INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.
IMAGING OF COMPLETE SAMPLES OF Z ~ 1 3C SOURCES

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

ASTRONOMY

DECEMBER 1995

By

Susan E. Ridgway

Dissertation Committee:

Alan Stockton, Chairperson
Kenneth C. Chambers
Lennox Cowie
Charles Hayes
Esther Hu
Abstract

We present the results of a HST and ground-based imaging study of a complete sample of $z \sim 1.5$ 3C quasars and 5 3C galaxies. We have obtained deep WFPC2 rest-frame UV and deep rest-frame 1$\mu$m images of this sample. We resolve continuum structure around all of our quasars in the high resolution WFPC2 images, and are able to resolve some nebulous structure in all but one of the near-infrared images. Four of the quasars have some optical structure that is aligned with the radio axis or is directly coincident with the radio structure. The total optical and $K'$ magnitudes of the quasars is consistent with those of the radio galaxies within the observed dispersion in our sample. The distributions of $K'$ magnitudes of both radio galaxies and quasars exhibit similar mean and dispersion as that found for other radio galaxies at this redshift.

We see morphological evidence of interactions in our objects; in one, we may see a tidal tail. We see very blue and/or edge-brightened structures that lie within the probable quasar opening angle; these are likely the result of illumination effects from the active nucleus, i.e. scattered quasar light or photoionization.

In 3C 212, we see an object that lies beyond the radio lobe that looks morphologically quite similar to a radio hotspot and tail; this object is bright in the infrared and has a steep spectral gradient across the tail. We have detected an
optical counterpart to a radio jet in the quasar 3C 245, and an optical counterpart to a radio lobe in 3C 2. Both of these structures have such a high-resolution, point-to-point correspondence with the radio structures that they are very likely the result of optical synchrotron radiation. The spectral indices in 3C 2 are consistent with this hypothesis.

Based on the correspondence between the total magnitudes in the radio galaxies and quasars, and the first detection of aligned components in quasars, we conclude that this study provides general support for the unification hypothesis of radio galaxies and quasars. However, there seem to be significant morphological differences between the aligned structure in the two samples. The extension around the quasars in some cases is likely due to stars, and in others is almost certainly optical synchrotron emission.
Chapter 5: Discussion of Individual Fields

5.1 3CR 2

5.1.1 Morphology

5.1.2 3C2 Component Spectral Energy Distributions

5.1.3 Discussion

5.2 3CR 175.1

5.2.1 Image Editing

5.2.2 Morphology

5.3 3CR 196

5.3.1 Morphology

5.3.2 Discussion

5.4 3CR 212

5.4.1 Morphology

5.4.2 Photometry

5.4.3 Discussion

5.5 3CR 217

5.5.1 Morphology

5.5.2 Discussion

5.6 3CR 237

5.6.1 Morphology
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6.2</td>
<td>Discussion</td>
<td>55</td>
</tr>
<tr>
<td>5.7</td>
<td>3CR 245</td>
<td>56</td>
</tr>
<tr>
<td>5.7.1</td>
<td>Morphology</td>
<td>56</td>
</tr>
<tr>
<td>5.7.2</td>
<td>Analysis and Discussion</td>
<td>57</td>
</tr>
<tr>
<td>5.8</td>
<td>3CR 280</td>
<td>58</td>
</tr>
<tr>
<td>5.8.1</td>
<td>Morphology</td>
<td>58</td>
</tr>
<tr>
<td>5.8.2</td>
<td>Details of Analysis</td>
<td>59</td>
</tr>
<tr>
<td>5.8.3</td>
<td>Discussion</td>
<td>63</td>
</tr>
<tr>
<td>5.9</td>
<td>3CR 289</td>
<td>65</td>
</tr>
<tr>
<td>5.10</td>
<td>3CR 336</td>
<td>66</td>
</tr>
<tr>
<td>5.10.1</td>
<td>Morphology</td>
<td>66</td>
</tr>
<tr>
<td>5.10.2</td>
<td>Discussion</td>
<td>67</td>
</tr>
<tr>
<td>Chapter 6</td>
<td>Magnitude and Moment Analysis of the Images</td>
<td>83</td>
</tr>
<tr>
<td>6.1</td>
<td>Magnitudes</td>
<td>83</td>
</tr>
<tr>
<td>6.2</td>
<td>Position Angle Determination</td>
<td>85</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>Modelling the Quasars with the Radio Galaxies</td>
<td>93</td>
</tr>
<tr>
<td>Chapter 8</td>
<td>Properties of the Sample</td>
<td>99</td>
</tr>
<tr>
<td>8.1</td>
<td>Magnitudes and Alignment</td>
<td>99</td>
</tr>
<tr>
<td>8.2</td>
<td>Linear Galaxies</td>
<td>101</td>
</tr>
<tr>
<td>8.3</td>
<td>Optical Synchrotron Emission</td>
<td>101</td>
</tr>
<tr>
<td>Chapter 9</td>
<td>Summary</td>
<td>113</td>
</tr>
</tbody>
</table>
Appendix A: Determination of Principal Axes of an Ellipse ............... 116

References ................................................................. 118
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HST Sample Characteristics</td>
</tr>
<tr>
<td>2</td>
<td>HST WFPC2 Observations</td>
</tr>
<tr>
<td>3</td>
<td>Log of Ground-based Imaging Observations</td>
</tr>
<tr>
<td>4</td>
<td>HST PSF Star Observations</td>
</tr>
<tr>
<td>5</td>
<td>3C 2 Component Photometry</td>
</tr>
<tr>
<td>6</td>
<td>Photometry of Components</td>
</tr>
<tr>
<td>7</td>
<td>Quasar HST Photometry</td>
</tr>
<tr>
<td>8</td>
<td>Radio Galaxy HST Photometry</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>3C sample: ( z ) vs. ( P_{178} )</td>
</tr>
<tr>
<td>2</td>
<td>PSF Subtraction Method</td>
</tr>
<tr>
<td>3</td>
<td>PSF Subtraction Tests</td>
</tr>
<tr>
<td>4</td>
<td>3C2 (quasar)</td>
</tr>
<tr>
<td>5</td>
<td>3C175.1 (galaxy)</td>
</tr>
<tr>
<td>6</td>
<td>3C196 (quasar)</td>
</tr>
<tr>
<td>7</td>
<td>3C212 (quasar)</td>
</tr>
<tr>
<td>8</td>
<td>3C217 (galaxy)</td>
</tr>
<tr>
<td>9</td>
<td>3C237 (galaxy)</td>
</tr>
<tr>
<td>10</td>
<td>3C245 (quasar)</td>
</tr>
<tr>
<td>11</td>
<td>3C280 (galaxy)</td>
</tr>
<tr>
<td>12</td>
<td>3C289 (galaxy)</td>
</tr>
<tr>
<td>13</td>
<td>3C336 (quasar)</td>
</tr>
<tr>
<td>14</td>
<td>Spectral Energy Distributions of 3C 2 Components</td>
</tr>
<tr>
<td>15</td>
<td>Optical-Radio SED of 3C 2 Northern Component</td>
</tr>
<tr>
<td>16</td>
<td>3C 280 Elliptical Isophotal Fits</td>
</tr>
<tr>
<td>17</td>
<td>( K' ) Position Angle Determination for 3C 175.1</td>
</tr>
<tr>
<td>18</td>
<td>The Quasars Modelled with the Radio Galaxies</td>
</tr>
<tr>
<td>Page</td>
<td>Title</td>
</tr>
<tr>
<td>------</td>
<td>-----------------------------------------------------------------------</td>
</tr>
<tr>
<td>19</td>
<td>Isophotal Optical Flux Densities</td>
</tr>
<tr>
<td>20</td>
<td>Total Optical Annular Flux Densities</td>
</tr>
<tr>
<td>21</td>
<td>Total $K'$ Annular Flux Densities</td>
</tr>
<tr>
<td>22</td>
<td>Histograms of Optical-Radio Alignment: Low Isophotes</td>
</tr>
<tr>
<td>23</td>
<td>Histograms of Near-Infrared–Radio Alignment</td>
</tr>
<tr>
<td>24</td>
<td>Histograms of Optical-Radio Alignment: High Isophotes</td>
</tr>
<tr>
<td>25</td>
<td>Component Colors</td>
</tr>
<tr>
<td>26</td>
<td>Selected Linear Galaxy Images</td>
</tr>
<tr>
<td>27</td>
<td>Distribution of Linear Galaxies in the WFC fields</td>
</tr>
</tbody>
</table>

xi
Chapter 1

Introduction

Powerful radio sources, and the objects associated with them, remain the most available probes of the Universe from \( z \sim 1 \) up to the highest redshifts at which discrete objects have been detected. Over the past decade, observations of radio sources at high redshift have focussed primarily on high-\( z \) galaxies, since the extended hosts of quasars are much more difficult to observe. These studies have been reviewed by McCarthy (1993); below we summarize the most relevant aspects.

1.1. High Redshift Radio Galaxies

Radio galaxies at \( z \gtrsim 0.8 \) have distorted, multi-component optical continuum morphologies and often have associated emission-line regions extending many tens of kpc. They also show a high incidence of close companions. Both the emission-line and the continuum morphologies tend to be elongated along the direction of the radio axis (Chambers, Miley, & van Breugel 1987, McCarthy et al. 1987), whereas similar alignments have been observed only rarely in the lower-redshift (\( z \leq 0.6 \)) 3C sample (Baum & Heckman 1989, McCarthy & van Breugel 1989). In fact, low-radio power, \( z \sim 0.1 \), elliptical 3C galaxies tend instead to have their minor axes aligned with the radio jet (Guthrie 1979, Palimaka et al. 1979).

This alignment effect may also be a function of wavelength; Rigler et al. (1992) imaged a \( z \sim 1 \) 3CR galaxy sample in several optical passbands and in the near-infrared and found that morphologies became rounder and less-aligned with increasing wavelength. Some \( z \sim 1 \) radio galaxies do show significant alignment in the infrared (Eisenhardt & Chokshi 1990, Chambers 1988), however, and Dunlop & Peacock (1993) found the near-infrared elongated component in a \( z \sim 1 \) 3CR galaxy sample
(similar to that of Rigler et al.) possibly to be better aligned with the radio axis than the optical component. They still concurred with Rigler et al.'s conclusion that the overall strength of the aligned component is less in the near-IR than in the optical.

If the alignment effect is wavelength-dependent, we should not expect to see a similar alignment in low-z and high-z objects when observing in the same passband. It cannot be assumed, therefore, that the differences between the high and low redshift galaxies arise solely from evolutionary effects. Optical imaging of high redshift galaxies samples the rest-frame ultraviolet, which is observable only with great difficulty from the ground for their low-z counterparts. Recent imaging of low-redshift radio galaxies in the ultraviolet indicates a lesser, but still significant, degree of alignment with the radio axis than in high-redshift galaxies (Cimatti & di Serego Alighieri 1995, Dey et al., in prep.). Another difference between the high-z and low-z samples is that the radio power of the low-redshift sources is systematically lower than that of the high-z objects. Dunlop & Peacock (1993) have addressed this problem by comparing near-infrared alignments in a sample of Parkes faint radio galaxies in the same $z \sim 1$ redshift range as a sample of 3CR galaxies. They find no evidence of alignment between the radio and optical morphologies in the low radio power sample, in contrast to the significant alignment they see in the 3CR sample. However, a study in progress by Chambers (private communication) has found evidence for significant alignment in high-resolution, near-infrared images of a complete sample of 6C galaxies, with mean radio power comparable to that of the Parkes sample of Dunlop & Peacock (1993).

