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HUBBLE SPACE TELESCOPE OBSERVATIONS OF SYNCHROTRON JETS

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ABSTRACT

The *Hubble Space Telescope* for the first time enables optical and UV images of jets to be obtained with spatial resolution comparable to radio interferometric techniques. Because synchrotron emission at these wavelengths is a diagnostic of particles several orders of magnitude higher in energy and correspondingly shorter in lifetime than those probed by radio, the sites of particle acceleration may be more readily identified in the optical and UV. Short-lifetime optical synchrotron emission in the SE inner radio lobe of M87 argues strongly for the presence of an invisible counterjet. A detailed comparison of *HST* and VLA images of the M87 jet shows there are very strong similarities in overall morphology, but that there are also significant differences. The optical and UV radiation is more localized within the knots than the radio emission and appears more confined toward the jet center. These differences may arise from localized shocks, sited at the optical knots with diffusion of relativistic particles away from those knots, or else they may be due to nonuniform magnetic fields and distributed acceleration processes. The UV fluxes of the knots are consistent with a single power law from optical to X-ray. Optical jets in other radio galaxies show diverse properties—the jet of PKS 0521−36 is smoothly resolved by *HST* while that of 3C 66B shows previously unsuspected filmentary structure. Likewise, the jet of 3C 273 shows newly observed optical filaments and an intensity distribution quite unlike that of the radio emission. Like M87, the optical jet of 3C 273 is narrower than the radio jet. The serendipitous discovery of a new optical synchrotron jet in 3C 264 suggests that optical jets may be relatively common.

Subject heading: galaxies: jets

1. INTRODUCTION

This review is concerned primarily with *Hubble Space Telescope* (*HST*) observations of optical nonthermal synchrotron jets in radio galaxies. At radio wavelengths, it is well-established that the characteristic large double-lobed structures are associated with, and presumably powered by, highly collimated jets emerging from the galactic nuclei which often terminate at a hot spot within the lobe (c.f. Bridle & Perley 1984; Muxlow & Garrington 1991). In a few cases, counterparts to these jets are seen at optical wavelengths. These *optical jets* constitute a diverse sample ranging over many orders of magnitude in size and luminosity and with very different characteristics. Where it is seen, the optical emission, like the radio, is highly polarized and to a good approximation, has a power-law spectrum. It is commonly believed therefore that the emission process is synchrotron radiation in both wavelength regimes. In the case of M87 the jet is also observed at X-ray wavelengths, Biretta, Stern, & Harris (1991) and the X-ray intensities appear to be consistent with an extrapolation of the optical power law. In § 2, we show that the UV flux distribution, intermediate between the optical and X-ray, is also consistent with such an extrapolation.

The interesting feature of optical synchrotron emission, and even more so at UV and X-ray wavelengths, is that the lifetime of particles required to produce such emission is very short, which taken in conjunction with the extremely high spatial resolution of *HST* offers the prospect of identifying the locations within the jet at which relativistic particles are generated. The FWHM of the *HST* point spread function is typically ≈ 60 mas, which for the first time gives astronomers a chance to compare optical and UV imaging data directly to the excellent high spatial resolution radio data from long baseline interferometers such as the VLA[2] or MERLIN.

In addition to the short lifetime, optical emission is free from Faraday rotation effects and so an ambiguity in magnetic field mapping is removed. The relativistic electron population is of much higher energy, Lorentz factors $\gamma \sim 10^6$, than electrons responsible for the radio emission, $\gamma \sim 1000$, and the higher contrast one might expect at optical wavelengths offers the possibility of detecting proper motion in the jet. The detection of optical jets has previously been hampered by light from the host galaxy, the poor spatial resolution of ground-based images and the lack of UV sensitivity. With *HST* these drawbacks are overcome, and the serendipitous discovery of a new synchrotron jet in 3C 264 indicates that optical synchrotron emission may be quite common. Finally, at optical wavelengths it is straightforward to glean information on the nature of the host galaxy and to explore the environment in which the jet occurs. This is likely to add substantially to our knowledge of what at present is an extremely poorly understood phenomenon, despite the fact that highly collimated outflow is quite ubiquitous in the universe.

Most of the data to be described were obtained using the European Space Agency's Faint Object Camera (FOC) onboard the *HST*. This camera offers the highest spatial resolu-

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[2] The VLA is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under contract with the National Science Foundation.

tion available on the *HST* and is sensitive across a broad-wavelength range from 6000 Å in the red to 1200 Å in the far-UV (see Paresce 1992).

For other recent reviews, including *HST* observations, see Macchetto (1991, 1992). For an inventory of optical jets, and summary of up-to-date thinking on optical ground-based observations, see Meisenheimer (1991). Other comprehensive review material includes Hughes (1991) and Burgarella, Livio, & O'Dea (1993).

