OPTICAL SPECTROSCOPY OF CANDIDATE HOT SPOTS IN RADIO GALAXIES AND QUASARS

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ABSTRACT

We present low-dispersion spectrophotometry (0.5–1.0 μm) for several objects previously identified as candidates for optical emission from hot spots in radio galaxies and quasars. Detailed spectral fits were used to discriminate between power-law continua and other types of spectra, including associated galaxies and foreground stars. Of the objects observed, the 3C 319 "hot spot" proves to be a galaxy in the associated cluster, and the most prominent candidate for the 3C 390.3 hot spot is a foreground K star. We confirm that the spectrum of the 3C 247 hot spot is best fit by a power-law form, and together with published K-band data, find evidence of a turnover in the synchrotron spectrum at about 1.3×10^{14} Hz. The pure continuum nature of the 3C 303 hot spot is confirmed; in fact, in none of the hot spots observed do we detect line emission. Our data for the hot spot near PKS 2135-147 are well represented by a power-law continuum, but other evidence indicates that this is another galaxy superposition (in which the strongest spectral features fall outside our observed range).

We measure the spectral shape of the 3C 273 jet in three regions, the outermost of which includes the radio hot spot at the end of the jet. This outer region has a much steeper spectrum ($\alpha = -4.5$) than the brightest part of the jet ($\alpha = -1.0$), breaking any pattern of higher cutoff or turnover frequencies in hot spots compared to optically-detected jets.

We discuss briefly some aspects of the nuclear spectra of the radio galaxies in the sample. Of particular note is simultaneous measurement of emission lines from [O II] λ3727 to Hα in 3C 330 at $z = 0.55$.

1. INTRODUCTION

Hot spots in extragalactic radio sources hold important clues to the structure and development of these sources. Their high inferred energy densities and short synchrotron lifetimes make them the best candidates for *in situ* particle acceleration and the possibility of seeing interactions between jet matter and surrounding decelerated matter.

A few hot spots have been reported as sources of detectable optical and even X-ray emission. These are of particular interest since the optically-emitting particles have much shorter synchrotron lifetimes than do those dominating the radio emission, so these cases furnish even stronger constraints on the emission and acceleration processes at work. Following reports of optical counterparts of a few hot spots (Simkin 1978), surveys by Saslaw, Tyson, & Crane (1978; STC) and Crane, Tyson, & Saslaw (1983; CTS) produced many faint optical candidates for hot-spot emission, most of which have had no additional observations published beyond their single-passband imaging. We report here low-dispersion spectroscopy of six candidate hot spots, plus the jet and hot spot of 3C 273. These data allow us to discriminate the characteristic power-law continuum shape of hot spots and chance alignments of galaxies or foreground stars even at faint magnitudes. Further, we can search for emission lines to faint limits; line emission could substantially alter the observed colors at some redshifts, and if present offers important diagnostics of the local physical conditions and ionizing source.

The spectra of the parent galaxies obtained simultaneously with the hot-spot spectra are also discussed; we have obtained several new measurements of the 4000-Å break at redshifts up to $z = 0.75$ and new information on emission spectra in the deep red. Our spectra also serendipitously confirm cluster membership for some galaxies surrounding the radio galaxies.

2. OBSERVATIONS

These observations used spectroscopy, rather than imaging, for these very faint sources so that we could test for any significant contribution from line emission to the broad-band flux, as well as testing for power-law versus stellar continuum spectra.

We observed the hot-spot candidates listed in Table 1 using the Faint-Object Spectrograph (FOS) at the 2.5-m Isaac Newton Telescope (INT). Even with a slit width usually 2.5 arcseconds, the spectra are not well sampled along the dispersion (mean scale 1.18 arcseconds/pixel). Observations were broken into segments of 10-15 minutes' duration, to increase dynamic range when the central object fell on the slit and allow better cosmic-ray rejection. Most hot-spot candidates were acquired by setting the slit at the appropriate position angle across the central galaxy or QSO, which could itself be seen and centered using the slit-viewing TV camera.