A simple explanation for this correlation of optical and infrared morphologies with the radio axis remains elusive, and observations probably rule out any single cause. In one of the best studied examples of an aligned radio galaxy, 3C 368, at $z=1.13$, the aligned emission is highly polarized in the optical, and the polarization
position angle is consistent with the aligned light being scattered from a buried quasar nucleus (di Serego Alighieri et al. 1989, Scarrott, Rolph & Tadhunter 1990). Cimatti et al. (1993) found similar levels of polarization (\(\sim 10\%\)) in 3C 277.3 and number of other radio galaxies. It is clear that scattered radiation is a significant component of the light observed in the optical (rest frame UV) (Fabian 1989, Cimatti et al. 1993, di Serego Alighieri et al. 1994). Yet deep spectroscopy of 3C 368 has so far failed to detect a broad Mg II \(\lambda 2798\) component as might be expected were the emission scattered radiation from a hidden quasar (Hammer et al. 1991, Stockton, Kellogg, & Ridgway 1995). In 3 other \(z \sim 1\) quasars, however, di Serego Alighieri et al. (1994) detect evidence for polarized broad MgII lines, consistent with a scattered-quasar-light origin for the aligned component. In Keck spectra of 3C 324, Dickinson, Dey & Spinrad (1995) also detect broad components to MgII and CIII with widths consistent with an origin in scattered quasar light. WFPC2 imaging of several \(z \sim 1\) radio galaxies, including 3C 368, has not revealed a "scattering cone" morphology as is seen in low redshift AGN such as NGC 1068; the alignment comes from discrete lumps and wiggles of structure (Longair et al. 1995, Dickinson et al. 1995). In addition, Longair et al. find that their three galaxies have qualitatively different high-resolution morphologies, and though they all exhibit some degree of alignment, the nature of the correspondence with the radio morphology varies from source to source. 3C 368 has material confined quite closely to the radio axis, and some correspondence between radio and optical hotspots. In 3C 324, the emitting material is entirely interior to the radio lobes, and it is clumpy and aligned along the axis that connects the near sides of the lobes and that is associated with the radio jet (Dickinson et al. 1995). In the third of Longair et al.'s galaxies, the emission is diffuse and off of the radio axis; however, when smoothed the intensity distribution has a position angle close to that of the radio axis.
Interactions are an attractive and natural way to explain the distorted morphologies, wispy gas, and close companions. Some recent theoretical work (West 1994) has provided a framework in which brightest cluster member galaxies (BCM) would form by mergers occurring anisotropically along an axis preselected by large-scale structure in the vicinity of the cluster. Gas from the merging galaxies would collapse to a central disk, with its angular momentum vector aligned with the major axis in a prolate galaxy and the minor axis in an oblate galaxy. If, as West theorizes, high redshift radio galaxies are BCMs in formation, an accreted or forming black hole would soon have its spin axis oriented along the major axis of the forming, prolate galaxy, and radio jets would therefore emerge aligned with this preferred direction. This model then predicts that material and galaxies would be roughly aligned over a large scale range; it allows as well for an inverse correlation of alignment with radio luminosity, in that the galactic mass is likely proportional to the black hole mass, which is in turn proportional to the radio luminosity. Selecting on radio luminosity then selects out the brightest, most massive proto-BCGs.

Another possible contributor to the aligned emission is radio-jet-induced star formation (Chambers et al. 1987, Begelman & Cioffi 1989, de Young et al. 1989, Rees 1989, Daly 1990). There is so far no conclusive evidence for a case in which stellar emission is likely to dominate an aligned component. Chambers & McCarthy (1990) found some evidence for stellar absorption features in summed spectra of aligned regions in two different radio galaxies. More recently, di Serego Alighieri et al. (1994) have found indirect evidence for the 4000Å break in non-polarized light in some radio galaxies; they find that an evolved stellar population likely contributes ~15% of the UV light in one case. Detections have been made of stellar features in the $z \sim 1$ radio galaxy 3C 65 (Stockton, Kellogg, & Ridgway 1994), but this is one of the reddest and least aligned of the $z \sim 1$ sample, and detection of an old stellar population here puts
no serious constraints on the likely origin of the blue, aligned material in the \( z \sim 1 \) sample in general. Other suggested contributors to the aligned UV continuum in these galaxies are thermal emission from a hot plasma, optical synchrotron radiation, and inverse Compton scattering of microwave background photons by relativistic electrons (Chambers et al. 1988, Daly 1992a,b). Some of these mechanisms require that the optical morphology directly trace the radio structure: such a correspondence is observed in some smaller scale radio objects such as 3C 368 (Chambers et al. 1988) and 4C 41.17 (Miley et al. 1992), but cannot account for the multitude of objects in which the radio lobes are of much greater scale than the UV emission.

Despite the great variety in observed optical morphologies, the \( K \) magnitudes of the galaxies correlate tightly with redshift from \( z \sim 0.2 \) to \( z \sim 4 \). The low dispersion in the relation (\( \sim 0.35 \) mag ) has been taken as evidence that the \( K \)-band light is dominated by old stellar populations in radio galaxies at redshifts approaching 4, which would place severe constraints on the epoch of galaxy formation (Lilly 1989, Rigler et al. 1992, Dunlop & Peacock 1993). Eales & Rawlings (1993) argue that the \( K \) passband is heavily contaminated by emission lines, and that therefore the continuity of the \( K \) magnitude is not a reflection of the dominance of an old stellar population in the near-infrared. They favor a young age for the stellar population in these galaxies, as do Chambers & Charlot (1990), who find that the stellar population fits to broad band color galaxy spectral energy distributions give ages that are model-dependent, and young starbursts fit as well as an old stellar population. The detection of stellar absorption lines in the morphologically round, red radio galaxy 3C 65 placed a probable lower limit to its age of 4 Gyr (Stockton, Kellogg & Ridgway 1995), but similar searches in the highly elongated, aligned, blue galaxy 3C 368 have so far failed to reveal stellar absorption lines (Hammer, Le Fèvre, & Proust 1991, Stockton et al. in preparation).
1.2. QSO Host Galaxies

Far less is known about the hosts of high redshift quasars than about radio galaxies. Until recently, studies of QSO host galaxies have concentrated primarily on the low redshift range. Evidence has accumulated that QSO activity might be triggered by interactions or mergers: the extensive ground-based work on these $z < 1$ QSOs has shown a significant fraction of them to have asymmetries, distortions, tidal features and a tendency to have close companions. Their host galaxies have colors bluer than normal ellipticals, which would be consistent with interaction-triggered star formation. (Heckman 1990, Stockton 1990 and references within). In the past 5 years, several groups have studied radio-loud and radio-quiet QSOs at $z = 2$ to 3 (Heckman et al. 1991, Lehnert et al. 1992, Hutchings et al. 1994b, Arextaga et al. 1995). They have been able to resolve extensions around a reasonable percentage of the high-$z$ QSOs they have studied in optical and/or the near-infrared ($\sim 50\%$); the groups find similar results in that the extended portion contributes $\sim 20\%$ of the total quasar flux. Lehnert et al. (1992) found the extended quasar light to be redder than that of the quasar itself; if so, this increases the likelihood that the infrared extension seen is due to a stellar host galaxy rather than to scattered nuclear emission. They also found that the 5 quasars in their sample have total $K$ magnitudes significantly brighter than those of radio galaxies in a comparable redshift range. In the optical studies of the same sample, Heckman et al. (1991) saw no evidence for alignment of the quasar extensions with the radio axis. These two results seem to pose difficulties for theories in which radio galaxies and quasars differ solely in orientation (Barthel 1989); radio galaxies at these redshifts are quite aligned in the UV.

Of course, the study of QSO host-galaxy properties is complicated by the bright nucleus which contaminates or swamps any extended component that underlies the seeing disk. For this reason, the Hubble Space Telescope is well-suited to study of
QSO host galaxies, and even more so for these high redshift objects in which (at $z = 1$) $\sim 6 \text{kpc}^1$ of physical scale would be hidden under a typical $1''$ diameter ground based seeing disk. A number of recent studies of QSO host galaxies with WFPC2 imaging have been made, with differing and somewhat controversial results. These include the major GTO survey of $z \sim 0.2$ QSOs of Bahcall et al. (1994,1995a,1995b,1995c), a survey of 4 QSOs by Disney et al. (1995), and several low-z QSOs studied by Hutchings et al. (1994). We will discuss specifics of these other programs as they become relevant, but summarize the major results: Bahcall et al. have found nine QSOs in which they detect no host galaxy as bright as $L^*$, the characteristic luminosity of the Schecter luminosity function (Bahcall et al. 1994, 1995a); they do find the QSOs to have a high incidence of close companions. In another few QSOs they have found extensions brighter than $L^*$ (Bahcall et al. 1995a), and examples of what appear to be normal galaxy hosts: one elliptical and one spiral at $z \sim 0.16$ (Bahcall et al. 1995c). In PKS 2349-014, they have found tail and wisp-like features that are reminiscent of classical merger remnants (Bahcall et al. 1995b). Disney et al. (1995) found normal elliptical hosts and close companions in 4 QSOs, one of which was studied by Bahcall et al. without detection of a host galaxy.

In this paper, we present the results of a ground-based and WFPC2 imaging study of a complete sample of 5 radio galaxies and 5 quasars at redshifts close to 1. This survey will enable us to make a direct comparison of the radio galaxy and quasar host properties in objects identically selected (by radio properties generally considered isotropic; there are some caveats we will discuss), and observed homogeneously.

$^1 H_0 = 75 \text{ km sec}^{-1} \text{ Mpc}^{-1}, q_0 = \frac{1}{2}$ throughout this paper.
1.3. Unified Models

The optical spectra and extended radio properties of radio galaxies and quasars have many similarities, inspiring attempts to explain the differences between the two classes as due primarily to orientation (Orr & Browne, Scheuer 1987, Barthel 1989). In this view, FR II radio galaxies and quasars are drawn from the same sample; the non-thermal optical continuum and broad spectral features seen in the quasars are obscured in the radio galaxies by a torus oriented perpendicularly to the radio jet. That radio sources have strongly beamed, relativistic jets is well-established from the observed jet asymmetries, apparent superluminal motion, and depolarization asymmetries between the jet and counter-jet-side radio lobes of quasars (Laing 1988, Garrington et al. 1988, Ghisellini et al. 1993). Orientation must play a part in how we view and classify such beamed objects.

Unified hypotheses of AGNs in general have been reviewed recently by Antonucci (1993) and of radio-loud AGNs in particular by Urry & Padovani (1995). Spectrophotometric studies of 3C 234 and seven other radio galaxies revealed obscured broad-line regions (Antonucci & Barvainis 1990, see review by Antonucci 1993). These studies, the recent probable discovery of broad Mg II in emission in the very nearby powerful FR II galaxy Cygnus A (Antonucci et al. 1994), and detections of broad Pa-α from some narrow-line radio galaxies (Hill et al. 1995), provide direct support for this unification of radio galaxies and quasars. Another way to test the unification hypothesis for quasars and narrow-line radio galaxies is to compare properties that should be isotropic in matched, complete, and unbiased samples of radio galaxies and quasars selected on the basis of some other supposedly isotropic property.

As summarized by Urry & Padovani (1995), a number of such tests can and have been made. The extended, steep-spectrum lobes of FRII radio galaxies are
believed to be optically thin and unbeamed; thus extended lobe radio luminosities in
the radio galaxies and quasars should be comparable. The range in extended radio
luminosity in flat- and steep-spectrum quasars matches that of radio galaxies (Urry
& Padovani 1995). There is, however, some evidence for beaming effects in the lobe
emission: Garrington et al. (1991) found that the spectral index is flatter on the
jet-side, consistent with a beamed contribution to the lobe flux. The contribution is
considered minor (Urry & Padovani 1995), but this is nonetheless a potential source
of bias in our (and any other) radio-lobe-luminosity selected sample.

In standard quasar models, narrow emission lines originate in diffuse clouds that
are exterior to the broad-line region and the posited obscuring dust. In this case,
narrow-line luminosities should be comparable in radio galaxy and quasar samples
selected on extended radio properties. Jackson & Browne (1990) found that [O III]
luminosities in quasars are 5–10 times greater than in a matched sample of radio
galaxies; however, [O II] luminosities in the two classes of objects seem to match well
(Hes, Barthel, & Fosbury 1993). A possible explanation for this seeming contradiction
is that the [O III] luminosity is likely to come mainly from the inner part of the narrow-
line region, which could still be partially obscured (Hes et al. 1993, Urry & Padovani
1995).

Other properties that are predicted to be similar in radio galaxies and quasars
are the far-infrared luminosities, the source environments, cosmic evolution of the
number counts and radio sizes, and the host galaxy morphologies and colors. All of
these have been tested; results are mostly either consistent with some form of the
unification hypothesis, or are indeterminate. Coadds of IRAS data, however, suggest
that the far-infrared luminosities of quasars is significantly higher than those
of radio galaxies (Heckman et al. 1992, 1994); this result should be qualified with
the caveat that the far-IR radiation is not necessarily isotropic (Pier & Krolik 1992,
Heckman et al. 1994). Some of the arguments pro and con the existence of differences in space densities and linear sizes in the 3C radio galaxy and quasar samples are discussed in Saikia & Kulkarni (1994); they present a reanalysis of currently available data and find the data are consistent with the unified theory. They derive an opening angle of $\sim 45 - 50^\circ$, which is consistent with that originally derived by Barthel (1989) in his analysis of the 3CR sources.

There is no evidence for a difference in clustering environment around the two classes of objects at $0 < z < 0.5$ (summary by Urry & Padovani 1995); but studies are few. Many studies of quasar host galaxies have been made, some of which we discuss above, but results have generally been contradictory: some workers find significant differences in quasar host galaxy magnitudes from radio galaxy magnitudes (Smith & Heckman 1989), others do not (Dunlop et al. 1993). As noted above, magnitudes and morphologies of quasar host galaxies are difficult to determine without systematic effects.