2. THE JET OF M87

HST has observed the most famous optical synchrotron jet, that of M87, discovered by Curtis (1918). The synchrotron nature of the ~ 2 kpc long jet has been demonstrated over the years through ground-based polarization and spectral index studies, and the overall correspondence between optical and radio morphology has been well-established (e.g., Baade 1956; Warren-Smith, King, & Scarrott 1984; Schlötelberg, Meisenheimer, & Röser 1988; Fraix-Burnet, LeBorgne, & Nieto 1989; Stiavelli, Møller, & Zeilinger 1991). The Wide-Field/Planetary Camera image of M87 and some discussion of the nonthermal core of the galaxy may be found in Lauer et al. (1992), where, in addition to the optical synchrotron jet, the underlying galaxy and its associated globular clusters may be seen.

The question of whether the jet is intrinsically two-sided has been revitalized by the discovery of an optical synchrotron hot-spot opposite to the bright jet (Stiavelli et al. 1992; Sparks et al. 1992). The short optical synchrotron lifetime, of order 100 yr, is much less than the light travel time from the nucleus, of order 10,000 yr, and strongly suggests that energy is being supplied to the SE lobe at the present time and that the jet has an invisible but otherwise roughly symmetric counterpart.

Turning to the *HST* observations of the main jet, Figure 1 shows an ultraviolet FOC image of the jet alongside a VLA image at the same scale and resolution, as shown in Boksenberg et al. (1992). Immediately obvious is the filamentary structure familiar from the ~ 0″.1 resolution VLA radio