The FOS uses a grism as the primary dispersing element, with a cross-dispersing prism to separate first and second orders. This removes any problems of second-order contamination over the instrument's wide spectral range (5000-10,000 Å at 10.26 Å per pixel), at the expense of somewhat more subtle data-reduction issues. The undersampling of these spectra (in both dimensions) also required attention during reduction. Processing of the spectra proceeded as follows:

An internal tungsten lamp was used to construct a flat-field image, with illumination corrected for vignetting by observations of blank twilight sky. Sky subtraction was performed before either wavelength linearization or correction for curvature produced by the cross-disperser, to reduce the effect of interpolation on night-sky residuals. A CuAr lamp gave the wavelength mapping, supplemented at the far-red end by Paschen and [S III] lines from the planetary nebula NGC 7027. To check for any effects of interpolation in undersampled data, we extracted object spectra both by linearizing the spectra along the slit and by extracting spectra following an appropriately curved path. As it happened, the differences between spectra covering the same spatial region obtained by both methods are well within the internal noise. Flux calibration used observations of HZ 44 and Feige 110 reduced in the same manner as the other objects. The component of atmospheric dispersion along the slit was removed by the spectrum-tracing procedures. We estimate the wavelength-dependent light loss due to dispersion out of the slit (e.g. Filippenko 1982) by computing the component normal to the slit for each observation between 5000 and 10,000 Å ; the need for specific position angles did not usually allow the luxury of orientation near the parallactic angle. However, the amount of differential refraction over this wavelength range normal to the slit orientation never exceeded 0.5 arcsecond, approaching this value only for PKS 2135-147.

We track internal errors from photon noise in two ways. Direct Poisson errors were computed for each spectral point from the number of detected counts in object and sky within the relevant aperture (particularly transparent in this case since the GEC CCD in the FOS was operated at a gain of unity). For continuum objects, we also estimate errors from the standard deviation of 10-pixel regions of the spectrum. The two error estimators track one another well. Note in the figures that the signal-to-noise ratio per unit wavelength varies across the spectrum by an order of magnitude.

The effects of possible systematics in the data at low levels are difficult to assess, but the effects of errors in sky subtraction can be indirectly addressed from our two different internal-error indicators. The Poisson errors assume perfect sky subtraction, while the point-to-point scatter (evaluated over 10-pixel spectral regions) will include effects of improperly subtracted night-sky contamination. In the deep red, the skyglow is dominated by OH emission bands with a structure that is strongly modulated on 10-Å scales, so improperly subtracted sky emission will result in a much larger scatter than would be implied by Poisson statistics alone. In fact, such scatter will exist even in the mean sky level at each wavelength is correct, due to the spectral undersampling of data with an imperfectly aligned grism and CCD (though the alignment for these observations was quite respectable). In general, the scatter averaged over 10 pixels would be lower than the mean Poisson error prediction by $10^{1/2}$, while for typical data the improvement deep in the red is closer to a factor 2. Most of this is contributed by residuals from the subtraction of individual lines or bandheads, due to the limited wavelength sampling. Errors in sky level will be smaller, since the typical peak brightness of the hot spots is below 1% of sky; note that this means that we require correspondingly good linearity of detector and reduction procedures.

While synchrotron spectra seen in the optical range may show gradual features or turnovers (Keel 1988), over the single octave covered by our spectra a single index is a good approximation (see, for example, Fig. 12 of that paper). We can always fit a power law numerically to any given spectrum, but the goodness of fit (evaluated with a χ^2 criterion using photon noise) is important. Does a particular candidate spectrum fit better a power-law-like continuum, some kind of galaxy spectrum at the parent galaxy's redshift, or might it be an unfortunate projection of a Galactic star? We display each extracted spectrum as a full-resolution plot of F_λ versus wavelength with associated error spectrum, and in 100-Å bins with error bars of each mean. The full-resolution spectrum may be used to set limits on line emission, while the binned spectrum offers a clearer view of the continuum shape in the presence of strongly wavelength-dependent error levels. To test for the possibility of a foreground star, we used a digital version of the Jacoby, Hunter, & Christian (1984) stellar spectral atlas rebinned to match the FOS spectral pixels. For each trial fit, we excluded spectral bins around strong telluric absorption bands and confined the fit to the central (better-exposed) part of each spectrum.