In summary, although it is certain that viewing angle has affected our classification of radio galaxies and quasars, precise and unambiguous tests of the hypothesis that all objects in these separate apparent classes belong to the same intrinsic population are difficult. The total sample of objects cannot be wholly homogeneous, and the objects must have a certain dispersion in physical properties such as opening angle; in addition, various insidious selection effects from the beamed properties of the objects are likely to bias samples chosen to measure isotropic properties.

Recent successes at resolving quasars at $z > 1$ have prompted us to undertake a project to image a complete sample of $\sim 15$ quasars at $z \sim 1$ in order to address the issues of the relationship between radio galaxies and quasars and possibly, of the alignment effect in high redshift radio sources. We seek to minimize the bias in our
samples by selecting on radio-lobe properties alone; unaddressed biases may still exist in this sample, as discussed by Urry & Padovani (1995). We have taken deep WFPC2 imaging of a small but complete subset of these quasars and the matched complete sample of radio galaxies in hopes that the higher resolution of HST will enable us to make our comparison of radio galaxy and quasar host properties less hindered by systematic effects than previous ground-based studies. We present here the results of the WFPC2 and groundbased imaging of the HST subsample and then the results of the groundbased imaging survey of the larger sample of quasars.
Chapter 2

Sample Selection

The revised 3C (3CR; Bennett 1962, Laing 1978) catalog has long provided the only large sample of radio sources selected at low frequency for which both optical identifications and redshifts are now essentially complete. For this reason, we have concentrated on 3CR objects to form our samples. We have defined a sample of 3CR quasars chosen to match the 3CR galaxy sample of Rigler et al. (1992) as closely as possible in extended radio properties and in redshift range. We therefore included all 3CR quasars in the range $0.8 < z < 1.25$ whose steep-spectrum flux is above the survey limit of $9 \text{ Jy at 178 Mhz}$. We define as "steep-spectrum" objects with spectral indices $\alpha$ (computed from 6 cm to 11 cm) $> 0.5$, where $f_\nu \sim \nu^{-\alpha}$. We limit the sample to the steep-spectrum quasars whose total flux is not brought above the survey limit by a flat spectrum compact core, in order to guarantee that we are selecting on an isotropic property. We also include a quasar, 3C 94, from the original 3C catalog of Edge et al. (1957), which is excluded from the 3CR catalog solely because its declination ($-7^\circ$) falls below the southern limit ($-5^\circ$) of the revised 3C survey. The resulting sample consists of ten quasars with extended double-lobed radio structure, and six quasars with compact radio sources (angular diameter $\lesssim 1^\circ$). These steep-spectrum compact sources are expected to be isotropically emitting (Fanti et al. 1990), and it is therefore reasonable to include them in a test of the unification hypothesis. The radio-power—redshift diagram for this sample of $z \sim 1$ 3C quasars, and for the matching galaxies, is shown in Figure 1; also shown is a representative sample of moderate radio luminosity quasars that we have observed and will discuss in a forthcoming paper. We have obtained WFPC2 imaging of a subsample of the 3C $z \sim 1$ quasars and radio galaxies; these objects are represented by filled symbols in the figure. Inspection of the diagram shows that the $z \sim 1$ epoch
is the only region in the 3C luminosity/epoch plane that provides matched samples of reasonable size (~15–20 each of radio galaxies and quasars) at an epoch (or radio luminosity) at which the radio galaxies begin to exhibit their unusual morphologies. To create a complete sample with reasonable numbers of objects at higher redshifts, a much broader redshift range (and corresponding radio luminosity region) must be included. It is for this reason that completion of redshift and optical identification of lower radio luminosity samples such as the 6C are important (Hales et al. 1993 and references therein).

For our HST observations, we have defined a complete subset of the above $z \sim 1$ 3C sample. We include all 3CR objects which fulfill the radio flux, morphology and spectral index constraints of the quasar sample, as well as having a redshift within the range $0.8 < z < 1.05$ and a $\delta < 60^\circ$; in this range the WFPC2 filters F622W and F675W can give passbands centered at restframe $\sim 3300$ Å with little or no contamination from emission lines. After deleting 3C 22 because of high extinction ($A_B = 1.09$) along the line of sight, we are left with a sample of 5 radio galaxies and 5 quasars; these are listed in Table 1 along with some information about their optical and radio properties. The 10 sources all have double-lobed radio structure; eight have largest angular sizes (LAS) (from lobe hotspot to hotspot) $\geq 7''$; 3C2 has LAS $\sim 5''$ and has sometimes been termed a “compact steep spectrum” source (Saikia et al. 1987). 3C 237, with a LAS of $\sim 1''3$, is included in most samples of compact steep spectrum objects (e.g. Fanti et al. 1990).
Fig. 1.— Redshift vs. radio luminosity at 178 MHz for the 3C sample. The triangles are the quasars, the circles are the galaxies, and the squares are a representative sample of moderate radio power quasars. Filled symbols correspond to members of our HST sample.
## TABLE 1

### PROPERTIES OF SAMPLE

<table>
<thead>
<tr>
<th>Source</th>
<th>Type</th>
<th>RA (J2000)</th>
<th>DEC (J2000)</th>
<th>Redshift</th>
<th>E(B-V)*</th>
<th>S178</th>
<th>α</th>
<th>LAS</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C 2</td>
<td>Q</td>
<td>00 06 22.59</td>
<td>−00 04 24.69</td>
<td>1.037</td>
<td>0.013</td>
<td>14.9</td>
<td>0.71</td>
<td>5″</td>
<td>(9)</td>
</tr>
<tr>
<td>3C 175.1</td>
<td>G</td>
<td>07 14 04.62</td>
<td>14 36 20.55</td>
<td>0.920</td>
<td>0.128</td>
<td>11.4</td>
<td>0.91</td>
<td>7″</td>
<td>(6)</td>
</tr>
<tr>
<td>3C 196</td>
<td>Q</td>
<td>08 13 36.03</td>
<td>48 13 02.58</td>
<td>0.871</td>
<td>0.040</td>
<td>68.2</td>
<td>0.91</td>
<td>6″</td>
<td>(8)</td>
</tr>
<tr>
<td>3C 212</td>
<td>Q</td>
<td>08 58 41.43</td>
<td>14 09 43.97</td>
<td>1.049</td>
<td>0.020</td>
<td>15.1</td>
<td>0.75</td>
<td>10″</td>
<td>(1)</td>
</tr>
<tr>
<td>3C 217</td>
<td>G</td>
<td>09 08 50.03</td>
<td>37 48 18.19</td>
<td>0.898</td>
<td>0.005</td>
<td>11.3</td>
<td>0.77</td>
<td>12″</td>
<td>(7)</td>
</tr>
<tr>
<td>3C 237</td>
<td>G</td>
<td>10 08 00.01</td>
<td>07 30 16.38</td>
<td>0.877</td>
<td>0.000</td>
<td>20.9</td>
<td>0.53</td>
<td>1 1/3</td>
<td>(10)</td>
</tr>
<tr>
<td>3C 245</td>
<td>Q</td>
<td>10 42 44.58</td>
<td>12 03 31.18</td>
<td>1.029</td>
<td>0.005</td>
<td>14.4</td>
<td>0.66</td>
<td>8″</td>
<td>(3)</td>
</tr>
<tr>
<td>3C 280</td>
<td>G</td>
<td>12 56 57.06</td>
<td>47 20 19.32</td>
<td>0.995</td>
<td>0.000</td>
<td>23.7</td>
<td>0.81</td>
<td>13″</td>
<td>(4)</td>
</tr>
<tr>
<td>3C 289</td>
<td>G</td>
<td>13 45 26.21</td>
<td>49 46 32.13</td>
<td>0.967</td>
<td>0.000</td>
<td>12.6</td>
<td>0.81</td>
<td>10″</td>
<td>(5)</td>
</tr>
<tr>
<td>3C 336</td>
<td>Q</td>
<td>16 24 39.02</td>
<td>23 45 12.72</td>
<td>0.927</td>
<td>0.035</td>
<td>11.5</td>
<td>1.05</td>
<td>28″</td>
<td>(2)</td>
</tr>
</tbody>
</table>

*E(B-V) values are derived from Burstein & Heiles (1984); errors in these values are 0.015.

Chapter 3
Observations and Reduction

3.1. HST WFPC2 Imaging

Table 2 gives the log of HST observations. Total exposure times for each object in our sample were calculated to give roughly the same signal-to-noise level to a given proper surface brightness limit; actual total integration for our WFPC2 observations are given in Table 2. Our general technique was to take two, three or four separate exposures of 900 – 1100 seconds at the same pointing to aid in removal of cosmic rays, but to dither the telescope by 10.5 pixels between subsequent sets of exposures to aid in removal of hot pixels and to increase resolution. HST points accurately to \( \sim 3 \text{ mas} \) (0.03 pixel), and we found that using the intended pointings to shift and combine the dithered images gave better final image quality than re-assessing the offsets by centering on the undersampled stars.

We tried recalibrating the raw data with several different types of STScI-provided bias-dark combinations, and found the best standard deviation in final combined frames from using using the pipeline-supplied biases (averaged from 40 individual bias frames close in time to the observations) and a super-dark (an average of 100 darks). The recalibration routine generates bias-subtracted, dark-subtracted, and flattened files, as well as associated bad pixel mask ("DQF") files. We resampled the images by a factor of two to a size of 1600 by 1600 using the IRAF blkrep task, then aligned by shifting in integer (resampled) pixels. For combination and cosmic ray removal, we used primarily the STSDAS gcombine routine. We first rejected all pixels marked as bad or saturated in the data quality files (DQF) generated by the recalibration routine. We then rejected pixels that were more than \( 3\sigma \) from the median, using the rejection algorithm "rsigclip" to compute a median and sigma
that are robust against unidentified outliers. We then compute each output pixel value from the average of the remaining unrejected pixels. We centered the object on WFC3 for these observations, which has a plate scale of 0'1 pixel\(^{-1}\) (undersampling the point-spread function). From all summed frames in which we had unsaturated stars, we measured an average stellar FWHM of 0'14 with a 1\(\sigma\) variation of 0'02.

We have derived the flux density in our images from the calibration information provided by ST, \textit{i.e.}, from the PHOTLAM calibration keyword generated by SYNPHOT in the pipeline calibration. These calibrations are determined from knowledge of the instrumental sensitivities and filter bandpasses and supplemented with WFPC2 imaging of known standards. We normally will give our photometric results in terms of flux densities for the optical images in this paper, since we use non-standard filters. We may also refer to AB and ST magnitudes, which provide a direct conversion from flux density to magnitudes. The AB magnitude is defined as 
\[ -2.5\log(f_\nu) - 48.59, \]
where \(f_\nu\) is measured in ergs s\(^{-1}\) cm\(^{-2}\) hz\(^{-1}\). The AB magnitude system is therefore defined to have a constant zero point for fluxes measured per frequency interval; the ST magnitude system is defined to have a constant zero point for fluxes measured per unit wavelength; \textit{ST MAG} = \( -2.5\log(f_\lambda) - 21.1 \). This system is distinct from the WFPC2 magnitude system, in which zeropoints are defined relative to \(\alpha\)-Lyrae in order to give magnitudes and colors for standard stars that are similar to ground-based Johnson magnitudes and colors. For the F675W filter, \( m_{ST} - m_{AB} = 0.44 \). For the F622W filter, \( m - m_{AB} = 0.16 \).

We have ground-based images of all of the quasars taken in very similar filters, and we used these to make consistency checks on the validity of the HST calibrations.
3.2. Ground-based Optical Imaging

The ground-based optical continuum images were taken at the University of Hawaii 2.2-m telescope with an anti-reflection-coated, thinned Tektronix 2048x2048 CCD. We observed each quasar in an interference filter chosen to sample a line-free continuum region of the quasar spectral energy distribution, at $\sim 0.33 \mu m$ in the rest frame. The filters we used have approximately square profiles with peak transmissions around 90%; we label them with their approximate central wavelengths in Angstroms followed by their width: 6120/960, 6475/900, 7000/900. For 3C2 we also obtained an image in a redder passband near Mould $I$: 8964/1063. We observed each object for about 1.5 hours total integration time, shifting the telescope between $\sim$10 minute integrations to enable creation of sky flats. We kept exposure times short enough that neither the quasar nor at least one star of comparable brightness would saturate; the stars were used for determination of the point spread function. We also obtained dome flats for each filter. Seeing and photometric conditions varied. In Table 3 we present a summary of all ground-based observations. We will not display all of this data; in fact, we do not show any of the ground-based quasar continuum images in the passband that matches the WFPC2 data. These were used primarily as a consistency check both on structure seen in the WFPC2 images and on the absolute calibration provided by ST. The high resolution of the WFPC2 images makes them far superior to the ground-based in resolving extensions to the quasar, although in some cases our ground-based images go slightly deeper on the sky.