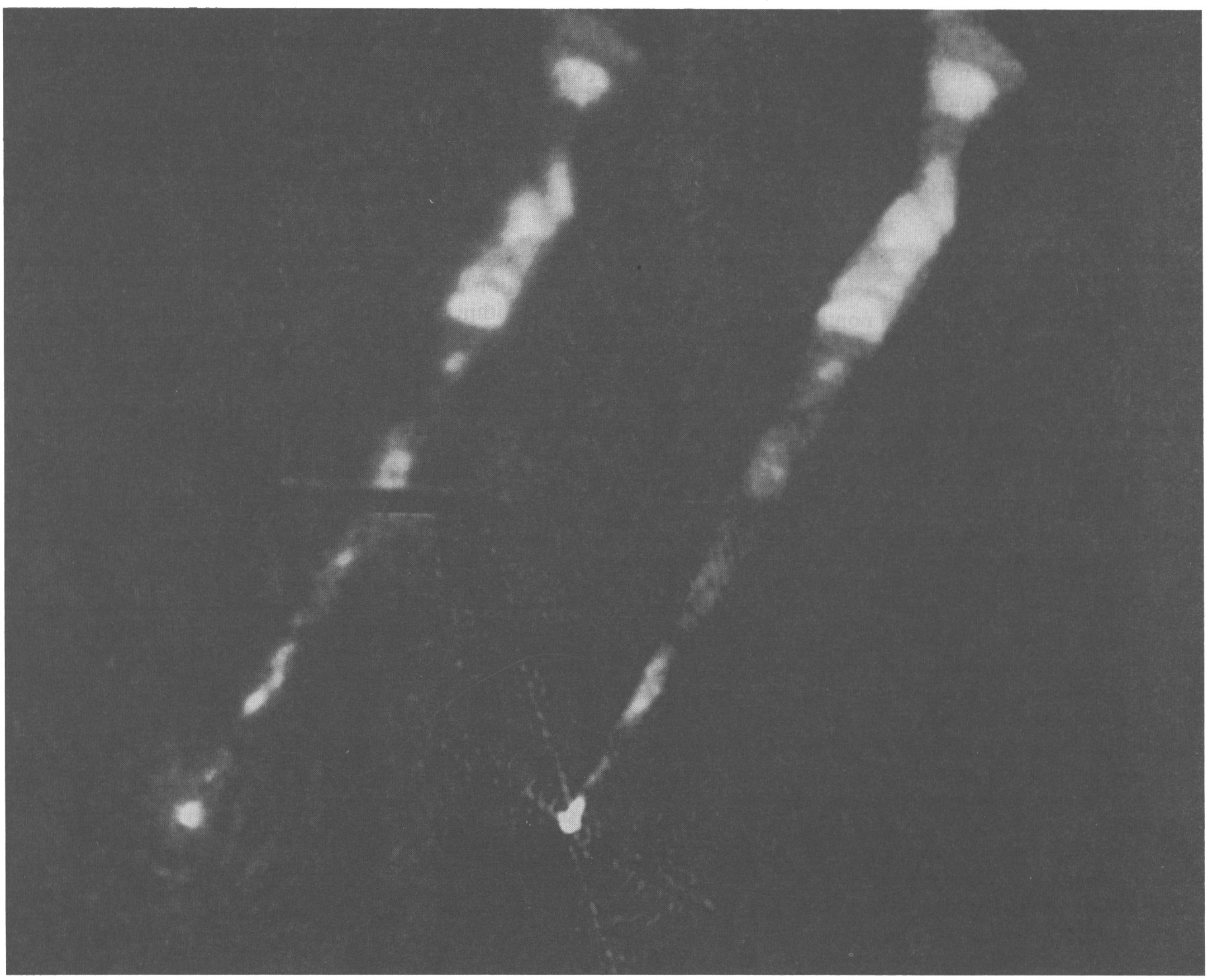

FIG. 1.—Ultraviolet FOC (*left*) and Very Large Array 15 GHz (*right*) images of M87 jet. The total length of the jet is ~20″ (1.6 kpc), and the top is oriented toward P.A. ~ −41°. FOC image from Boksenberg et al. (1992); VLA image from Owen, Hardee, & Cornwell (1989).

images of Owen, Hardee, & Cornwell (1989). Both ground-based data (Stiavelli et al. 1991), and early analysis *HST* observations, Boksenberg et al. (1992), emphasise the striking similarity of the radio and optical/UV data, which is very clear in this image. Knots and filaments in the radio show a one-to-one correspondence to knots and filaments in the UV data. This result requires a particle acceleration process that can explain a very similar electron energy distribution everywhere in the jet. A recent suggestion has been that the electron energy distribution is the *same* distribution everywhere because it is generated at the nucleus and propagates down a loss-free channel to be emitted at some location along the jet, Owen et al. (1989). Alternatively, a process such as first-order Fermi acceleration at strong shocks which produces a characteristic electron energy spectrum could be responsible.

Having established the strong similarity, we may proceed a step further and investigate in more detail the relative structures in optical and radio. Figure 2 shows a composite FOC image derived by scaling and mosaicing many separate images taken at different times and pointings. The effective wavelength is ≈ 3700 Å and the deconvolution method is the Lucy (1974) iterative method. (Results are described in detail in Sparks, Biretta, & Macchetto 1994). Alongside that image is reproduced the VLA image, with knots identified. Although similar, they are *not* identical, and to summarize the *differences:* the optical data are more contrasty than the radio data; the jet is narrower in the optical than in the radio, an effect which is seen most easily at knot A; the optical jet is more confined to the center of the jet than is the radio; the faint interknot radio emission is not present in the optical with the present S/N; the inner knots have different detailed structures; and knot A is convex to the nucleus rather than concave. Another way of characterizing these differences is by producing a map of the radio to optical spectral index. In this way, it is clear that the peaks of the optical emission have the flatter radio-to-optical spectra.