3. RESULTS FOR HOT-SPOT CANDIDATES

We discuss here our results for each object. The spectra are displayed in threefold illustrations, showing at the top the reduced FOS spectrum after flux calibration; in the center, the 1σ error spectrum computed from photon statistics including the sky contribution, and at bottom, the same spectrum in 10-pixel (103-Å) bins with the associated error bars, along with our best-fit interpretation of the spectrum. The full-resolution spectrum indicates the limits we can set on any line emission; in no case did we see any emission lines. In each case, bins included in the χ^2 fit are denoted by filled points; open points are measurements affected by telluric absorption or with very large errors from photon statistics (where small systematic effects might have disproportionate impact). Expected wavelengths of strong emission lines are marked (for the parent galaxy redshift) to illustrate the lack of detection of significant line emission. For power-law fits, each figure is shown with the best-fitting index as fit to F_λ versus wavelength, the quantities closer to the measured domain; in labelling the fits and in the discussion we give the spectral index α in the usual F_ν versus frequency definition given by $F_\nu \propto \nu^\alpha$ (which differs from a direct fit in wavelength space by an additive value of 2).

3C 247 – This red object was noted by Laing et al. (1978), and detected in the near infrared at a 2.2μ flux of 250 ± 27 μJy (K=16.0±0.1) by Allan (1983). Those observations allowed the possibility that this is a foreground M star, though surface-density arguments rendered such a superposition unlikely. Our data (Fig. 1) can help resolve this issue; we could detect strong absorption bands (mostly from TiO) if the object is a star as cool as its observed $(R-K)=5.4$ implies. From the Jacoby et al. stellar atlas we find that type M4 matches the overall slope of the *optical* spectrum best. Fits to appropriately binned spectra of a range of K and M stars (specifically dwarfs, since galactic giants at this latitude would appear much brighter for any likely distance) exclude stars later than about K7, since such stars have TiO bands too strong to be allowed by our spectrum; this applies strictly to wavelengths in common with the stellar spectral library, shortward of 7300 Å . A power-law form is also a better fit (reduced $\chi^2 = 1.3$) than is an old stellar population at this redshift (reduced $\chi^2 = 2.1$, measured by scaling the central galaxy's continuum); Fig. 1 shows the lack of any significant 4000-Å break, which would be observed near 7000 Å . We find a very red power-law continuum shape ($\alpha = -5.3$), which is much steeper than the radio-infrared slope. A truncated synchrotron model, produced as in Keel (1988), can fit these measurements with a critical frequency for electrons at the cutoff of 1.3×10^{14} Hz (in the observed frame, corresponding to 2.3×10^{14} Hz in the frame of 3C 247).

3C 273 – The slit was oriented along the jet axis for our spectra. The 3C 273 data were obtained using an occulted slit, with a 1" central obscuration to keep the core of the quasar spectrum from saturating and bleeding across the chip. Short unocculted exposures were used to measure the instrumental quasar spectrum needed to correct for scattered light near the inner end of the jet. The data quality here was limited by the accuracy of the slit function derived from twilight-sky observations, since the intruding quasar light meant that sky subtraction had to be based on regions farther from the jet than were available for our other target objects. The spectrum was summed for three segments of the jet (Fig. 2), with the hot spot located in the outermost region (indicated in Fig. 3 on an I-band image). Imaging data have shown that the hot spot must be very red as compared to the optically prominent jet (for example, Keel 1988), and our spectroscopic results confirm this.