We also observed 4 quasars and 2 of the radio galaxies in narrow-band [OII] interference filters. These filters are high-transmission ($\sim 90\%$), square filters with widths $\sim 30\AA$, centered at redshifted $\lambda 3727\AA$ for each of the objects. The narrow-band images were taken at UH 2.2m with the Tektronix 2048x2048 CCD, and at the
CFHT with SIS fast guiding and the Orbit1 CCD; specifics of the seeing conditions (FWHM) and filter positions can be found in Table 3.

We followed standard CCD data reduction procedures, with a few adjustments for some of the peculiarities of the detectors. The Tek2048 has a very variable and structured bias, so we model and subtract a bias frame created from the average of biasses taken in the same half of the night. After subtracting the modelled bias frame, subtracting a constant dark value (very small), interpolating over bad columns, and scaling the images to the same median sky value, we median averaged the raw images (while masking objects out of the median), in order to create a sky flat-field. We compared the results of using sky flats versus dome flats for flattening the raw frames; in general, the sky flats worked better. In a few cases, bright stars left residuals that we could not successfully mask out, and in this situation we adopted the dome flats. For many of the Tek2048 frames, saturation streaks along rows associated with bright stars were created by the CCD readout. A similar problem occurs in data taken prior to 1993; shifts in bias during the CCD readout could cause broad stripes across the frame. Both of these problems were removed by running the IRAF task background to subtract the median value of each row. This process in some cases left negative residuals near bright stars. Each frame was corrected for atmospheric extinction using mean extinction coefficients. The narrow-band images were treated similarly, except that, because we needed long exposures to approach sky-noise-limited statistics in the background, we normally obtained only 3 dithered frames and could not construct good sky flats. We therefore used dome flats to flatten the images.

To produce our final CCD images, we median-averaged the separate frames after aligning each to an accuracy of ~0.1 pixel (0’02), using the brightest unsaturated stars in each field. We then flux-calibrated using Kitt Peak spectrophotometric standard stars with data to 1µm (Massey et al. 1988, Massey & Gronwall 1990). To determine
the standard star flux in our non-standard continuum and narrowband filters, we approximated our filters as square with width equal to the full-width-half-maximum of the filter profile, and integrated the stellar spectral flux within this region.

3.3. Infrared Imaging

The near-infrared images were taken at the UH 2.2 m, CFH, IRTF, and Keck telescopes. All objects were observed at Mauna Kea $K'$ (Wainscoat & Cowie 1992). This filter is centered at 2.1 μm (shorter than standard $K$) in order to reduce thermal background. A few objects were observed at standard $H$ as well, which is centered at 1.65 μm. At the UH 2.2 m, we used the Nicmos3 256x256 infrared array at f/10, with a pixel scale of 0.37 pixel$^{-1}$, and at f/31, with 0.12 pixel$^{-1}$. We also used the 1024 × 1024 QUIRC chip, with a scale of 0.18 pixel$^{-1}$ at f/10. At the CFHT, we used the UH Nicmos camera in March 1992, with a scale of 0.3 pixel$^{-1}$ and the CFHT Redeye Camera, (also a 256×256 Nicmos device), in November 1993 with a scale of 0.2 pixel$^{-1}$. The IRTF observations were made with NSFCam, a 256×256 InSb array. NSFCam has an adjustable plate scale; we chose to use 0.15 pixel$^{-1}$ and 0.3 pixel$^{-1}$ on separate occasions. Seeing and photometric conditions were variable; best seeing was 0.5 FWHM and worst ∼1.3. We give the specifics of each observation in Table 3. We offset the telescope slightly between each exposure on a field to facilitate creation of sky flats and removal of bad pixels. Dome flats were created by subtracting observations of the incandescent-illuminated dome minus observations of the dome with the lights off. Except at Keck, the standard readout procedure for these devices leaves little or no bias. Our integrations were sky-limited; the worst case is data from two nights at the UH 2.2m with f/31, in which sky-variation limitations on the length of the exposure time meant that the sky flux in each frame was a only a factor of ∼6
over the read-noise squared. These images were of insufficient depth to be useful in this analysis.

We outline our reduction procedure for the UH 2.2m Nicmos3 observations, and afterwards indicate variations made for other devices. We used an iterative process to flatten the data and replace the bad pixels. First a bad pixel mask was created from the dark frames and dome flat field frames. The raw object frames were then normalized by their median sky value and combined to create a sky frame. (Every calculation of a median sky value excluded the masked-off regions associated with that frame). This sky frame was then scaled to each raw frame and subtracted. The subtracted frames were flattened with the dome flats. These rough flattened images were aligned to the nearest pixel using stars or the quasar itself and median-averaged to create a rough combined image. A mask was made from this combined frame of the positions and extents of the objects. The portion of this overall mask that was associated with each individual frame was added to the bad pixel mask to create an object mask for that frame. The process was then repeated; using the object mask to mask objects out of the sky frame, we created superior flattened frames, recalculated the centering and alignments, and created a better combined image. This combined image was then used to replace the bad pixels in each flattened frame with the median of good pixels from the rest of the frames. We then interpolated and resampled the bad-pixel-corrected flattened frames; since most of our infrared data are under-sampled, the magnification factor was generally in the range 4–8. We recalculated the centering (bad pixels may skew centering significantly), and for each frame calculated the fluxes of a number of photometric objects we had previously specified. Using these photometric fluxes to scale each frame to the median flux value, we made a final combined frame, using sub-pixel alignment with an accuracy of \(~0.2\) pixel \((\sim0'.07)\). In cases where we had variable extinction from clouds, we scaled the
individual frames to the maximum flux recorded. This process treats incorrectly any
correction from the dark current, which was scaled along with the sky, but the
effect should be negligible as long as the dark contribution is a small percentage of
the total background. For the NICMOS chip, the uncertainty in the level of dark to
subtract is greater than any resulting uncertainty this process may add.

The 1024×1024 QUIRC chip (at the UH 2.2m) has a much stabler dark pattern,
and we generally subtracted a dark frame from the object exposures prior to creation
of the sky flat. With NIRC at Keck, twilight sky flats were used instead of dome flats.
A bias must be subtracted, which we obtained from dark frames at the beginning and
end of each night. The plate scale is 0.15 pix−1, resulting in a field of view of 38″.
This meant that we were not able to have a star on the frame in all cases. Otherwise
reduction procedures followed were similar to that for the Nicmos at the UH 2.2m.

We calibrated our near-infrared data with standards from the UKIRT faint
standard list (Casali & Hawarden 1992) and from the Elias et al. (1982) list of
moderately bright standards. We used α-Lyrae as our magnitude zero point for H
and K; we used the fluxes for α-Lyrae from the IRTF photometry manual (Tokunaga
1988). These values are 4.07 × 10−10 W m² s⁻¹ μm⁻¹ and 1.12 × 10⁻⁹ W m² s⁻¹
μm⁻¹, for K and H respectively. We corrected for the color difference between K
and K' as described in Wainscoat & Cowie (1992); the resulting flux difference was
~ 2–3%; this is generally less than the error in our absolute calibration. We made
a secondary check on our absolute calibrations by comparing fluxes of stars between
separate observations of the same field. Since we have Keck observations for all objects
except for 3C2, we compare any other observation to our Keck data. We find that the
average percentage difference in absolute calibration is 0.4% with standard deviation
5.1% and a maximum mismatch of 12% (from 3C 237, 3C 212, 3C 245, 3C 336, and
3C 175.1 duplicate observations); this standard deviation flux difference corresponds
to a magnitude difference of 0.05. This will generally be less than other magnitude errors, but we will add this systematic error to our photometric error estimates for the objects in which the absolute calibration is less secure. In 3C2, we have two $H$ band images as well; the absolute calibrations in these frames differ by only 2% as measured by an ensemble of objects shared in both images.
<table>
<thead>
<tr>
<th>Source</th>
<th>Filter</th>
<th>Mean $\lambda_0$(Å)</th>
<th>$\Delta \lambda_0$(Å)</th>
<th>Exposure</th>
<th>Normalized 1σ Detection Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C 2</td>
<td>F675W</td>
<td>3298.6</td>
<td>181.9</td>
<td>16 x 1100 s</td>
<td>1.53</td>
</tr>
<tr>
<td>3C 175.1</td>
<td>F622W</td>
<td>3221.4</td>
<td>201.7</td>
<td>16 x 1000 s</td>
<td>1.87</td>
</tr>
<tr>
<td>3C 196</td>
<td>F622W</td>
<td>3305.8</td>
<td>207.0</td>
<td>8 x 900 s</td>
<td>1.83</td>
</tr>
<tr>
<td>3C 212</td>
<td>F675W</td>
<td>3279.2</td>
<td>180.9</td>
<td>16 x 1100 s</td>
<td>1.75</td>
</tr>
<tr>
<td>3C 217</td>
<td>F622W</td>
<td>3258.8</td>
<td>204.1</td>
<td>8 x 900 s</td>
<td>1.31</td>
</tr>
<tr>
<td>3C 237</td>
<td>F622W</td>
<td>3265.2</td>
<td>208.3</td>
<td>16 x 1100 s</td>
<td>2.18</td>
</tr>
<tr>
<td>3C 245</td>
<td>F675W</td>
<td>3311.6</td>
<td>182.6</td>
<td>16 x 1100 s</td>
<td>1.83</td>
</tr>
<tr>
<td>3C 280</td>
<td>F622W</td>
<td>3098.8</td>
<td>194.0</td>
<td>8 x 1100 s</td>
<td>1.78</td>
</tr>
<tr>
<td>3C 289</td>
<td>F622W</td>
<td>3144.5</td>
<td>196.9</td>
<td>8 x 1000 s</td>
<td>1.66</td>
</tr>
<tr>
<td>3C 336</td>
<td>F622W</td>
<td>3209.7</td>
<td>201.0</td>
<td>8 x 900 s</td>
<td>1.97</td>
</tr>
</tbody>
</table>

*The 1σ detection limit in our images, normalized to $z = 1$ and $E(B - V) = 0$, measured in $10^{-19}$ ergs cm$^{-2}$s$^{-1}$Å$^{-1}$ arcsec$^{-2}$.
TABLE 3
LOG OF GROUND-BASED IMAGING OBSERVATIONS