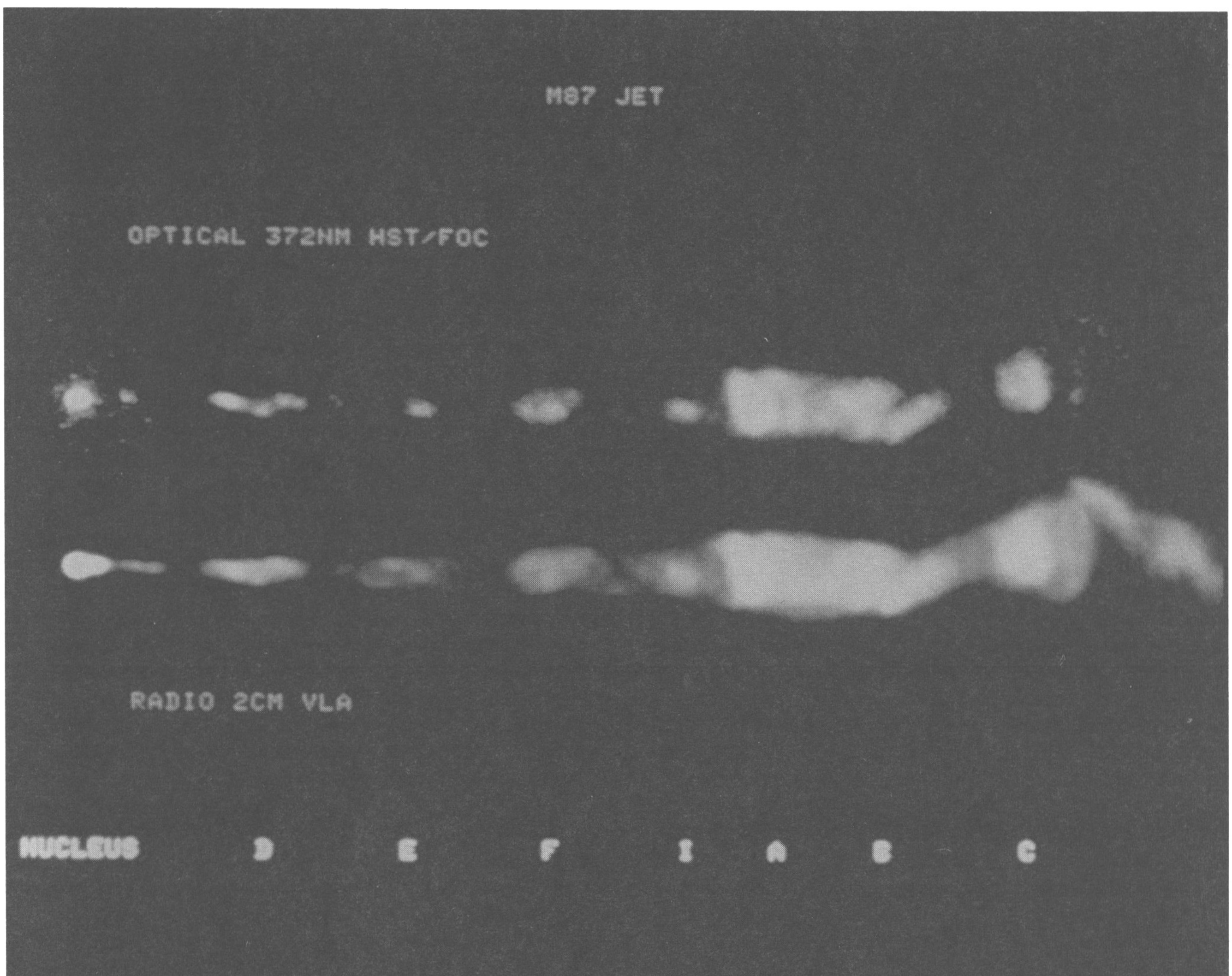

FIG. 2.—Composite, Lucy-deconvolved FOC image (*top*) of the M87 jet derived by scaling and mosaicking many separate images taken at different times and wavelengths. A 15 GHz VLA image (*bottom*) is shown for comparison. The total length of the visible optical jet is ~20″, and the top is oriented toward P.A. ~ 21°.

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Hence we have the second result, which is that although similar in structure, there are subtle differences in the optical-to-radio spectral index, with the peaks of the optical emission being more well defined and showing higher contrast over their surroundings than those of the radio. Possible reasons for this are that we are witnessing the effects of differences in the strength or topology of the magnetic field, which in turn causes slightly different electron energy spectra to be generated. Similarly, if we are seeing the same electron distribution everywhere, perhaps produced by the active nucleus, then the effects of a changing magnetic environment may be responsible for the small differences in spectral index. Note that the break frequency in regions of higher magnetic field would need to move to higher values so synchrotron losses are unlikely to be dominant in that interpretation. Alternatively, localized particle acceleration at may be occurring at shock sites which are defined by the more compact optical knots, with subsequent diffusion and steepening (i.e., the break frequency moves to lower values) away from the knot center, as in Heavens & Meisenheimer (1987). The synchrotron lifetime is typically ~ 100 yr, which, if particles can diffuse at speeds close to light, is resolved by these observations. On the other hand, if diffusion speeds are constrained to be much less than such a value, then a distributed emission mechanism would be preferred. Secular variations in the speed of the jet may also play a role, e.g., Rees (1978), and we note there is some evidence for flares in the nucleus (Morabito, Preston, & Jauncy 1988). The compact nature of the optical emission and the concentration to the jet

