Interferometry of Extragalactic Radio Sources

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1. Introduction

Most of the brightest cosmic radio sources are produced by active galaxies or quasars at great distances in the Universe. Their radio luminosities are from 10^2 to 10^6 times those of "normal" galaxies such as the Milky Way, which are radio sources primarily because a small fraction of the energy released throughout them by nuclear processes in stellar cores "trickles down" to radio wavelengths. Normal galaxies emit only about one millionth as much power at radio wavelengths as in the visible. Because it is basically powered by stellar processes, most of this emission comes from the volume occupied by their stellar population. In contrast, the radio luminosity of "radio galaxies" and "radio loud quasars" can equal their visible energy output. Remarkably, this emission often arises tens, or even hundreds, of kiloparsecs outside the associated visible objects. (A parsec is 3.26 light-years).

This aspect of the powerful sources was first uncovered by Jennison and Das Gupta (1953) using a 125-MHz post-detection correlation interferometer to study the radio galaxy Cygnus A. They found that its emission comes from two "lobes" well outside the parent galaxy, posing one of the most enduring and difficult problems in extragalactic physics — to explain how such powerful radio emission can be maintained so far from the visible stellar populations (and by inference from most of the mass) of the parent objects. Since then, every major advance in radio interferometry has uncovered a new facet of the powerful extragalactic sources. This article reviews recent developments in the field and outlines one role that the proposed Canadian Long Baseline Array (Legg 1982) will play in defining the physics of extragalactic sources.

2. Phase Stable Aperture Synthesis

In the 1960s, Martin Ryle's group at the Cavendish Laboratory developed the technique of earth-rotation aperture synthesis, wherein the output of a set of phase-stable interferometers is recorded while they rotate relative to the sky as the Earth turns. Such observations sample the two-dimensional Fourier Transform of the distribution of radio brightness over the area of sky within the field of view of the individual antennas. A high-resolution image of this sky area can then be derived by standard techniques of two-dimensional Fourier inversion. This method was used throughout the 1960s and 1970s at the Cavendish Laboratory, in Holland, the U.S.A., Australia and Canada, to map many hundreds of extragalactic sources at centimetre wavelengths with resolutions of a few arc seconds or tens of arc seconds.

2.1 Cores and Hot Spots

Such studies showed that the powerful extragalactic sources usually have much fine structure (see Figure 1). Their lobes often contain bright "hot spots" near their outer edges, and most of the sources have unresolved radio "cores" at the centres of the optical objects. The large-scale structure usually has an approximately $\nu^{-0.75}$ spectrum and is linearly polarized. As synchrotron emission is the most efficient process that is likely to produce radio emission over these scales, and this mechanism leads to linearly-polarized radiation, it is widely supposed that these structures are synchrotron sources. In that case the $\nu^{-0.75}$ radio spectrum would correspond to a $E^{-2.5}$ electron energy spectrum, similar to the energy spectrum of cosmic rays in our galaxy.

The discovery of the radio "cores" reinforced the suspicions of many astrophysicists that the primary energisers of the extended radio sources reside in the deep gravitational potential wells at the centres of massive galaxies or quasars. The MINIMUM energy budgets of the lobes (estimated assuming that they are indeed synchrotron sources) are typically equivalent to the rest-mass of from 10^5 to 10^7 solar masses. With plausible energy conversion efficiencies, masses of order 10^7 to 10^9 solar masses must somehow be implicated in the emission process. It was hard (although not impossible, given the inventiveness of astrophysicists) to see how the massive energy suppliers could be located in the lobes themselves. Optical spectroscopic evidence for highly-excited gas around active galactic nuclei was also accumulating in the 1960s and 1970s. Speculation that the lobes of the powerful sources are somehow fuelled from activity in the central objects therefore grew.