The spectral indices we find range from -1.0 for the middle segment, through -1.9 for the inner portion, to a very steep -4.5 for the outermost region (the one containing the radio hot spot). The fit χ^2 values are 1.7–2.1, which we regard as acceptable at these low signal levels. These are in reasonable accord with the values found from broad-band imaging polarimetry by Röser & Meisenheimer (1991), as is a steepening of the spectrum going outward along the jet. Our value is much steeper, however, at the outer end for which they give $\alpha = -1.8$. It is not clear at this point whether different spatial sampling or the errors entailed in our fitting over a limited wavelengths range in the red region (which is less sensitive to power-law slope than bluer data) might be responsible for the difference. If we construct broad-band slices along the jet by summing spectral pixels, we get results in overall accord with Fig. 13 of Röser & Meisenheimer. Note that the inner region is most sensitive to proper correction for scattered QSO light, and this is more difficult to insure for spectroscopic than for imaging data.

3C 303 – Imaging photometry (e.g. Keel 1988) showed that this bright hot spot is well described by a single power law from radio through optical regimes. Our spectrum confirms that the radiation comes from a pure continuum, with low limits on line emission (Fig. 4). The photometric data are overplotted as a comparison, running 10-20% higher than the in-slit flux from the spectrum. Such a difference is not surprising in view of uncertainties in spectrophotometric calibration, especially since the hot-spot image may be slightly resolved. The power-law index is not as well constrained from the spectrum alone as from the imagery; observations at shorter wavelengths are most effective at measuring the spectral slope. The imaging data suggest a flatter spectrum, and the error from the spectrum is large enough that the results do not conflict.

3C 319 – This candidate was reported by CTS as a good positional match for the northeast hot spot mapped by Bridle & Fomalont (1979). It is extraordinarily bright for a hot spot at $z \sim 0.2$; CTS quote V=19, which is consistent with both our in-slit flux and imaging results. Our spectrum (Fig. 5) is an excellent match for the continuum shape of an elliptical galaxy at the 3C 319 cluster redshift; the fit to a power-law continuum is much worse (reduced $\chi^2 = 2.07$ for the galaxy spectrum and 3.4 for the best power-law spectrum). This seems to be a chance superposition of a cluster member near the hot-spot location.

The slit location for 3C 319 (Fig. 6, shown on a Lowell Observatory 1.1m image) crosses two additional galaxies near 3C 319 itself. Both exhibit line emission close to the redshift of the radio galaxy (Fig. 7). We estimate redshifts including the effects of light centroids off the slit centerline, using positions and light profiles from the Lowell image. The object denoted G1 lies 11.7 arcseconds from 3C 319 at position angle 41.0°, and has redshift $z = 0.1910$. Similarly, G2 lies at a projected distance of 20.6 arcseconds at PA 48.8°, having redshift $z = 0.1923$. In both cases, Hα and [N II] emission are prominent, with a detection of [S II] in G1. For comparison, we measure an emission-line redshift for $z = 0.192$ for 3C 319 itself, which exhibits only weak Hα and [N II] emission. A third galaxy (G3 in Fig. 6, 46 arcseconds away at position angle $-133.9°$) was also detected on the slit, but the data quality allows us to say only that its continuum shape is consistent with its also lying at the same redshift as the other members of this group or cluster.

3C 330 – CTS report a possible detection of diffuse light from the hot-spot position. Our spectrum shows nothing at this location, even after summing large wavelength bands. If the object is real, it is too diffuse for detection with this instrument using a 2.5-arcsecond slit.

3C 390.3 – This is a crowded field at moderate galactic latitude. STC reported several possibly associated optical objects close to the northern hotspot. Our spectrum was centered on the brightest of these which they denoted 3C 390.3/18.2; the perhaps more plausible faint object immediately south of this was lost in the light from this object. The spectral fit is excellent to a foreground star; Fig. 8 shows a binned spectrum compared with the K4 star HD 21110 from Jacoby, Hunter, & Christian (1982). The continuum matches in detail, with the only major departure being deeper (blended) H$\alpha$and Ca absorption in the 3C 390.3 candidate (such absorption at zero redshift qualifying this as a local star of some kind). This spectral type accords reasonably well with the color $(B-V)=1.7\pm0.2$ quoted by STC. Any genuine optical counterpart to this hot spot must lie at a fainter level.