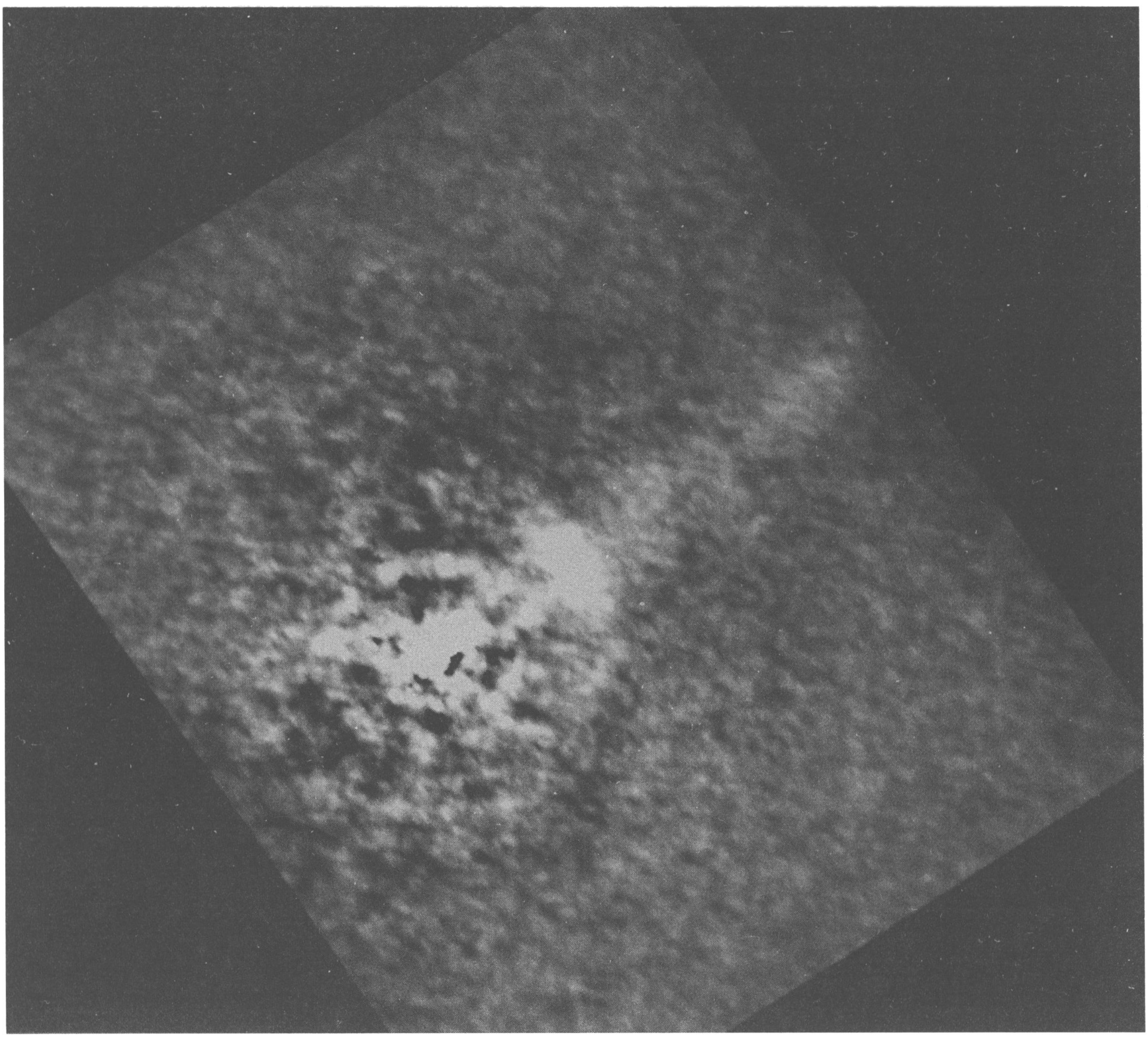

FIG. 3.—Deconvolved and galaxy-subtracted FOC image of PKS 0521−36 jet. The length of the visible jet is ~6″.5 (7 kpc); north is oriented toward the top. From Macchetto et al. (1991a).

center, in conjunction with rather little evidence of "limb brightening," is an argument against a simple boundary layer model in which the jet emission arises solely from the thin walls of an otherwise loss-free channel.

Finally, the M87 FOC images span the wavelength range from 5000 to 1200 Å, and calculation of the knot spectra, Boksenberg et al. (1992), show that they are consistent with an extrapolation of the optical data, or an interpolation of the optical and X-ray observations. This lends support to the view that the X-ray emission also is synchrotron in nature, and if that is so, then the lifetime arguments for X-ray emitting electrons become very stringent. Future high spatial resolution X-ray imaging will be most interesting in this regard.

3. OPTICAL JETS IN OTHER RADIO GALAXIES

The Faint Object Camera Investigation Definition Team have observed a number of other previously known optical jets, including those in PKS 0521−36, and 3C 66B; see Macchetto et al. (1991a, b). The jet of PKS 0521−36 (Fig. 3) is fully resolved having a width typically 0″.4, corresponding to a width of several hundred parsecs, and a length ∼ 10 kpc. Only