<table>
<thead>
<tr>
<th>Source</th>
<th>Date</th>
<th>Telescope</th>
<th>Detector</th>
<th>Plate scale (per pixel)</th>
<th>Filter</th>
<th>Exposure</th>
<th>Data Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C 2</td>
<td>1992 Nov 26</td>
<td>UH88</td>
<td>Tek2048</td>
<td>0'22</td>
<td>7000/900</td>
<td>10 x 600 s</td>
<td>O'86</td>
</tr>
<tr>
<td></td>
<td>1993 Sep 21</td>
<td>UH88</td>
<td>Tek2048</td>
<td>0'22</td>
<td>8964/1063</td>
<td>21 x 300 s</td>
<td>O'76</td>
</tr>
<tr>
<td></td>
<td>1993 Nov 27</td>
<td>CFHT</td>
<td>Nic256</td>
<td>0'3</td>
<td>K'</td>
<td>27 x 180 s</td>
<td>O'70</td>
</tr>
<tr>
<td></td>
<td>1993 Nov 28</td>
<td>CFHT</td>
<td>Nic256</td>
<td>0'2</td>
<td>K'</td>
<td>38 x 150 s</td>
<td>O'63</td>
</tr>
<tr>
<td></td>
<td>1993 Dec 23</td>
<td>IRTF</td>
<td>InSh256</td>
<td>0'153</td>
<td>K'</td>
<td>53 x 50 s</td>
<td>O'67</td>
</tr>
<tr>
<td></td>
<td>1994 Aug 10</td>
<td>IRTF</td>
<td>InSh256</td>
<td>0'15</td>
<td>H</td>
<td>44 x 90 s</td>
<td>O'78</td>
</tr>
<tr>
<td></td>
<td>1994 Nov 21</td>
<td>UH88</td>
<td>Nic1024</td>
<td>0'18</td>
<td>H</td>
<td>23 x 180 s</td>
<td>O'64</td>
</tr>
<tr>
<td>3C 175.1</td>
<td>1993 Nov 28</td>
<td>CFHT</td>
<td>Nic256</td>
<td>0'2</td>
<td>K'</td>
<td>36 x 180 s</td>
<td>O'63</td>
</tr>
<tr>
<td></td>
<td>1994 Nov 19</td>
<td>UH88</td>
<td>Nic1024</td>
<td>0'18</td>
<td>K'</td>
<td>13 x 150 s</td>
<td>O'70</td>
</tr>
<tr>
<td></td>
<td>1995 Mar 20</td>
<td>Keck</td>
<td>InSh256</td>
<td>0'15</td>
<td>K'</td>
<td>23 x 120 s</td>
<td>O'63</td>
</tr>
<tr>
<td>3C 196</td>
<td>1992 Apr 14</td>
<td>UH88</td>
<td>Nic256</td>
<td>0'37</td>
<td>K'</td>
<td>29 x 90 s</td>
<td>O'68</td>
</tr>
<tr>
<td></td>
<td>1992 May 07</td>
<td>UH88</td>
<td>Tek2048</td>
<td>0'22</td>
<td>7000/900</td>
<td>2 x 2400 s</td>
<td>O'78</td>
</tr>
<tr>
<td></td>
<td>1993 Dec 23</td>
<td>CFHT</td>
<td>Nic256</td>
<td>0'2</td>
<td>K'</td>
<td>53 x 50 s</td>
<td>O'67</td>
</tr>
<tr>
<td></td>
<td>1994 Nov 21</td>
<td>UH88</td>
<td>Nic1024</td>
<td>0'18</td>
<td>K'</td>
<td>23 x 180 s</td>
<td>O'64</td>
</tr>
<tr>
<td></td>
<td>1995 Mar 20</td>
<td>Keck</td>
<td>InSh256</td>
<td>0'15</td>
<td>K'</td>
<td>27 x 96 s</td>
<td>O'65</td>
</tr>
<tr>
<td>3C 212</td>
<td>1992 May 11</td>
<td>CFHT</td>
<td>Nic256</td>
<td>0'3</td>
<td>K'</td>
<td>37 x 90 s</td>
<td>O'69</td>
</tr>
<tr>
<td></td>
<td>1993 Apr 17</td>
<td>UH88</td>
<td>Tek2048</td>
<td>0'22</td>
<td>7000/900</td>
<td>7 x 900 s</td>
<td>O'83</td>
</tr>
<tr>
<td></td>
<td>1993 Dec 23</td>
<td>IRTF</td>
<td>InSh256</td>
<td>0'15</td>
<td>K'</td>
<td>126 x 50 s</td>
<td>O'83</td>
</tr>
<tr>
<td></td>
<td>1994 May 04</td>
<td>UH88</td>
<td>Nic256</td>
<td>0'12</td>
<td>K'</td>
<td>10 x 360 s</td>
<td>O'84</td>
</tr>
<tr>
<td></td>
<td>1995 Jan 17</td>
<td>UH88</td>
<td>Nic1024</td>
<td>0'06</td>
<td>K'</td>
<td>25 x 300 s</td>
<td>O'53</td>
</tr>
<tr>
<td></td>
<td>1994 Apr 05</td>
<td>UH88</td>
<td>Tek2048</td>
<td>0'22</td>
<td>8964/1063</td>
<td>21 x 300 s</td>
<td>O'76</td>
</tr>
<tr>
<td></td>
<td>1995 May 19</td>
<td>Keck</td>
<td>InSh256</td>
<td>0'15</td>
<td>K'</td>
<td>27 x 120 s</td>
<td>O'67</td>
</tr>
<tr>
<td>3C 217</td>
<td>1994 Mar 19</td>
<td>Keck</td>
<td>InSh256</td>
<td>0'15</td>
<td>K'</td>
<td>18 x 120 s</td>
<td>O'83</td>
</tr>
<tr>
<td>3C 237</td>
<td>1994 Nov 22</td>
<td>UH88</td>
<td>Nic1024</td>
<td>0'18</td>
<td>K'</td>
<td>14 x 120 s</td>
<td>O'74</td>
</tr>
<tr>
<td></td>
<td>1995 May 19</td>
<td>Keck</td>
<td>InSh256</td>
<td>0'15</td>
<td>K'</td>
<td>15 x 120 s</td>
<td>O'65</td>
</tr>
<tr>
<td></td>
<td>1995 Mar 20</td>
<td>Keck</td>
<td>InSh256</td>
<td>0'15</td>
<td>K'</td>
<td>15 x 120 s</td>
<td>O'66</td>
</tr>
<tr>
<td>3C 245</td>
<td>1992 May 11</td>
<td>CFHT</td>
<td>Nic256</td>
<td>0'3</td>
<td>K'</td>
<td>18 x 90 s</td>
<td>O'74</td>
</tr>
<tr>
<td></td>
<td>1993 Apr 12</td>
<td>UH88</td>
<td>Nic256</td>
<td>0'37</td>
<td>K'</td>
<td>50 x 90 s</td>
<td>O'11</td>
</tr>
<tr>
<td></td>
<td>1993 Apr 16</td>
<td>UH88</td>
<td>Tek2048</td>
<td>0'22</td>
<td>6475/900</td>
<td>10 x 600 s</td>
<td>O'80</td>
</tr>
<tr>
<td></td>
<td>1994 Apr 06</td>
<td>UH88</td>
<td>Tek2048</td>
<td>0'22</td>
<td>7571/31</td>
<td>3 x 1800 s</td>
<td>O'78</td>
</tr>
<tr>
<td></td>
<td>1995 May 19</td>
<td>Keck</td>
<td>InSh256</td>
<td>0'15</td>
<td>K'</td>
<td>18 x 120 s</td>
<td>O'65</td>
</tr>
<tr>
<td>3C 280</td>
<td>1994 Apr 06</td>
<td>UH88</td>
<td>Tek2048</td>
<td>0'22</td>
<td>7449/31</td>
<td>3 x 1800 s</td>
<td>O'73</td>
</tr>
<tr>
<td></td>
<td>1995 Feb 23</td>
<td>CFHT</td>
<td>Orb2048</td>
<td>0'12</td>
<td>K'</td>
<td>23 x 360 s</td>
<td>O'79</td>
</tr>
<tr>
<td></td>
<td>1995 Mar 19</td>
<td>Keck</td>
<td>InSh256</td>
<td>0'15</td>
<td>K'</td>
<td>27 x 96 s</td>
<td>O'68</td>
</tr>
<tr>
<td></td>
<td>1995 May 19</td>
<td>Keck</td>
<td>InSh256</td>
<td>0'15</td>
<td>K'</td>
<td>24 x 120 s</td>
<td>O'64</td>
</tr>
<tr>
<td></td>
<td>1995 Mar 20</td>
<td>Keck</td>
<td>InSh256</td>
<td>0'15</td>
<td>K'</td>
<td>24 x 120 s</td>
<td>O'63</td>
</tr>
<tr>
<td>3C 336</td>
<td>1992 Apr 13</td>
<td>UH88</td>
<td>Nic256</td>
<td>0'37</td>
<td>K'</td>
<td>12 x 90 s</td>
<td>O'70</td>
</tr>
<tr>
<td></td>
<td>1992 Apr 14</td>
<td>UH88</td>
<td>Nic256</td>
<td>0'37</td>
<td>K'</td>
<td>30 x 90 s</td>
<td>O'75</td>
</tr>
<tr>
<td></td>
<td>1992 May 07</td>
<td>UH88</td>
<td>Tek2048</td>
<td>0'22</td>
<td>6475/900</td>
<td>8 x 600 s</td>
<td>O'80</td>
</tr>
<tr>
<td></td>
<td>1992 May 10</td>
<td>CFHT</td>
<td>Nic256</td>
<td>0'2</td>
<td>7571/31</td>
<td>3 x 1800 s</td>
<td>O'84</td>
</tr>
<tr>
<td></td>
<td>1993 Apr 17</td>
<td>UH88</td>
<td>Tek2048</td>
<td>0'22</td>
<td>6475/900</td>
<td>8 x 600 s</td>
<td>O'80</td>
</tr>
<tr>
<td></td>
<td>1994 Apr 05</td>
<td>UH88</td>
<td>Tek2048</td>
<td>0'22</td>
<td>7192/28</td>
<td>2 x 2100 s</td>
<td>O'74</td>
</tr>
<tr>
<td></td>
<td>1994 May 02</td>
<td>IRTF</td>
<td>InSh256</td>
<td>0'15</td>
<td>K'</td>
<td>144 x 36 s</td>
<td>O'74</td>
</tr>
<tr>
<td></td>
<td>1994 May 03</td>
<td>UH88</td>
<td>Nic256</td>
<td>0'12</td>
<td>K'</td>
<td>9 x 360 s</td>
<td>O'72</td>
</tr>
<tr>
<td></td>
<td>1995 Feb 24</td>
<td>CFHT</td>
<td>Orb2048</td>
<td>0'12</td>
<td>7192/28</td>
<td>3 x 2100 s</td>
<td>O'64</td>
</tr>
<tr>
<td></td>
<td>1995 Mar 19</td>
<td>Keck</td>
<td>InSh256</td>
<td>0'15</td>
<td>K'</td>
<td>27 x 96 s</td>
<td>O'49</td>
</tr>
</tbody>
</table>
Chapter 4

Analysis

4.1. Point Spread Function Determination

To determine the morphologies and magnitudes of the extended material underlying the quasar nuclei, we must remove the contribution of the nuclear component. We describe here some of the details of how we determine the point spread function (PSF) that we use to subtract off this nucleus.

4.1.1. The HST Point Spread Function

For the HST data, we observed a PSF star in association with each of the quasar observations. We planned the exposures to try to match as closely as possible the observational procedure for the quasars themselves; to this end, we followed the same dithering procedure we discuss in Section 3.1, and calculated the PSF exposures times in order to saturate the PSF to the same extent that we saturated on the quasars themselves. In Table 4, we give the PSF star we observed in conjunction with each quasar, the filter in which each was taken, the integration times, and the greatest extent of saturation in any dimension for both the QSO and PSF. As can be seen, our predictions of QSO and PSF magnitudes weren’t quite perfect, and the saturation diameters range from 0 to 0'25. We note here that these saturation regions are the intersection of whatever pixels were marked as A-to-D-converter-saturated by the DQF files; we mask out entirely these saturated pixels and replace those data with other data values from the stack of images if other pixels are not saturated. Therefore, because we dithered our exposures by half-pixel steps, and saturation may vary slightly from exposure to exposure, we may end up with a saturated diameter
of 1 resampled pixel (0'05), which is equivalent to half an original resolution element of the WFC. We will discuss in Section 4.2 the possibility that there may be some non-linearity of data values beyond this "officially" saturated region.

The PSF varies across the field, so we checked the observed QSO and PSF positions on the chip. This positioning was very stable: the variation in the distance from the mean column position for all PSFs and QSOs was $\sigma_{\text{column}} = 0'35$, and the maximum deviation was 0'7, for the 3C245 PSF. The row positioning varied a little more ($\sigma_{\text{row}} = 0'6$), but the maximum deviation from the mean position was 1'2 for the PSF star of 3C336. As we have more than one measurement of the PSF in each filter, and our mean positions on the frame do not vary much, we can now consider averaging the PSFs in each filter to increase our signal-to-noise. In order to assess how much the PSFs differ from each other, we determined their relative centers and scalings in annuli outside of their respective saturated regions and subtracted them. (We use the same centering and subtraction techniques that we used for subtracting the PSFs from the quasars, though these cases are of course not complicated by the existence of extensions. We discuss these techniques in the next section). The PSFs in the same filter subtract well from each other with few systematic residuals. The inner 0'35-0'45 radius is very noisy, and we find in the subsequent quasar minus PSF subtractions that we are unable to recover much information from this region, even when not saturated. We note that the diffraction spikes (especially in the region close to the center of the PSF) may leave some residuals. We show some examples of these PSF-minus-PSF subtractions in Figure 3. We then average the 2 F622W PSFs, associated with quasars 3C196 and 3C336, and the 3 F675W PSFs, associated with quasars 3C 2, 3C212, 3C245, using the normalizations and centers determined from the subtraction technique. We mask out the saturated regions in making the
combined PSFs, and replace saturated values with values from unsaturated stars in the average if available.

We display in Figure 3D the combined PSF for the F622W filter (the average of the 3C196 and 3C336 PSF stars). We have also checked the residual of the difference between the two average PSFs, and we find that there are significant differences between the two filters; we did not, therefore, average all of the PSFs together.

4.1.2. The Infrared Point Spread Function

The ground-based PSFs are, of course, very dependent on the details of the atmospheric conditions throughout the observations, and must be determined from stars taken as simultaneously as possible. For both the Keck and CFHT images that we present here, the observational field is small enough that we must usually take exposures of a star (of comparable brightness to the quasar) interleaved with the object observations in order to determine the PSF. The one exception in the quasar sample is 3C 212, which has a star of sufficient brightness within the NIRC field. We also obtained PSF stars for the Keck observations of the radio galaxies. (For the radio galaxies, the star need not be so bright; there were therefore unsaturated stars of sufficient brightness on each radio galaxy field except for 3C 280 and 3C 217).