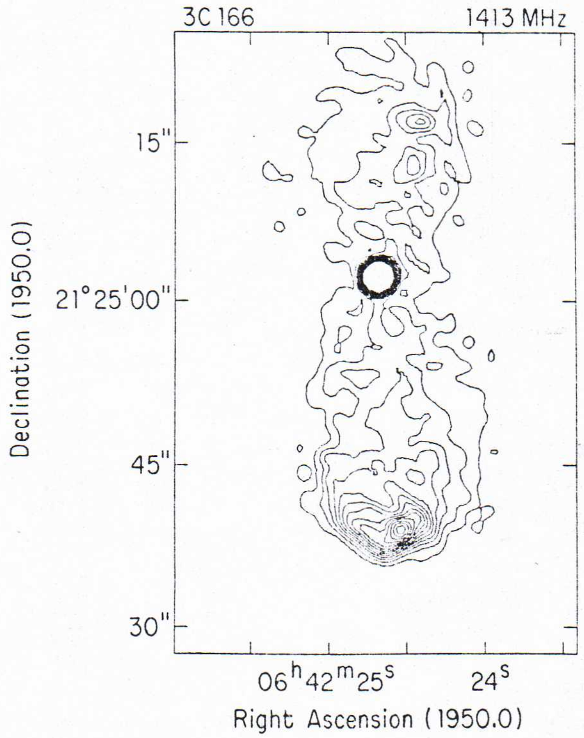

Fig. 1 Radio isophotes of the radio galaxy 3C166 mapped using the Very Large Array with 1.6 arc second resolution at 1.4 GHz. The bright central core (at which many isophotes have been omitted for clarity) coincides with a faint galaxy whose redshift is 0.246. The source is about 110 kiloparsecs across. Note the "hot spot" and bright outer rim in the lower lobe. Unpublished data of S.R. Spangler and A.H. Bridle.

Most theorists now agree that infall of ambient material into deep gravitational potential wells in the active cores is the most likely source of the primary energy supply in the extragalactic soufces. The efficiency of energy release per unit mass can be as high as 40% (greatly exceeding the 1% efficiency of nuclear fusion). Furthermore, supernovae, pulsars and the powerful X-ray sources in binary stars demonstrate that gravitational energy can indeed be converted to relativistic particles at fairly high efficiency in astrophysical systems.

Models of galactic evolution show that massive galaxies and quasars can accumulate dense gaseous disks at their centres by accretion of stars and gas from their slowly-rotating outer regions, or by the accretion of their smaller galactic neighbours (the process picturesquely termed "galactic cannibalism"). Blandford and Rees (1974) initially proposed that relativistic particles and fields produced in the "central engines" of active galaxies and quasars break out along the minor axes of such disks, thereby becoming collimated into twin "beams" which can transfer bulk kinetic energy to the radio lobes. Various authors (e.g. Blandford 1976, Lovelace 1976, Abramowicz and Piran 1980) later showed that the inflow of $\simeq$ 1 solar mass per year to the neighbourhood of a central black hole with 10^8 to 10^9 solar masses could also lead directly (either by radiation pressure or by electrodynamic effects) to the collimated expulsion of relativistic particles and fields at powers of 10^{39} watts, sufficient to energise a powerful extragalactic source. The basic notion that energy is transported from the cores to the lobes by collimated flows has recently been strongly supported by data from radio interferometers.

2.2 Jets

In the late 1970s, new image-processing algorithms permitted the removal of short-term tropospheric and ionospheric phase fluctuations from radio interferometric data, and hence the making of radio images with better than 30dB dynamic range. Maps of this quality made with the Westerbork Synthesis Radio Telescope in Holland and with the Very Large Array in New Mexico have shown (e.g. Figure 2) that many large-scale radio galaxies and quasars have bright narrow bridges of radio emission linking their cores to the radio lobes. These bridges often end at the hot spots in the lobes. As the emission bridges occur along the paths of the hypothesised outflows from the cores to the lobes, they are described as "jets" by radio astronomers, although we do not know directly that anything moves along them. (Unless the flow velocities are relativistic, features in the jets would have angular motions too slow to be measured over time scales of a few years by phase-stable interferometry, whose resolution is presently limited to about 0.1 arc second). It is therefore an ASSUMPTION that these bridge structures are produced by radiative inefficiencies in the proposed material outflows from the cores.