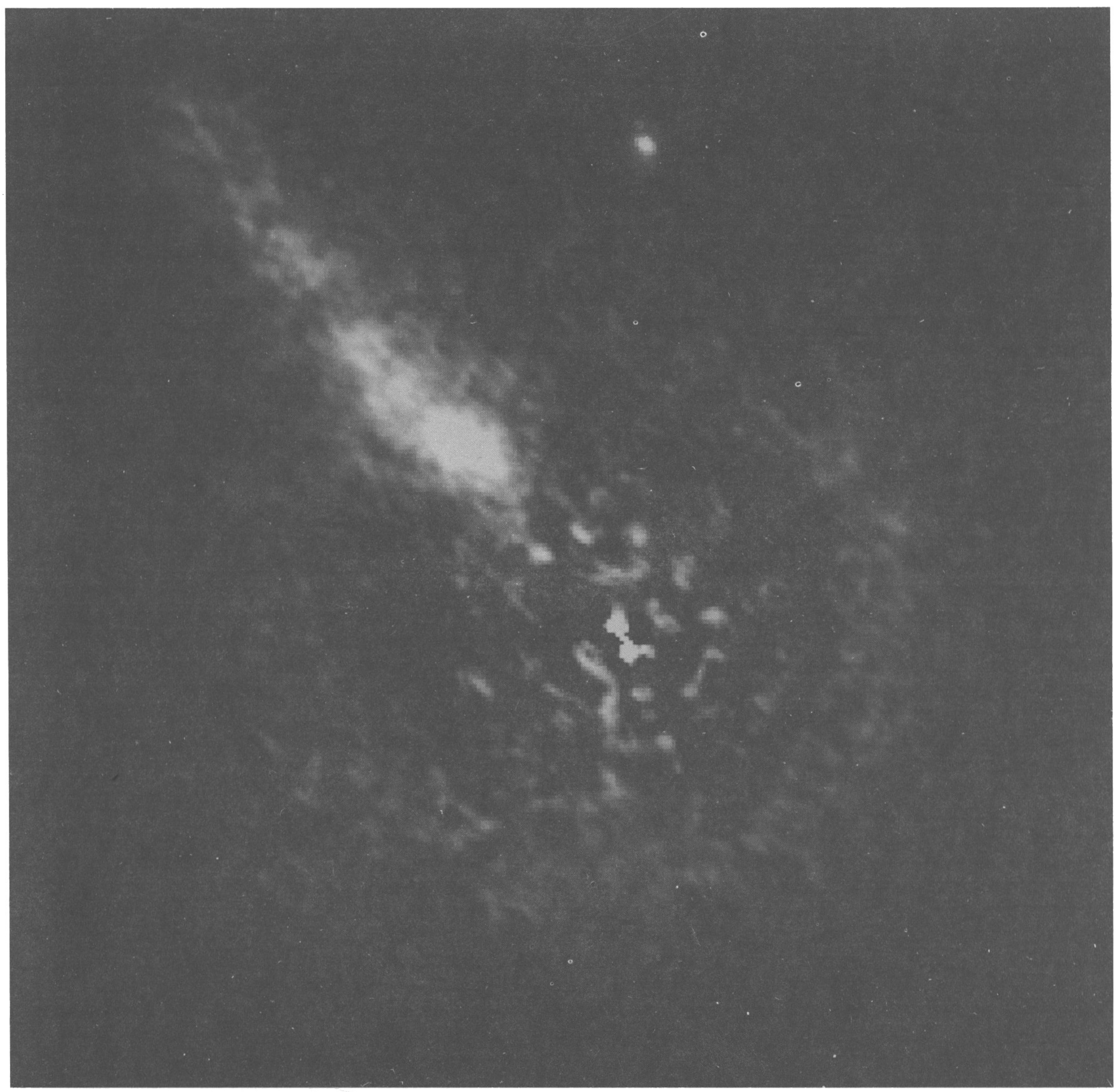

FIG. 4.—Deconvolved and galaxy-subtracted FOC image of 3C 66B jet. Length of the visible jet is ∼6″ (2.5 kpc); north is oriented toward the top. The nucleus is ∼3″ SW of the brightest region of the jet. From Macchetto et al. (1991b).

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smoothly distributed emission is seen. 3C 66B, on the other hand, with similar observational material and intrinsic dimensions about half the size of the PKS 0521−36 jet, shows fine strands in the optical (Macchetto et al. 1991b; Fig. 4) that had not previously been seen in 0″.3 resolution radio data (Leahy, Jägers, & Pooley 1989). Jackson et al. (1993) present new radio images that now reveal fine structure in the radio data as well as in the optical images.

Several radio galaxies have been observed by the Faint Object Camera for other purposes. In one of them, 3C 264 (NGC 3862; see Baum et al. 1988), a new optical jet was discovered, Crane et al. (1993). Figure 5 shows the Lucy-deconvolved image of the jet. The length is only 0″.6, and it is barely resolved, if at all, across its width. The corresponding metric length is only of order 400 pc which makes it the shortest optical/radio jet known. The synchrotron nature of the feature has yet to be unambiguously established through polarimetry and detailed comparison to high-resolution radio data; however, the qualitative appearance and quantitative colors are strongly suggestive that this is indeed a new optical synchrotron jet. The optical spectral index is consistent with those of other synchrotron jets.