When we must interleave observations of a PSF star with the actual object integrations, we want to sample as well as possible the seeing conditions and any PSF field variations. We therefore bracketed the object observations with observations of the PSF, and alternated between the PSF star and object as often as efficiency considerations allowed (generally within 15 minutes). We used the same dithering pattern in the two sets of integrations to make sure that any PSF variations in the field or caused by our dithering and centering technique is similar in the two cases;
we also used the same effective individual integration times where possible. Despite these precautions, natural variations in the ground-based seeing conditions result in some systematic PSF residuals; these are generally confined to the inner region of the PSF seeing disk.

4.2. Point Spread Function Subtraction

To determine the morphologies and magnitudes of the extended material underlying the quasar nuclei, we must remove the contribution of the nuclear component. We will discuss some of the uncertainties in this process, and some differences between the ground-based and HST data. (All of the PSF subtraction was done in the original combined images, before subsequent rotations and transformations which would smooth the images and affect their pixel-to-pixel noise characteristics).

Some information is not recoverable from the PSF subtraction process; for example, a compact peaked host galaxy might be indistinguishable from extra flux in the PSF and would be subtracted. We can make, however, reasonable assumptions about the probable behavior of the host galaxy and use these to estimate the total magnitude of the nebulosity. The simplest technique is to fit the PSF to the quasar nuclear component in a specified inner region \( \text{(i.e., to center, then subtract the quasar flux in this region to zero)} \).

Subtraction to zero should give a lower limit to the magnitude of the extended material if any exists, but will oversubtract if there is any extended flux in the inner region. Some simulations of ground-based observations of low-redshift quasars, where the host galaxies were assumed to be normal spirals and ellipticals, found that subtraction to zero affected derived magnitudes by \( \sim 0.2 \text{ mag} \) (Smith et al. 1986,
Abraham et al. 1992). A more realistic criterion would be to require that the host galaxy increase monotonically or at least remain constant from the outer regions that are mostly unaffected by the PSF subtraction into the interior, hidden under the PSF. Even this monotonicity criterion will likely underestimate the total host galaxy flux, if the galaxy peaks at all in the center, as would a normal spiral or elliptical. We calculate two subtraction limits for our quasars, both a subtraction-to-zero lower limit, and a monotonic-across-inner-region best estimate. In those objects in which we find little or lumpy extended flux, these two cases end up essentially the same.

In the interests of objectivity, we have tried to automate the subtraction process, though visual inspection of the subtraction residuals remains a useful cross-check on the process. We have developed IRAF scripts that allow us to center and scale the PSF to the quasar, display the residuals in a defined annulus, and calculate the reduced $\chi^2$ of the PSF fit to the quasar. We first estimate the proper centering and scaling by calculating the fluxes and the $x$ and $y$ first moments of both the PSF and the quasar in an inner defined annulus, correcting for partial pixels. The annulus used is one of the most subjective parts of this process: it is chosen to exclude any saturated interior region, to be small enough to minimize the host galaxy contribution, yet large enough to provide decent statistics. For the HST data, the inner radius we use varies from $0''0-0''35$, and the outer from $0''2-0''45$. Our HST data are only minimally saturated (several pixels or $0''25$ at the most; see Table 4).

We then optimize the centering by calculating the $\chi^2$ values of the difference in the defined annulus over a grid of $x$ and $y$ shifts; we reject pixels from the $\chi^2$ sum that deviate by $3\sigma$ from the mean difference value to reduce the effect of intrinsic PSF/QSO shape differences. We fit a quadratic to each of the $\chi^2$ vs. $\delta x$, $\delta y$ plots, and take the minima as the optimum $\delta x$, $\delta y$. Though this procedure incorrectly treats the $\delta x$, $\delta y$ and the QSO: PSF scaling as independent, the centering does not
change significantly with any reasonable scaling. In addition, the centering is well-determined, while the scaling is a much more arbitrary and subjective quantity. When we center by hand, by inspecting the residuals, the best center is determined to about 0\'01, and matches the results of automatic centering to within this tolerance.

To obtain the best scaling, we use a minimization technique similar to that we use for the centering: we vary the scaling around the initial value, using the already determined best center, then fit a quadratic. In Fig. 2 we show the determination of the $\chi^2$ minimum scaling for the HST image of 3C 2. The minimum $\chi^2$ corresponds to the "best fit" between the QSO and the PSF two-dimensional distributions; as discussed above it is probably generally an oversubtraction of any extended flux, but provides a lower limit to the host galaxy flux. Further evidence of this is the fact that the minimum $\chi^2$ is usually reached at different scalings depending on what annulus is chosen; using annuli including data at a greater radial distance from the QSO center causes the QSO:PSF scaling ratio to increase, as may be expected if the QSO is contributing more extended material than the PSF star at these radii. In part, we have adopted this approach of estimating the $\chi^2$ minimum of the fit in order to provide a good comparison to the Bahcall et al. (1994,1995a,b,c) results, in which they minimize the $\chi^2$ of their fit with respect to 3 variables, the $x$ and $y$ shifts between the quasar and PSF, and the QSO:PSF scaling. Their subtractions correspond, therefore, to "subtraction-to-zero" lower limits; similar conservative limits are used by Heckman et al. (1992), and Lehnert et al. (1992) We also wish to automate an objective version of the "monotonicity" constraint; this is similar to that used in a variety of studies of low-z quasars, such as the HST study by Disney et al. (1995) and the groundbased studies such as that of McLeod & Rieke (1994a,b). To establish the monotonicity of the profile difference requires averaging the difference profile in annuli with some width; generally this will be equivalent to requiring our interior annulus to have a
mean value equal to the annulus immediate exterior to it. We therefore define an annulus exterior to our inner annulus, and record the mean and median of the values in both the inner and outer annuli (after 3σ rejection, to minimize the effects of PSF residuals in skewing the mean and median). Once again, this width of this annulus is subjective, and changes in it change the resulting scaling. We desire to sample as narrow a width as possible of the profile that will still give signal-to-noise adequate to prevent the scaling being dominated by statistical noise. These outer annuli had widths from 0\textquoteleft 1-0\textquoteleft 2 for the HST images. Any monotonicity constraint applied requires some such assumption; the wider the annular width used, the more host galaxy is subtracted. We check the average values in the profile difference in annular steps of this width for monotonic behavior, but it is the inner two areas that set the scaling. In Fig. 2 we show how we automate this constraint; we plot the decreasing average values in the two inner annuli and take as the scaling the point at which lines fit to these two basically linear functions intersect. This gives us a better estimate of the proper subtraction, and if there is no extension, the $\chi^2$ minimum scaling and the monotonic limit scaling are the same. In addition, much of the structure we see is lumpy and irregular, and when averaged radially, results in a mean value in the annulus that is much less than the intrinsic surface brightness of the clumps. We can then estimate the missing flux by extrapolating across the masked out central portion with a constant value or a low order polynomial fit obtained from the surrounding outer annulus for each of these subtracted limits images. This estimate is still conservative; a constant extrapolation will often underestimate the flux that might be hidden under the PSF if continuous with the higher surface brightness regions.

We subtracted all of our ground-based quasar images in an identical fashion, forming both the $\chi^2$ minimum limit and monotonic limit. As the ground-based
observations were never saturated, we were able to use the very central portion of the profiles, and varied the annular widths according to the seeing. As one example of radii used, for the CFH $K'$ observations of 3C 2, we used the circular region within 0.4 to calculate the $\chi^2$ minimum scaling, and an annulus with width 0.4 exterior to that to calculate the scaling which satisfies the monotonicity constraint. We have checked our subtraction techniques by subtracting PSF stars from each other, as mentioned in Section 4. We have made other consistency checks on our PSF subtraction results: for the HST data, we have subtracted each object both with the average PSF for its filter and with the PSF observed close in time, and found no systematic differences. Detailed discussion of the individual objects will be presented in Chapter 5. There is an interior region in the HST profiles, as can be seen in Figure 3 that is dominated by noise and systematic residuals (within $\sim 0.3$ radius; this may extend to $0.5$ radius in some cases).

4.3. Magnitudes and Colors

4.3.1. Total and Isophotal Magnitudes

For the WFPC2 data, we planned our exposure times to achieve similar detection limits in all of our 10 images, after normalization for redshift and reddening. In Table 2, we give the $1 \sigma$ sky we actually achieved in our WFPC2 images for each of our 10 objects, after normalization to $z=1$ and $E(B-V)=0$. (The sky sigmas for the quasar images were derived from the profile-subtracted sky regions at a radius of a few arcsec; subtraction generally increased the sky sigma by 10% or less at a radius of $2''$. This is both because our final averaged PSF stars were of higher signal-to-noise than the quasars, and because the sigma in the sky has a significant component from readout noise, imperfect flat-fielding and bias-subtraction. The noise contribution
from subtraction will be greater in the inner regions where the Poissonian noise from the PSF may dominate). We correct our image for galactic extinction. We obtained $E(B - V)$ values for our sources from Burstein & Heiles (1984); we converted these to galactic extinctions at the appropriate HST filters (F622W and F675W) using the values given in Table 12A of Holtzmann et al. (1995). For each object, we align all our ground-based images to the HST scale and reference frame, using the IRAF tasks *geomap* and *geotrans*. This reference frame is in general rotated from standard astronomical position angle. Without further rotation or distortion of the images, we made smoothed isophotal masks.

Since our primary goal is to make an objective comparison between the radio galaxy and quasar sample properties, optimally we would compare magnitudes and morphologies at identical (normalized to $z=1$) isophotal flux limits. In practice this is complicated somewhat by the very irregular nature of the extended material we have resolved around the quasars; unresolved or linear features do not lend themselves so well to isophotal analysis as smoothly varying galaxies. For this reason, we also will calculate simple aperture and annular magnitudes.

For the isophotal analysis, we average the observed normalized 1σ sky deviations to obtain an average sigma deviation. To investigate how the fluxes and intensity moments of the images depend on the choice of limiting flux, we normalize the images to $z = 1$ and make a series of masks from the normalized images corresponding to isophotal levels of interest. We investigate magnitudes and moments in apertures with no flux limit, then calculate flux densities in apertures defined by standardized surface brightness cutoff levels. We will discuss further details of our method of magnitude and moment analysis when we present the properties of the whole sample. We will first discuss the morphology of each object individually and present photometry of its components. To this end, we may sometimes use the isophotal masks we
have generated (at least this technique). When we discuss the properties of a PSF-subtracted quasar, we generally discuss and present the results from the monotonic-subtraction-limit; however, we use the $\chi^2$ minimum fit as useful check, both as a means of error estimation, and as an indication of how dependent on our PSF subtraction method our results may be.

4.3.2. Colors and Spectral Energy Distributions

Since we are dealing here with images of extremely different resolutions, we take a two-step approach to determining the magnitudes and colors of various components in the images. Inspection of the original HST image can be used to verify the existence of components that occur close to the quasar nucleus or that are not visible at the resolution of the ground-based data. We then smooth the HST image to match the resolution of the ground-based image in question, so that an aperture will encompass a similar portion of the component's flux. We will then use the same apertures (simple or tailored) in each bandpass. There is generally a straightforward correspondence between the HST data and the ground-based data, but sometimes components that may be resolved from others at HST seeing cannot be resolved or are simply not visible at ground-based resolution. Thus we cannot get a $K'$ magnitude for every component for which we have HST fluxes; in cases in which the residuals from the subtraction process obscure the component at ground-based seeing, we cannot even obtain a useful upper limit.
### TABLE 4
**PSF STAR OBSERVATIONS**

<table>
<thead>
<tr>
<th>Quasar Name</th>
<th>Star Name</th>
<th>Filter</th>
<th>Integration Time</th>
<th>QSO Saturation Diameter</th>
<th>PSF Saturation Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C 2</td>
<td>GSC4663-00365</td>
<td>F675W</td>
<td>12×4 s</td>
<td>0</td>
<td>0.25</td>
</tr>
<tr>
<td>3C196</td>
<td>GSC3411-03379</td>
<td>F622W</td>
<td>12×4 s</td>
<td>0.2</td>
<td>0.05</td>
</tr>
<tr>
<td>3C212</td>
<td>GSC0817-00892</td>
<td>F675W</td>
<td>12×16 s</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>3C245</td>
<td>GSC0842-00459</td>
<td>F976W</td>
<td>12×3 s</td>
<td>0.25</td>
<td>0</td>
</tr>
<tr>
<td>3C336</td>
<td>...</td>
<td>F622W</td>
<td>12×50 s</td>
<td>0.20</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Fig. 2.— PSF Subtraction Method: We show one example of how we determine the (QSO/PSF) scalings in our PSF subtraction procedure. We show in the upper panel the $\chi^2$ of the PSF subtraction residuals in an annulus versus the scaling of the subtracted PSF for the 3C 2 $K'$ image. The minimum in this plot gives the scaling for the lower-limit quasar subtraction. In the lower panel we plot the mean flux in an inner and outer annulus versus the PSF scaling; the circles are the outer annulus, the squares are the inner circle. At the intercept of these two lines, the flux in the residual extension will be constant (monotonic) across the entire inner region. This example (3C 2 at $K'$) is the quasar image with the greatest contribution of symmetric nebulosity.
Fig. 3.— We present the results of subtracting our observed stellar PSFs from each other with the centering and scaling technique described in text. The images are to the same scale as the magnified panels in Figures 3-14; the distance between tick marks is 1" and a scale bar is shown in panel (d). Panel (a) gives the 3C 212 PSF minus the 3C 245 PSF, both observed in the F675W filter. Panel (b) shows the 3C 2 PSF minus the 3C 212 PSF, in the F675W filter. Panel (C) shows the difference of the 3C 196 PSF minus the 3C 336 PSF, in the F622W filter. Note that the diffraction spikes subtract poorly close to the stellar profile in this case. In Panel (D), we show the average F622W PSF, from the addition of the 3C 196 PSF and the 3C 336 PSFs.
Chapter 5
Discussion of Individual Fields