Supposing this interpretation of the "jets" to be correct however, the velocity of matter transport along them can be estimated by assuming that they replace the energy radiated by the lobes at sufficient thrust to enter the hot spots against the pressure of the relativistic particles there. The observations of typical powerful sources then require flow velocities of 1000 to 10,000 $km.s^{-1}$ if little of the delivered energy is thermalised. If conversion of the flow energy to relativistic particles and fields is inefficient, the flows might however have bulk velocities approaching that of light.

Whatever the conversion efficiency, it is virtually certain that the flows are supersonic. As supersonic flows cannot "know" how far away from the parent object any circumgalactic gas has been pushed, they will end at shocks in this material. At such shocks their bulk kinetic energy will be randomized, and thermal particles may be accelerated to relativistic velocities. The "hot spots" in the lobes could be the termination regions of such flows. The lobes themselves would result from anisotropic diffusion of these particles away from the hot spots, the anisotropy being due to the presence of the bow shock associated with the jet front as it pushes into the surrounding gas.

Studies of the linear polarization of the large-scale jets show that the magnetic flux they contain is not randomly configured. Degrees of linear polarization up to 65% have been detected in the jets at centimetre wavelengths. Such values are close to the theoretical maximum for the synchrotron radiation of an $E^{-2.5}$ spectrum of electrons moving randomly in a magnetic field whose component perpendicular to the line of sight is perfectly ordered. Measurements of the orientations of the electric vectors in the jet radiation at several frequencies determine the amount of Faraday rotation in the magnetoionic media along the line of sight to the jet (the interstellar gas of the Milky Way, gas in the parent galaxy or quasar, and the jet material itself may cause Faraday rotation of these vectors). Once the Faraday effects are removed, and the intrinsic (i.e. zero-wavelength) electric vector orientations are known, the projected magnetic field configuration in the jet can be inferred, because the acceleration of the electrons in a synchrotron source is perpendicular to the local magnetic field direction.

Figure 3 shows a typical example of the projected field structure in a radio jet. The field lines are initially stretched parallel to the jet axis, as expected if they were frozen into an accelerating flow (or subject to shearing along the jet axis). Evolution from this to a perpendicular configuration farther down the jet can be due to jet expansion, if magnetic flux is conserved as a jet widens. Parallel field expands with the jet area, so it decays as jet radius R^{-2}, whereas the perpendicular component expands with an element of the jet circumference, and hence decays as R^{-1}. What remains unclear is the origin of parallel-field edges to the regions dominated by perpendicular field (Fig. 3). Are these the edge components of a helical field structure seen in projection, or the results of shearing of the edges of the hets by interaction with an external medium, such as the galactic atmosphere? Such questions may be answered soon by sensitive high-resolution polarimetry across the widths of the jets.

That the jets may indeed be interacting with an external medium has been suggested by very high resolution maps of nearby radio galaxies using the Very Large Array. These show that the jets do not expand at constant rates (as they would if they were ballistic, or freely entering a low-pressure atmosphere). Instead they expand rapidly a few kiloparsecs from their cores and then recollimate some tens of kiloparsecs further out. It turns out that the pressures of the synchrotron-radiating particles and magnetic fields in these jets are comparable to the thermal pressures of the high-temperature (10^7 to 10^8 K) coronae discovered recently by the EINSTEIN X-ray observatory at heights of tens of kiloparsecs around several nearby active galaxies. This similarity of pressures raises the possibility that the radio-galaxy jets are collimated by the thermal pressures of extensive hot phases of their galactic atmospheres. This possibility will be tested fully by observations with the next generation of orbiting X-ray observatories. In some jets the organised magnetic fields may also contribute to the collimation process by focussing currents carried along the jets towards the jet axis.