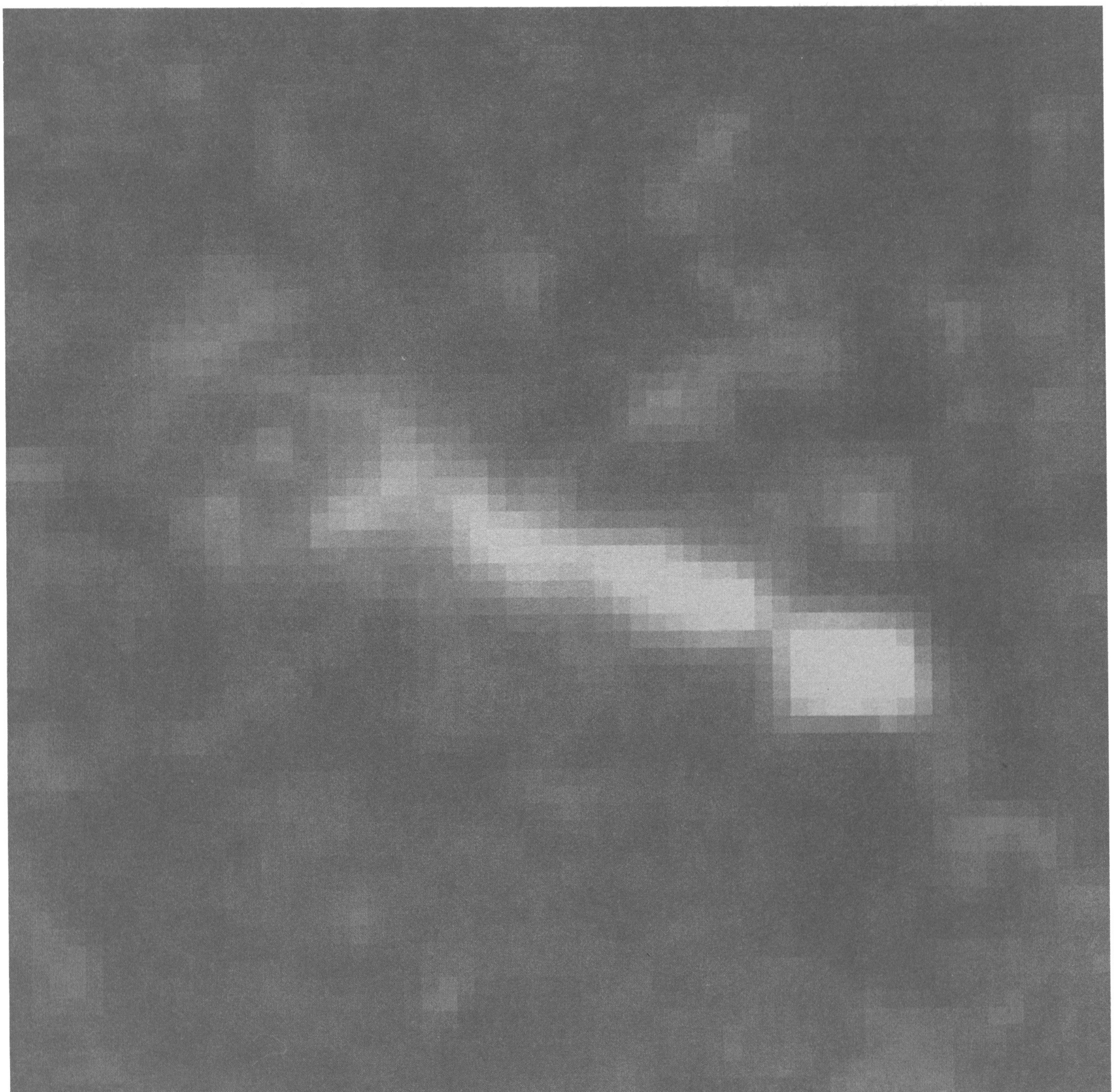

FIG. 5.—FOC image of 3C 264 jet at 3400 Å. The total length of the jet is ~0″.65 (400 pc), and the top is oriented toward P.A. ~ −28°. From Crane et al. (1993).

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The relatively nearby quasar 3C 273 ($z = 0.158$) hosts the largest known optical synchrotron jet, with an extent ~ 50–100 kpc (Fig. 6; Thomson, MacKay, & Wright 1993). The images show a wealth of detail, confirming in large part and improving upon the analysis of Evans et al. (1989). These data also utilized the imaging polarimetric capability of the FOC and show the magnetic field configuration along the length of the jet. Here the radio morphology (Conway et al. 1992; Thomson et al. 1993) is quite different from the optical. The radio emission peaks beyond the peak in the optical emission. Also, as in M87, the optical jet is narrower than the radio, with a radio width of order 1″ compared to the 0″.2–0″.3 of the optical data. It is interesting that M87 and 3C 273, which have the best radio and optical data among the jets described herein, both show a tendency for the optical jet to be appreciably narrower than the radio jet.