In this section we discuss and present the HST and $K'$ imaging of our 10 sources. We will discuss their morphologies and give photometry for components of interest, but will reserve the discussion of the quantification of the alignment effect and the properties of the sample as a whole for later. In the figures, (Figs. 4–13), we show the HST image and the $K'$ image at the same scale in the upper left and upper right panels, respectively. In the lower left panel we display a magnified version of the HST image, sometimes slightly Gaussian smoothed to bring up lower surface-brightness features. In the lower right panel, we display the continuum-subtracted [O II] image, if we have one for that object; if not, we generally display another version of the HST image, scaled or smoothed differently, or with radio map contours overlaid. In the top left panel, we give the positions of the radio lobes as white crosses (or show the direction to them as white arrows, if they lie outside the frame). Throughout the images, insets will display different intensity scalings or a non-PSF-subtracted version of a quasar. In all cases, N is at the top, and E is to the left. In Table 6, we give photometry for the components labelled in the figures.

5.1. 3CR 2

5.1.1. Morphology

3CR 2 has (relative to its nucleus) one of the more dominant host galaxies of the quasars in our sample; it shows clear signs of “fuzziness” even in groundbased unsubtracted images, especially in the $K'$ image. It also has the faintest nucleus of the 5 quasars we observed. In Fig. 4A, we display the HST and CFHT $K'$
images; the PSF-subtracted images show the monotonic limit. We label as \(a\), \(b\), and \(c\) the components within a few arcseconds that can be identified above the general nebulosity. Object \(a\) has a nearly stellar peak at a distance of 0\(\text{"}83\), and a position angle of 11\(^\circ\). We find it to be precisely coincident with the northern radio lobe of 3C 2.

The radio structure of 3C 2 consists of this northern lobe, while the southern lobe is at a position angle of \(-160^\circ\), at a mean distance of 4\(\text{"}5\) (Saikia et al. 1987). From Saikia et al.'s 2-cm map of the northern component, which has a similar resolution to our HST images (0\(\text{"}16 \times 0\text{"}1\)) we can see that even the details of the morphology of the northern radio component and the optical component \(a\) agree. The WFPC2 image shows a similar extension directly north, then a turn to the east to a bright peak. When we align the optical quasar and the radio core, the bright optical peak and bright radio knot align to within 0\(\text{"}02\). The optical image has the same fainter north-eastern extension that is seen in the radio map. (We display in an inset in Fig. 4C the contours associated with the northern lobe from the 2 cm radio map of Saikia et al. [1987]).

Though this object \(a\) definitely has a separate, almost unresolved peak in the WFPC2 data and therefore might be considered a companion object, its coincidence with the northern radio lobe and the “bridge” of connecting nebulosity means it is clearly closely associated with the quasar. Object \(c\), on the other hand, is clearly discrete (though it is also enveloped in the general nebulosity surrounding the nucleus in this case). Object \(b\) is diffuse and seems to connect into the noise-dominated inner region, and it shows no correlation with the radio structure. Of the three objects we have labelled, it is the only one that might be a feature of the host galaxy itself.

We make magnitude and moment calculations both with and without \(c\); we remove the object by extrapolation from the annulus of nebulosity surrounding it to
get the properties of the nebular component alone. The sky level for the 3C 2 HST observations was lower than expected; we reached a greater depth for 3C 2 and for 3C 217 than for any other fields. The extended nebulosity we observe in 3C 2 is mostly at a lower surface brightness than our lowest standardized contour level; it is possible therefore that a similar nebulosity might exist and have escaped detection in the objects in our sample that have a lower signal-to-noise background.

Our CFHT K-band data shows the three major components visible in the HST image as well as some extended nebulosity; our IRTF $H$ image shows similar structure but is not deep enough to show the general extended nebulosity.

5.1.2. 3C2 Component Spectral Energy Distributions

For 3C2, we have two extra passbands; one which is slightly redder than but which approximates the $I$ passband (8964/1063) and $H$. 3C 2 is the only object in our sample for which we have 4 passbands spanning the rest-frame range from 3300Å to 1μm. We will discuss here the spectral energy distributions of various components: the lobe structure labelled $a$ in Fig. 4A, the faint extension $b$, the nearby companion $c$, and the underlying nebulosity (seen best in the highest-contrast HST image panel, Fig. 4D). This faint extended structure appears relatively symmetric and has an angular extent of about 3″ radius, as measured at the 2σ sky level in the $K'$ image, where it seems brightest relative to the other components. In addition, we derive the SED of the quasar nucleus alone, with the contribution of the above components subtracted.

We wish to measure the colors of these components, and distinguish as well as possible between the contribution of the background extension and a superimposed compact feature. We make several steps toward this goal: we determine from an
unsaturated star lying on each of the frames the Gaussian smoothing that will bring each frame’s resolution to the 0.78 resolution of the $H$ band image. We then use the high resolution HST and $K'$ data to estimate how much the smoothing affects fluxes in the lower resolution data. To determine at what radius the nebulosity would be roughly unaffected by the inner components, assuming that their morphology is similar in all passbands, we compare the degraded and original HST and $K$ images.

Outside of a radius of 1.75 and within an encompassing radius of 3", the HST and $K'$ fluxes are unaffected by smoothing to match the $H$ band data, so we adopt this annulus to measure the spectral energy distribution of the underlying nebulosity. This approach will not give us a total magnitude of any kind, but it should allow us to get the color of the extension. Signal-to-noise in the $H$ and $I$ band images is insufficient to make maps of the color distribution.

For the discrete components, we make similar trials. We find that apertures with radius equal to the full-width-half-maximum of the degraded seeing contain most of the flux in the undegraded HST image for $a$ and $c$, both of which are quite compact. We then measure the fluxes of $a$ and $c$ in an aperture of this size, but excluding, of course, the central 0.5 radius around the nucleus that is dominated by PSF residuals. As we are interested in the components’ flux without the contribution from the underlying emission, we subtract off the background extension in the HST image before smoothing, then Gaussian smooth to the poorer resolution. This process may lead to systematic errors, so we estimate the background contribution in several different ways and use the dispersion as an estimate of our errors. The images with the poorest resolution have the greatest systematic uncertainty from the background subtraction process. We present the result of this photometric analysis for all the components in Table 5, and give there the exact apertures used for each component.
5.1.3. Discussion

Because of the detailed close correspondence between the optical and radio morphologies, it is seems likely that the northern lobe (component \( a \)) is due to optical synchrotron radiation.

To address this question, and to investigate the likely origin of the other components we have resolved, we plot the flux values for each component values versus the rest wavelength (assuming that all objects are at the narrow-line redshift of the quasar) in Figure 14 A and B. The fluxes are normalized to the flux value at \( \lambda_0 = 3300\AA \) (from the F675W HST image). Filled circles are the QSO nucleus (with all extension subtracted), stars are the nebulosity in an annulus from 1''5 to 3'', unfilled squares are the companion galaxy \( c \), filled triangles are the bright northern extension \( a \), and unfilled circles are the faint extension \( b \). In panel A, we show the \( a \), \( b \), and \( c \) component fluxes without the nebulosity subtracted; in B, with the nebulosity subtracted as discussed above. The nebulosity and quasar nucleus components are the same in both A and B. We show both the subtracted and unsubtracted fluxes since this background subtraction process is prone to possible large systematic errors, and comparison of the two plots shows that, though the details of each SED value change, each component’s SED shows the same qualitative behavior with or without the back ground subtracted.

Though broad-band colors alone are a notoriously inaccurate way to derive information about the nature of any single object, we may still gain some general indication of the probable origin of the radiation we observe and of the differences between the components. We see that the nebulosity and component \( c \) are both redder than the QSO (and than component \( a \)). This is what might be expected if they are dominated by a stellar population rather than by scattered quasar light. Lehnert
et al. (1992) found a similar result for the extensions in $z \sim 2$ quasars. In panel $B$, we plot some models: at the top middle of the figure, we show the SED of M31 from Coleman, Wu & Weedman (1984) with the alternately short- and long-dashed line; the bluer model (with the same line pattern) is their S0 SED. Dotted lines are Bruzual & Charlot models: the upper model is a stellar population with a Scalo IMF that has aged 4 Gyr since a delta-function starburst; the next two (in decreasing brightness at 1$\mu$m) have ages 2 Gyr and 1 Gyr (Charlot & Bruzual 1991, Bruzual & Charlot 1993). We see that none of these simple stellar models are a perfect fit, but component $c$ has a 4000Å break that is fit very well by the Bruzual & Charlot models. This is evidence that it is at the $z$ of the quasar and that it is stellar in origin. Reddening by dust, either internal or from the surrounding nebulosity, could explain the slightly redder colors in $c$ than in the 4 Gyr stellar models. The colors of the nebulosity fit any stellar model less well; this may mean that in this extended emission there is a significant contribution from a younger, bluer stellar population or perhaps from scattered quasar light. Component $b$ is of much lower flux, and very close to the nucleus; it was thus difficult to estimate its flux values, particularly for the two lower signal-to-noise images. Nonetheless, the colors are consistently bluer than either the nebulosity or $c$. Though it appears morphologically as if it could be a continuous extension from the nuclear region of the quasar, and therefore be part of a host galaxy, its colors are more consistent a scattered light origin, or perhaps a young stellar population.

We plot a a short-dashed line in panel $B$; it is a power-law fit to component $a$ with $\alpha = 1.36$, where $S_{\nu} \propto \nu^{-\alpha}$. (We weighted the fit with the errors on each point; for this reason, the $\lambda_0 = 0.44\mu$m contributes little to the fit). This optical $\alpha$ is similar to that seen in optical synchrotron counterparts of radio hot-spots (Meisenheimer & Roser 1989). In Fig. 15, we show our photometry of the northern lobe (component
a) with the radio photometry of Sakia et al. (1987) of the same component (crosses). The error bars shown on our data are 2σ errors. We plot the power-law fit to our data (with $\alpha=1.36$) with a solid line; a linear fit to the Saikia et al. points gives $\alpha=0.83$, and is plotted as a dashed line. It can be seen that our photometry is consistent with an optical synchrotron origin for the optical emission in the component $a$, where the synchrotron spectrum has a high frequency cutoff as normally results from the aging of the electron energy distribution due to synchrotron losses.

Saikia et al. suggest that the beam from the northern end of 3C 2 is deflected by collision with a dense intergalactic cloud, causing the directional change of the beam. They find that the eastern part of the northern lobe has a higher depolarization than the western part of the lobe; this depolarization is considered to be produced by gas heated and mixed in the collision.

5.2. 3CR 175.1

5.2.1. Image Editing

In the 3C 175.1 field, there are several bright stars near to the galaxy, and these caused various artifacts that had to be removed manually prior to further analysis. In the HST images presented in Fig. 5, a diffraction spike from a bright star to the south has been subtracted out. Since the diffraction spikes are some of the features that seem to vary most with position in the HST point-spread function, we were most successful in subtracting a radially averaged version of the star from itself rather than a separately measured PSF star. This process should have only added slightly to the noise, and there is no morphological feature in the radio galaxy that could be due to unsubtracted flux from the diffraction spike. In Keck NIRC images, bright stars bleed along rows in the readout direction. A bright star in the 3C 175.1 field has bled
through the radio galaxy; we subtract the extra flux by fitting a low-order polynomial along the row prior to rotating the images.

5.2.2. Morphology

Our HST image of this radio galaxy has an elongated component, in two parts, but it also has a strong nuclear source. The $K'$ band data (both our Keck and CFH data) show a round component which coincides with the HST nuclear component, with more elongation at the lower isophotal levels. In the Keck image, we may barely detect component $a$ to the southwest. We show the HST and Keck images in Fig. 5A and B respectively.