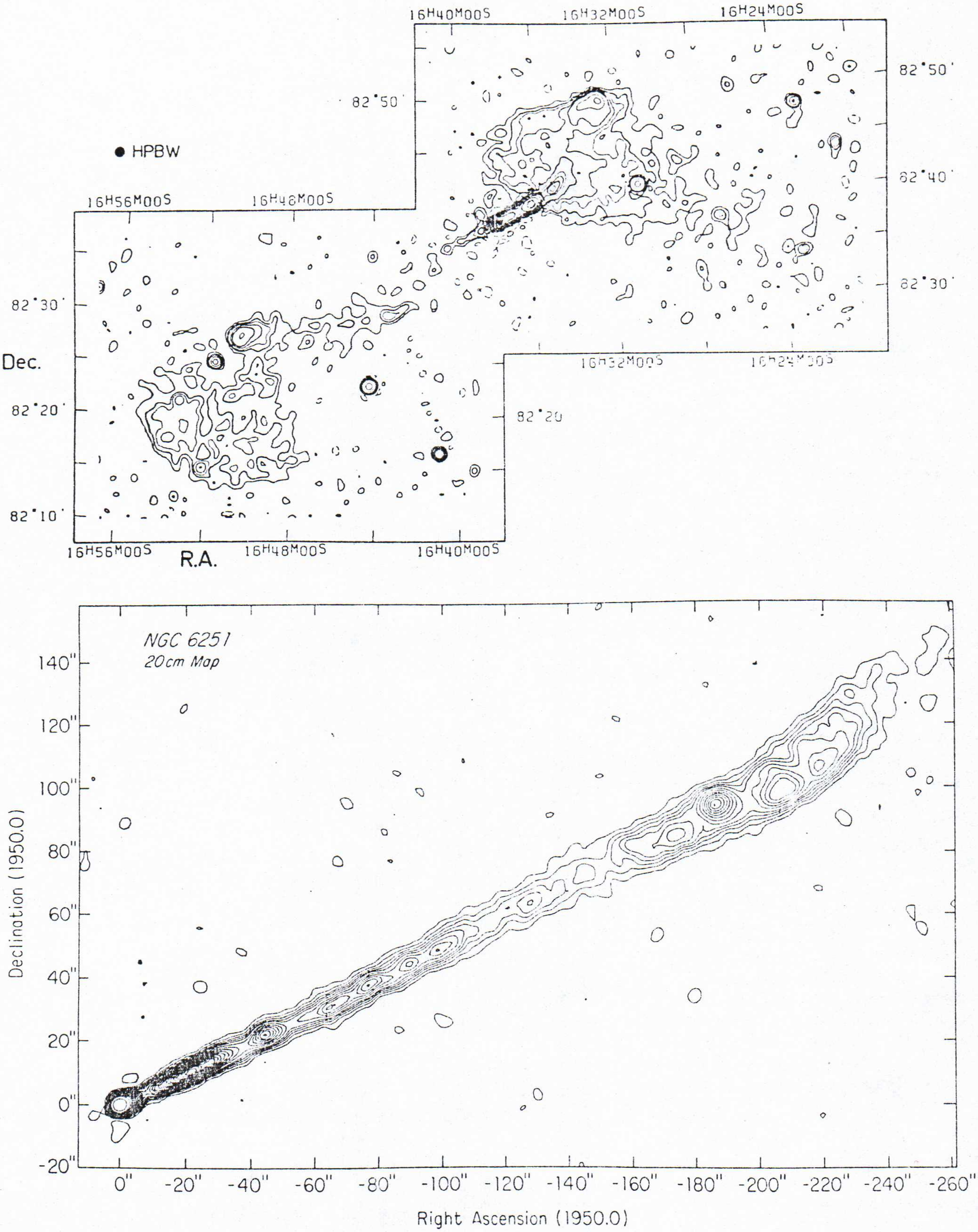

Fig. 2 (a) Isophotes of the radio galaxy NGC6251 mapped with the Westerbork Synthesis Radio Telescope with 50 arc second resolution at 610 MHz. The nucleus of the galaxy is marked with a cross. The bright feature extending into the upper right lobe structure is shown at much higher angular resolution in Fig. 2(b). "HPBW" indicates the resolution.
(b) Isophotes of the radio jet in NGC6251 mapped with the Very Large Array with 4 arc second resolution at 1.4 GHz. The overall length of the jet is about 90 kiloparsecs.
Both maps unpublished data of R.A. Perley, A.G. Willis and A.H. Bridle.

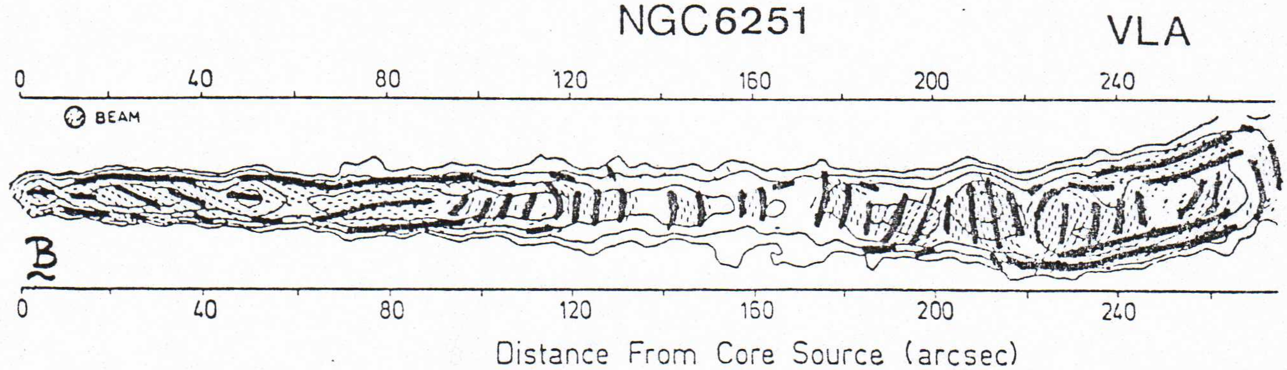

Fig. 3 The projected magnetic field structure in the jet of NGC6251, derived from observations at 1.4, 1.6 and 4.9 GHz with the Very Large Array. The heavy lines show the average field direction inferred from a large number of local field measurements (the underlying individual vectors). "BEAM" indicates the resolution. Unpublished data of R.A. Perley, A.G. Willis and A.H. Bridle.

Finally, there is a strong, and unexplained, correlation between the magnetic structures of the jets, their symmetry with respect to the optical objects, and the radio luminosities of the cores (Bridle 1982). Jets whose magnetic fields are stretched parallel to their axes are detected on one side only of the parent object, while the jets which have mainly perpendicular fields are usually detected on both sides. The fraction of a jet's length over which it remains field-parallel and one-sided increases with the radio luminosity of the core. Some attribute these phenomena to "Doppler favouritism" of the approaching side of two-sided relativistic flows. In this view, the differences between one and two-sided jet structures would be due to differing Lorentz factors in the outflows from cores of different luminosities, and also to differing inclinations of the jets to the lines of sight. A difficulty with this interpretation is that the energy fluxes in some of the one-sided jets would, if the flows are relativistic, greatly exceed the power output of the lobes, and it is not clear what could become of this "extra" energy. Another problem is that several long one-sided jets "wiggle" through appreciable angles without much change in their apparent brightness. If the flow velocities are parallel to the jets, and the jets are Doppler-enhanced, then there should be more noticeable changes in brightness where they bend.