4. SUMMARY

In conclusion, the high spatial resolution possible now at both radio and optical/UV wavelengths has given astronomers the chance to compare in great detail the different structures of jets seen at wavelengths corresponding to very distinct energy regimes within the relativistic electron populations. Filamentary structures are very common (although the case of PKS 0521−36 is a counterexample) when viewed with such resolution. In the best-studied jet, that of M87, there are very strong morphological similarities, yet nevertheless there are also subtle differences between optical and radio images. Taken together with the short electron lifetimes and diffusion lengths characteristic of the optical band we have the prospect of determining detailed properties of the inner jet structures and magnetic fields. We may be seeing particle acceleration at shocks, with diffusion away from those shocks, or else we may have distributed acceleration and variations in the magnetic field properties. The data are inconsistent with the simplest boundary layer models in which all emission arises on the surface of a nonradiating cone; and secular variations may also play a role.

Jets may be significantly more common than presently realized given the serendipitous discovery by *HST* of a new, previously unsuspected jet.

Future spectral index mapping *within* wavebands such as "radio" and "optical/UV" individually, together with similar

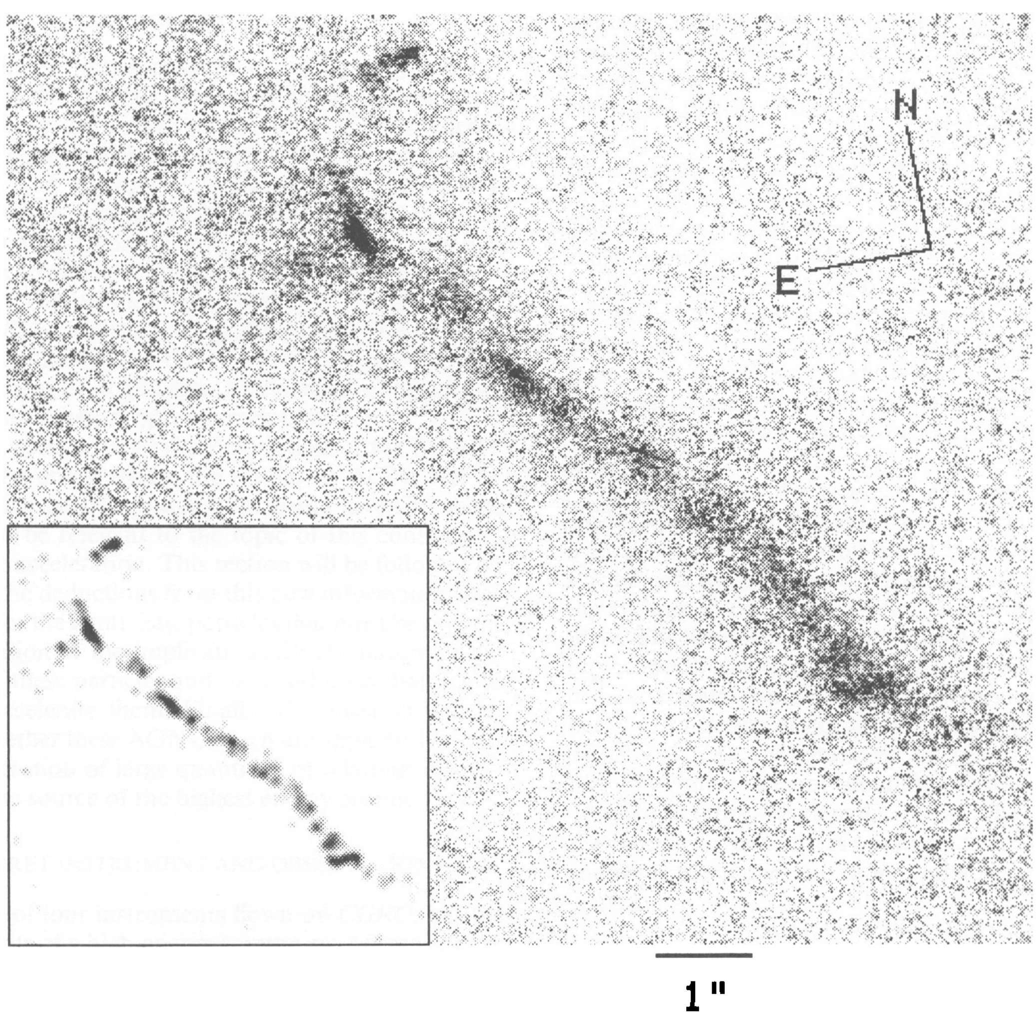

FIG. 6.—Observed *B*-band FOC image of the 3C 273 jet. The inset shows a maximum entropy reconstruction of the observed image. The scale and orientation are as shown (1″ = 2.5 kpc); the nucleus of the quasar is ~12″ beyond the NE end of the visible jet. From Thomson, Mackay, & Wright (1993).

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improvements in spatial resolution at X-ray wavelengths should enable significant progress to be made on understanding the nature of the jet phenomenon.

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