PKS 2135-147 – Hawkins (1978) reported a possible optical counterpart to the eastern hot spot in this quasar. This field is crowded with a variety of galaxies, many apparently associated with the QSO (Stockton 1978, 1982), so further information is needed to decide whether this is another case of optical synchrotron emission. Our data, shown in Fig. 9, are best fit by a power law of index $\alpha=-2.75$. A. Stockton (private communication) reports that this object shows Ca II H and K absorption and modest [O II] $\lambda3727$ emission at $z=0.186$, so it is evidently another galaxy superposition. This nature was not apparent from our spectrum alone, since none of these strong features lies within our spectral range at such a low redshift. The continuum shape is rather bluer than expected for an elliptical galaxy at this redshift, giving a poorer χ^2 than did the power-law form.

4. THE GALACTIC NUCLEI

Our spectra (Fig. 10, Table 2) add some interesting details to the available information on the central radio galaxies. Especially interesting is the measurement of emission lines from [O II] $\lambda3727$ to Hα in 3C 330, at $z=0.55$, using an instrument free of second-order overlap problems. Its rich emission spectrum shows the high ionization typical of such objects as Cygnus A and 3C 98. The ionization level is quite similar, from the [Ne III] and [Ne V] lines, though such lines as [N II] are relatively weaker in 3C 330. The Balmer decrement in 3C 330 may imply substantial reddening, though we caution that the flux calibration is not as well determined at 10166 Å as at shorter wavelengths and is a very strong function of wavelength in this region as well.

Among the other radio galaxies, 3C 247 shows moderately strong [O II] and [Ne

III] emission and weak Hβ and [O III]. In 3C 319, only weak Hα and [N II] are seen, as is typical for nearby low-power radio galaxies. The broad-line spectrum of 3C 303 has been discussed by Eracleous & Halpern (1994), with resolution high enough to separate distinct narrow and broad emission components. These radio galaxies span a wide range of ionization level and emission-line strength, even among those with well-attested hot-spot emission.

We measured amplitudes of the 4000-Å break in several radio galaxies, as listed in Table 2. These measures follow the definition used by, for example, Dressler & Schectman (1987), taking the ratio of F_ν between the windows 4050-4250 Å and 3750-3950 Å in the emitted frame. We list them here to add to the overall data on the evolution of the 4000-Å break with redshift, for use in concert with the many other sources of such data for radio galaxies at a wide range of redshift.

5. CONCLUSIONS

Low-resolution spectrophotometry of candidate hotspots in several radio galaxies have been used to discriminate synchrotron hotspots associated with the radio emission from superposed stars and galaxies, and to measure spectral indices over the 0.5–1.0 μ range. We confirm that the optical emission in 3C 247 and 3C 303 is consistent with a synchrotron origin; the 3C 247 hot spot shows evidence for a spectral turndown between 0.8 and 2.2 μ. The candidate hot spot in 3C 319 is a galaxy in the associated cluster. The most obvious candidate for the northern hot spot of 3C 390.3 is a foreground star.

The hot spots for which optical synchrotron emission has been confirmed or remains a strong possibility show that the hot spots have a range of optical spectral shape, and hence of upper electron energy cutoff, even wider than seen in optically-detected jets. Some hot spots have power-law spectra extending into the UV or even into the X-ray regime (Pictor A, 3C 303) while others have spectra truncated in the near-infrared (3C 247, possibly 3C 33S). Near-infrared imaging surveys may prove very effective in detecting the high-energy particle populations in further hot spots.

These results, in concert with the earlier measurements of spectral shapes for optically-detected jets, may have implications for the sites of particle (re)acceleration in radio sources. The X-ray flux of the Pictor A hot spot (Röser & Meisenheimer 1987) falls close to a simple extrapolation of its lower-frequency power law, most simply explained if its electron energy spectrum continues to appropriately high energies. In contrast, some hot spots (notably 3C 247 from our results) show strong cutoffs, well fit by truncated electron spectra. This is the situation found in optically-detected jets (i.e. Keel 1988). Are the hot spots as a group different? Certainly jets have not been observed with continuous power-law spectra extending into the X-ray regime, even under the most generous interpretation of the X-ray emission from M87 (Biretta et al. 1991). The fact that *any* of the few observable hot spots show such high-energy emission constitutes a difference, that might be traceable to higher particle energies from local acceleration, enhanced magnetic fields, or some combination (since the synchrotron spectral shapes measure essentially $B^2\gamma_{max}$).