3. Very Long Baseline Interferometry (VLBI)

Resolutions much better than 0.1 arc seconds are needed to resolve the cores of most extragalactic sources. At centimetre wavelengths interferometer baselines of thousands of kilometres are needed. Over such very long baselines connected-element real-time interferometry becomes intractable and it is necessary to record the outputs of the individual antennas for off-line correlation as described by Legg (1982). This "VLBI" technique, pioneered by researchers at NRC and Canadian universities in the mid-1960s, has been used for some years with ad hoc antenna networks to map the brighter radio cores.

3.1 Minijets

VLBI studies at arc-millisecond resolutions have shown that the cores of radio galaxies and quasars often contain miniatures of the one-sided larger-scale jet (e.g. Figure 4). There is usually a still-unresolved "inner core", whose linear size in a nearby radio galaxy is typically much less than a parsec. The resolved structures in the cores are often (but not always) elongated one-sided jet-like features, or "minijets".

These VLBI maps show that both the primary energy generation and the initial collimation processes occur on remarkably small scales in nearby active galaxies. The cores and minijets have linear dimensions as small as typical interstellar distances in our neighbourhood of the Milky Way, yet must contain about 10^8 solar masses of material in order to power the emission from the lobes. These results strongly encourage models in which the "central engine" of the radio sources is associated with the deep potential well around a massive black hole. They are reinforced by the fact that some active sources change their optical and X-ray output significantly on time scales of days; this means that a large part of their luminosity must be produced in regions that are only light-DAYS in linear extent. Virtually any astrophysical object that might contain 10^8 solar masses or so in such a small region, if not itself a black hole, would very probably evolve into one over the synchrotron radiative lifetime of the particles in a powerful radio source. Many theorists therefore believe that the small scale of the initial collimation of the minijets is associated with the funnel-like shapes of the central vortices in accretion flows near such massive black holes.

A recent VLBI study of the core of the quasar 3C273 by Pearson et al. (1981) used a method of image reconstruction from phase-corrupted data known as "hybrid mapping" to demonstrate directly and unambiguously that there is outflow along the minijet in this object (see Fig. 5).

More startling is the fact that the apparent expansion velocity, assuming the source to have the optical redshift of 3C273, is more than five times the velocity of light! Simple light travel time effects can produce such apparently "superluminal" expansions if (a) the flow velocity in a minijet is relativistic and (b) it makes a small angle to the line of sight. Features in a flow moving with Lorentz factor γ can appear to move at speeds up to γ times that of light when viewed at an angle of order $1/\gamma$ radians, or less, to the line of sight.

Clearly, only a minority of all extragalactic jets should lie close to our line of sight. Sources containing them would however appear intensified due to the Doppler brightening of the approaching side of flow, and may appear preferentially in surveys of strong radio sources. As the lobes should not move outwards with high Lorentz factors, the structures of such observer-aligned sources would appear core- or jet-dominated. There is indeed evidence, though not yet as clear as that for 3C273, for superluminal motions in half a dozen other core-dominated sources. One of these is a relatively nearby galaxy (3C120) for which there can be

