superluminals to ordinary sources, and they did not allow for bending of the extended sources and finite lobe sizes, in doing their de-projection. Ulvestad and I found that blazar projected linear sizes are consistent with foreshortening.

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