Particle acceleration in shocks has received considerable attention in analysis of radio sources, and hot spots are excellent candidates for locations of strong shocks (most likely the terminal shocks of advancing jets). We can use shock properties to limit the increase in spectral cutoff frequency that could be induced solely by crowding of field lines in a shock. The maximum increase in field intensity across a shock is the same as the density increase, a factor 4 in the limit of dynamically insignificant magnetic field. Simply because of the field strength enhancement, the synchrotron radiation from electrons entering the hot spot would be boosted in frequency by a factor up to 16, without invoking local acceleration. Any enhancement beyond this would constitute evidence for local acceleration of the emitting particles.

The most direct application of this criterion would require measurements of the high-energy cutoff frequency in a hot spot and the jet feeding it. No such pair (except in 3C 273, in which the relation to usual lobe-jet structure is unclear) has been detected in the optical; none of the known optical synchrotron jets feeds a hot spot, which fact may be significant for energy loss in jets. We can only compare ensemble properties, assuming for argument that the internal properties of the sources are similar for detected jets and hot spots. Jets always have at least a spectral steepening, if not a clear turnover, in the optical range. Hot spots may have such a steepening, but not all do. Can the difference be accounted for by a 16-fold frequency boost from field strength in a shock? Taking the M87 knot D spectrum from Keel (1988) as the highest-cutoff jet and blueshifting it by a factor 16 puts the highest-energy critical frequency (the reference turnover frequency in a truncated power-law model) near 3×10^{16} Hz, well below what is required to account for the spectral shape in Pictor A up to 5×10^{17} Hz. This is at least circumstantial evidence that the electron-energy distribution in hot spots really does extend to higher energies than in jets; that is, that reacceleration of particles is required in hot spots. The conclusion applies immediately to those hot spots with relatively straight high-energy continua (Pictor A, 3C 303), and given the similar radio structures probably to the others as well. The hot spot in 3C 273 shows a steeper spectrum than the jet, showing that the observed properties do not always require higher fields or particle energies at the hot spots.

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Allan, P.M. 1983, Nature 305, 45

Biretta, J.A., Stern, C.P., & Harris, D.E. 1991, AJ, 101, 1732

Bridle, A. & Fomalont, E.A.J. 1979, AJ, 84, 1679

Crane, P., Tyson, J.A., & Saslaw, W.C. 1983, ApJ, 265, 681

Dressler, A. & Schectman, S. 1987, AJ, 94, 899

Eracleous, M. & Halpern, J. 1994, ApJS, 90, 1

Filippenko, A. 1982, PASP, 94, 715

Hawkins, M.R.S. 1978, MNRAS, 185, 23P

Jacoby, G.H., Hunter. D.A., & Christian, C.A. 1982, ApJS, 56, 257

Keel, W.C. 1988, ApJ, 329, 532

Laing, R.A., Longair, M.S., Riley, J.M., Kibblewhite, E.J. & Gunn, J.E. 1978, MNRAS, 183, 547

Röser, H.-J., & Meisenheimer, K. 1987, ApJ, 314, 70

Röser, H.-J., & Meisenheimer, K. 1991, A&A, 252, 458

Saslaw, W.C., Tyson, J.A., & Crane, P. 1978, ApJ, 222, 435

Simkin, S. 1978, ApJL, 222, L55

Stockton, A. 1978, ApJ, 223, 747

Stockton, A. 1982, ApJ, 257, 33

Table 1

INT/FOS observations of hot-spot candidates

Name	Exposure	Position angle	z	V (hotspot)
3C 303	60m	98°	0.141	21.4
3C 390.3	75m	15°	0.056	19.6
PKS 2135-147	35m	114°	0.200	20:
3C 247	60m	79°	0.749	22:
3C 319	60m	45°	0.192	20.5
3C 330	60m	66°	0.550	24
3C 273	40m	50°	0.158	