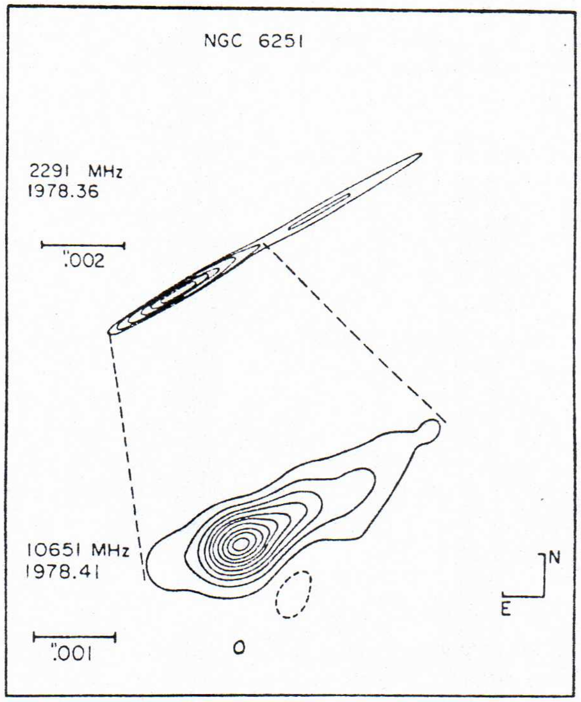

Fig. 4 Structure in the nucleus of the radio galaxy NGC6251 at two radio frequencies and resolutions. The upper panel shows 2291-MHz emission within about 1.6 parsecs of the centre of the galaxy, at a resolution of 2 by 0.4 arc milliseconds. The direction of lowest resolution is also that of greatest elongation of the structure, which aligns with the large-scale jet shown in Figure 2(b) to within a few degrees. The lower panel shows detail of the brightest part of this image, at 10651 MHz and at 0.5 by 0.6 arc millisecond resolution. (Note the different angular scales of the upper and lower panels, shown by the tic marks). The 10651 MHz map defines a bright "inner core" and a fainter "minijet" extending towards the large-scale jet. The faint emission detected at the upper right of the 2291-MHz map is a weak continuation of the minijet which lies below the limiting sensitivity of the 10651 MHz data. From Cohen and Readhead (1979), by permission of the authors and of the editors of Astrophysical Journal.

little doubt about the relationship of distance to the optical red shift. Systematic and repeated mapping of representative samples of core-dominated and lobe-dominated sources is now needed, to test whether the rate of incidence of superluminal motions is consistent with the random alignment of the sources, and with the statistics of core- and lobe-dominance.

It has also been found (e.g. Readhead et al. 1978) that the minijets in core-dominated sources are often misaligned with their lobe structure by tens of degrees. In contrast, the minijets in lobe-dominated sources align with the large-scale jets or the hot spots to within ten degrees, and often to within much smaller angles (Linfield 1981). These effects appear consistent with interpreting the "superluminal" sources as aligned relativistic jets — slight bends in jets lying near the line of sight would be magnified to larger misalignments by projection, while those near the plane of the sky would be seen correctly as small-angle deviations.

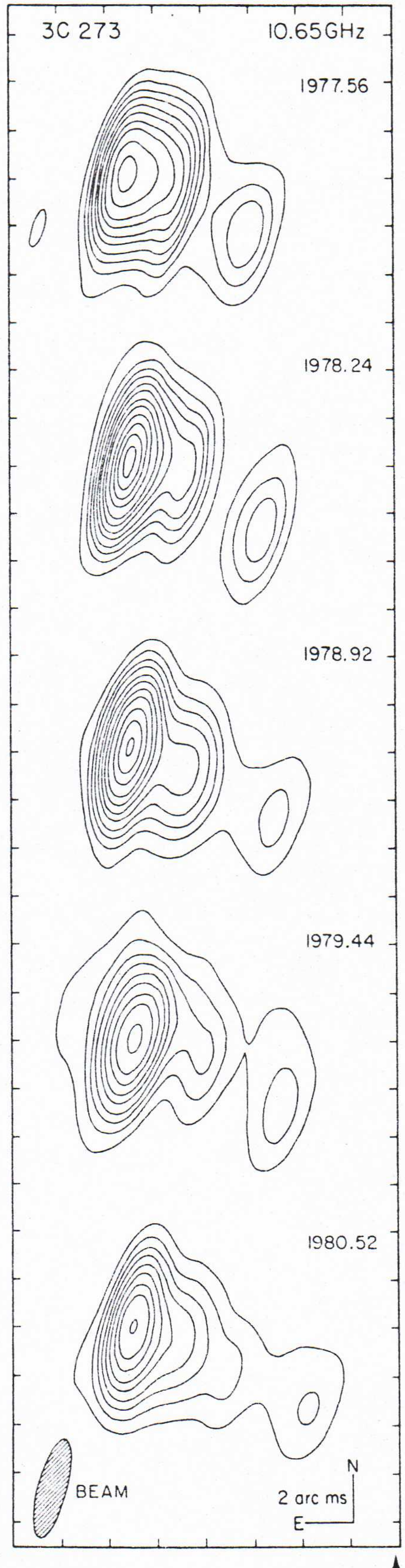

Fig. 5 VLBI maps of the core of the quasar 3C273 at 10651 MHz at five epochs, showing directly the outflow of material along the minijet. Each map has an angular resolution of 4.2 by 1.2 arc milliseconds (indicated by "BEAM"), the direction of lowest resolution being approximately perpendicular to the extension of the minijet. The maps were made with an ad hoc array of radio telescopes in California, Texas, West Virginia, Massachusetts and West Germany. From Pearson et al. (1981), by permission of the authors and of the editors of Nature.

3.2. Jet Research with the CLBA

The CLBA will be a powerful tool for studies of the phenomena in the radio cores, as it will be able to map the minijets with both high high dynamic range and a wide field of view. These capabilities are essential if the lateral expansions of the minijets are to be measured, and if the trajectory and intensity evolution of "superluminal" features in minijets is to be followed over a range of distances from the core in order to constrain theoretical models for this phenomenon.

Present VLBI studies of the minijets are unable to trace them out to the distances from the inner core at which phase-stable interferometry first detects them. A major puzzle associated with the large-scale jets is that many of them appear to brighten suddenly at distances of a few kiloparsecs from the inner cores. Some theorists believe that this brightening results from entrainment of ambient material into high-velocity flows that are initiated on the parsec scale of the minijets. The CLBA at its lower operating frequencies will be able to map the minijet structures on scales that are intermediate between the fields of view of current ad hoc VLBI networks and the resolution limits of phase-stable interferometers such as the Very Large Array. Knowledge of the properties of the jets in this range of angular scales is vital if we are to understand the collimation and particle-acceleration mechanisms in the extragalactic sources in any detail.

Unlike the ad hoc VLBI networks, the CLBA will be able to carry out polarimetry of the minijets. The very high polarizations of the large-scale jets, and the richness of their magnetic structures, suggest that this will be a profitable field. The densities of thermal matter in the minijets will be derivable from their Faraday rotation and depolarization properties. Comparison of the mass outflow rates on parsec scales with those in the larger jets will show whether entrainment into the flows is indeed significant.

Also important is the relationship of sidedness in the minijets to sidedness in the large-scale structures. The two lobes of lobe-dominated sources are usually similar in brightness, but the jets that feed them can be one-sided (in sources with powerful cores) or two-sided (in sources with weak cores). Do these symmetries carry over to the minijets? Are the one-sided minijets always on the side of the brighter large-scale jet? Does the sidedness of minijets ever change with time? The answers to such questions are crucial if we are to distinguish sidedness caused by relativistic flow velocities from effects that could be intrinsic, e.g. activity on one side of the parent object at a time, or differences in the efficiencies of production of radiating relativistic particles in the two sides of a two-sided outflow. The systematic investigation of these properties requires VLBI mapping of weak radio cores in sources with two-sided large-scale jets. Both the high sensitivity of the CLBA, with its eight 32-metre antennas and cooled GaAs FET amplifiers, and the exceptional angular resolution of the instrument will be essential for such work.

Possibly the most crucial result that could be obtained with the CLBA in its early years of operation would be a convincing settlement of whether or not the flow velocities in the minijets are indeed relativistic. If they are, it is highly probable that the minijets indeed originate from relativistic potential wells. A demonstration of the relativistic nature of the minijet flows based on direct observations of their temporal variations would confirm that our models for the central energy reservoirs in the powerful extragalactic sources are heading in the correct direction.

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