Table 2

Spectral Properties of Program Galaxies

	3C 247	3C 303	3C 319	3C 330
z	0.749	0.141	0.192	0.549
Break	1.77	—	—	1.39
F(5007)	5.2	221	< 7.0	6.52
[O III]/Hβ	1.2	6.6	—	7.8
EW(3727),Å	420	—	—	304
EW(5007),Å	16	51	< 8.3	760
Hα/Hβ	—	30.0	—	10.7
[O I]/[O III]	—	0.23	—	0.065
[O II]/[O III]	4.68	—	—	0.22
[Ne III]/[O II]	0.07	—	—	0.52
[Ne V]/[O II]	< 0.05	—	—	0.48
[N II] λ6583/Hα	—	—	0.92	0.67

Line fluxes are given in units of 10^{-16} erg cm^{-2} s^{-1}. Equivalent widths are in Å in the observed frame. Hα in 3C 303 refers to the broad component, including blended contributions from the adjacent [N II] lines.

Figure Captions

1. FOS spectrum for the 3C 247 hotspot candidate. In this and the following displays, the calibrated spectrum is shown at the top at the full observed resolution, with the $1-\sigma$ error spectrum based on photon statistics shown below it. At the bottom is the spectrum averaged in 10-pixel (108-Å) bins with internal error bars accompanied by the best-fitting model (power law in this case). Filled symbols show the portions of the spectrum included in the χ^2 fit; open symbols indicate data of much lower signal-to-noise ratio or compromised by telluric emission or absorption features (such as the A or B bands or residual [O I] airglow emission). The indicated power-law indices have been converted from the directly fitted index in F_λ to the usual $F_\nu \propto \nu^\alpha$.

2. Spectra for segments of the 3C 273 jet. The inner portion runs from 8.7-13.4 arcseconds from the core, the middle from 13.4-18.1, and the outer part from 18.1-22.8 arcseconds. A few averaged pixels were affected by a low-level charge trap and are omitted from the plot. The radio hot spot is in the "outer" region, which is clearly redder (steeper-spectrum) than the inner two.

3. The subregions extracted for the 3C 273 jet, shown on an I-band image from Keel (1988). The outermost includes the radio hot-spot location.

4. FOS spectrum of the 3C 303 hot spot, displayed as in Fig. 1. The broad-band fluxes from Keel (1988) are shown as boxes, with width corresponding to the filter half-transmission points and height given by the flux errors. The FOS data confirm that this is a pure continuum object, and are consistent with the broad-band spectral index. In this case, the bluer passband from imaging observations provides a strong constraint on the spectral slope.

5. FOS spectra for the 3C 319 hot-spot candidate. The best spectral fit is for an elliptical-galaxy continuum at the redshift of 3C 319 itself (in fact, the fit was made with respect to the spectrum of 3C 319 itself, since the nuclear line emission is quite

weak). This object is a superposition of a galaxy in the cluster around 3C 319 rather than a synchrotron hotspot.

6. The field of 3C 319, in a V-band CCD image from the Lowell Observatory 1.1-m telescope. The objects detected within the FOS slit observation are identified, with the hot-spot candidate marked HS and the other serendipitously observed galaxies as G1-G3.

7. Serendipitous spectra of galaxies near 3C 319, as identified in Fig. 6. G1 and G2 show line emission at redshifts closely matching that of 3C 319, and are thereby confirmed cluster members. G3 has a spectral shape consistent with that of an elliptical or S0 galaxy at the same redshift, but we found no uniquely measurable spectral features.

8. FOS spectrum of the brightest candidate for the northern hot spot of 3C 390.3. The best spectral fit is to a star of type K4 (the spectrum shown, binned to matching resolution, is HD 21110).

9. FOS spectrum of the PKS 2135-147 hot-spot candidate. The best fit is a power-law with index $\alpha = -2.75$, but identification as a true synchrotron source is spurious given detection of stellar absorption features and [O II] emission blueward of the spectral range covered here.

10. Spectra of radio-galaxy nuclei obtained simultaneously with the hot-spot data. Prominent emission lines are identified.