Neff, Roberts & Hutchings (1995) detect a radio core at 6 cm; we align this with the semi-stellar HST center and near-infrared center. We show their contours overlaid on our HST image in Fig. 5D. The radio structure is two-lobed, with an axis bent by 20°. The position angle between the two lobes alone (i.e., ignoring the central component) is 70° (Hutchings et al. 1994, Neff, Roberts, & Hutchings 1995), while the position angles of the two lobes with respect to the central component are 96° and −139°. A small extension to the NE from the radio core is at 70°; another to the SW is at −130°. These possibly correspond to the initial jet directions. Our images show some correspondence to these directions: the low-level extension to the HST image is aligned about 10° from the 70° core extension. We also note that object $a$ is very linear and parallel to the flattened, near edge of the southwestern lobe.

Dunlop & Peacock (1993) find the $K$ band light to be elongated with an aspect ratio of 1.48 and to be aligned at 70°; they conclude that the $K$ image is well aligned with the radio axis. (This was prior to the detection of the radio core; though this
position angle of 70° is now known not to correspond to the actual lobe position angle, it may still be relevant, as the radio core itself seems elongated in this direction).

In both our $K'$ band and HST data, there are companion objects to the north east of the radio galaxy; these are reasonably bright in the $K'$ band. Their average position is at a radius of 3″7 and a position angle of 70° relative to the radio galaxy core; the aperture used by Dunlop & Peacock (1993) has diameter 7″5 and thus would have been influenced by these objects. From their contour plot, it is seems likely that their seeing was insufficient to differentiate between these companion objects and the envelope of the central component, which our $K'$-band data shows to be round. This situation once again brings up the issue of deciding what is appropriate to include in analyses of the alignment effect. In this particular case, the conclusion of Dunlop & Peacock that the alignment is significantly better in the IR seems to have been strongly influenced by the presence of these objects. However, the objects are present in our HST optical image as well, where they appear completely discrete from the radio galaxy. Including them at ground-based seeing in a moment analysis of the optical image would skew the optical position angle towards 70°. Our moment analysis of the $K'$ radio galaxy gives a position angle that varies from 70° to 90° with isophotal cut-off level (see Section 6.2 for a more detailed discussion), but the axial ratio over the same range is 0.93–0.98. It transpires that this is fairly close to the actual PA (96°) of the eastern lobe; however, the optical moment analysis gives a position angle within 10° of the southwestern lobe. To summarize, there is no reason to conclude from our data that 3C 175.1 is better aligned in the IR than in the optical.
5.3. 3CR 196

5.3.1. Morphology

We display the PSF-subtracted HST and Keck images of this \( z = 0.87 \) quasar in Fig. 6A and B. This quasar has a large spiral galaxy superimposed to the southeast; this object is probably the source of a prominent 21-cm absorption line system at \( z = 0.437 \) in the quasar spectrum (Boisse & Boulade 1990). As this is a foreground object, we will exclude it in when analyzing the other extensions we see around the quasar. This procedure is not so much of a problem with the excellent resolution of the WFPC2 data but is difficult in the analysis of the ground-based data.

3C 196 has a LAS (lobe hotspot to hotspot) of 5\'6 (Reid et al. 1995), but shows a fairly wide, extended lobe structure. The extension that we see to the north extends almost directly north for several arcseconds, then extends to the east at the lowest detectable level on our image. The lowest level extension has a slight knot of emission that is coincident with the north-eastern radio lobe (best seen in panel C). At higher isophotal levels, as seen in panel A or the inset in panel C, component \( a \) appears semi-discrete and is elongated in the direction of the northern radio lobe. In addition, as noted by BB, there is a non-stellar object 6\'9 to the northeast that lines up approximately with the radio lobe direction (within 4\"), and is elongated perpendicular to the radio axis. We see a similar object to the other side of the radio source, at a position angle of \(-172^\circ\), elongated basically parallel to the other object. We will refer to these objects as companions (1) and (2) respectively.

Our [O II] image (in panel D) shows a bright asymmetric emission-line region whose morphology (inset in panel D) corresponds fairly well to the optical structure, and therefore with the radio morphology. At the lower isophotes, the morphology is curved symmetrically to the east both north and south of the quasar.
5.3.2. Discussion

Boisse & Boulade (1990; hereafter BB) bring up the possibility that 3C 196 could be lensed by the galaxy c. This seems likely from morphological considerations: The morphology of our [O II] image at low isophotal levels appears to arc around the location of the spiral galaxy. The elongation in component a and the general extension to the north east are all consistent with distortion by a mass at the location of the spiral galaxy. BB suggest that a secondary image of the quasar may lie within the image of the spiral; they posit this from the elongation of the companion galaxy and a difference in morphology between their B and R band images. The elongation they note is probably just the bar of the spiral that is obvious in our higher resolution HST image; they have, however, color information and see evidence for an extra blue component to the east of the center of the companion galaxy. We see a faint component in the bar of the spiral that might plausibly be associated with this nucleus, but could equally well be intrinsic to the spiral galaxy, as we have no knowledge of its color.

Could there be lensing of the radio source itself? The radio power of 3C 196 is greater by a factor of 2 than the average radio power of the other objects in this redshift range in the 3C sample, as can be seen in Figure 1. The radio lobes have bright extensions away from the primary hot spot positions shown in panel A, parallel to the position angle of the foreground galaxy c relative to the quasar nucleus. But this would probably require a large gas mass associated with a foreground cluster; BB find no evidence of an overdensity number of objects in the field. They also consider the possibility that companion (1) is a gravitational arc. On our images, both (1) and (2) are elongated, but are well-resolved in width; they do not have the narrow, round structure one would expect were they arclets. BB find companion (1) to be very blue in the optical, and favor the interpretation that it is associated with the
radio source, (through jet-induced star formation), though it lies beyond the radio lobe. This hypothesis is particularly interesting in light of our near-certainty that we have an example of such a situation in 3C 212: there we have an object (component f in Fig. 7A) that falls directly on the radio axis and is morphologically similar (in the optical) to a radio lobe, yet lies 4" beyond it. However, we find that companions (1) and (2) have similar and very blue optical-to-infrared colors; the optical-to-$K'$ flux ratios are 10.9 and 8.5, respectively, while the QSO itself has a flux ratio of only 4. As these objects appear very similar morphologically and in color, it is tempting to try to ascribe them to a similar origin. In this case, though the southern object is off of the radio axis by 20°, this is within a typical quasar opening angle (Barthel 1989, Saikia & Kulkarni 1994), and the blue objects may result from quasar light being scattered in a dusty galaxy. (This possibility was also considered by BB). In qualitative support of this explanation, the peak surface brightness in the farther companion is $\sim$0.25 the surface brightness of the nearer. In 3C 280, we may also see morphological evidence of quasar radiation impinging on and scattering from an existing structure.

5.4. 3CR 212

5.4.1. Morphology

Even casual inspection of the ground-based images of 3C 212 show an unusual clustering of objects around the quasar. With the high resolution of the HST image we see that several of these objects have morphologies and locations that make it likely that they are directly associated with the quasar, and indeed with the quasar phenomenon. Here we have a clearcut example of a quasar with optical and near-infrared continuum structures that are aligned with the radio axis; this example (and that of 3C 2) are the first such cases to be found. In Fig. 7A and B we show the HST
and Keck $K'$ images; in panel $C$ we show the HST image magnified $2\times$, and in panel $D$ the same image Gaussian smoothed to bring up low surface brightness features.

Close to the nucleus, we see a general nebulous extension, with some identifiable components. Most striking (and with the greatest surface brightness in the optical) are the three discrete blobs $a$, $b$, and $c$. They extend almost directly toward the NW radio lobe; they are resolved but compact ($b$, the brightest, has a FWHM $\sim 0''25$) and fairly blue. Though they are not resolved in the Keck image, there is a narrow extension in the $K'$ band structure at the positions of $b$ and $c$. The radio map of Akujor et al. (1991) shows a faint radio component at the position of the optical component $c$, though the detection of this radio component is marginal. (The correspondence would make sense, however, in the context of the close alignment of the optical “chain” with the direction of the radio lobe. Such close alignment might be more consistent with emission mechanisms that link the radio and optical radiation directly, such as synchrotron radiation.)

The next highest surface brightness object in the HST frame shown, component $f$, is also aligned with the radio axis; however, it lies directly outside the radio lobe hotspot, at least as observed at $5$ GHz by Akujor et al. (1991). Its morphology makes it quite obviously associated with the radio source: it looks very similar to a classical radio lobe, with a “hot spot” at the end of the radio jet axis that is barely resolved (FWHM $\sim 0''17$) and with a tail of emission that increases dramatically in redness away from the hot-spot. The next highest surface brightness object is object $g$, also aligned with the radio axis on the other side of the radio source, and beyond the radio lobe. In this case, there is less obvious morphological evidence that $g$ has some significant association with the radio jet. However, at the lowest contour levels in the WFPC2 image, it is slightly elongated perpendicularly to the radio axis and
has curved wisps from the SE edge that trail towards the radio source, similar to a bow-shock. It is also significantly redder than any other labelled component.

5.4.2. Photometry

To derive the colors of the components of interest, we smoothed the HST image in the normal fashion (Gaussian smoothing until the stellar and quasar profiles match in the two images), define an aperture in the smoothed image that includes most of the flux associated with the object in the unsmoothed image, and calculate the fluxes in both the $K'$ and HST image in this aperture. We subtract off any local background, though we estimate a color for the $K'$ extension containing the objects $b$ and $c$, and these flux values probably include contribution from the underlying nebulosity. The background was difficult in this case to remove, though we have attempted to determine the background from similar regions in the optical and near-infrared. We present the photometric results for these components in Table 6.

We ratio the cosmoothed images of the component $f$ and find that it exhibits a steep color gradient. This can be seen qualitatively by comparing the optical and $K'$ images; the $K'$ $f$ component peaks $\sim$1.8 south of the optical point source. The $K'$-to-optical flux ratio is 0.18±0.04 at the optical peak and 0.98±0.09 at the $K'$ peak.

5.4.3. Discussion

The object $f$ has a morphology very similar to a classical radio hotspot and lobe, and is directly associated with the observed radio axis. It is very likely that its emission is a direct result of radio jet interaction with the ambient material. We
probably see [O II] emission at the redshift of the quasar at this location; this is also consistent with radio jet interaction with the environment. Let us assume for the moment that the emission is synchrotron radiation, associated with some undetected extension to the radio lobe hotspot of Akujor et al. In this scenario, it would not be surprising that the optical-to-infrared ratio increases from the relatively blue hotspot out towards the tail. A steepening of the spectral index in tails extending away from a primary hotspot is observed in radio lobes like those of Cygnus A (Carilli et al. 1989) and well-described as outflow from the primaries in the 3D jet models of Cox, Gull & Scheuer (1991). The optical spectral index in $f$ at the optical hotspot is $\alpha \sim 0.50$, where $S_\nu \propto \nu^{-\alpha}$; at the $K'$ peak, $\alpha \sim 2.0$. Of course, we would expect to see radio continuum at this location if the emission mechanism is optical synchrotron.

5.5. 3CR 217

5.5.1. Morphology

We display in Fig. 8A and B our HST and $K'$ images of the radio galaxy 3C 217. This is the only object in our sample without a detected radio core available in the literature. This leaves some of our position angle interpretations slightly ambiguous. The lobes we display in Fig. 8 as white crosses are placed at the approximate distances of the radio lobes from the measured optical core position (Pedelty et al. 1989). The optical image consists of an elongated galaxy with a very faint nuclear peak (the faintest in our sample); this peak is best seen in the inset to the magnified version of the HST image, shown in panel C. D shows a the same magnified version, slightly Gaussian smoothed. The $K$ band image shows a fairly round elliptical galaxy centered on the optical peak.
There are also two semi-discrete components or companions (objects \(a\) and \(c\) in Fig. 8A). Component \(a\) is much redder than \(c\). If these are included in a position angle determination, the whole ensemble has a position angle of 63°. They are oriented at close to the angle of the elongation of the rest of the galaxy; however, if they are excluded on isophotal cutoff or aperture considerations, the galaxy position angle is 79°. Therefore the dominant morphology of the galaxy differs in orientation by ~ 30° from the position angle between that radio lobes (105°) regardless of the details of what is included in the moment analysis. However, there is an extension (\(b\) on Fig. 5) that is very linear at its highest isophotal level and has a position angle (relative to its own center) that matches the radio lobe position angle to within a degree. This “spine” of emission is seen best in panel C.

5.5.2. Discussion

The linear feature \(b\) hints that the radio source may be playing a direct role in producing the UV continuum even in a relatively non-nucleated, not-very-aligned source like 3C 217. It must be remembered, however, that the feature might be dominated by line-emission contamination of our HST filter; if such were the case, the feature would have little to do with the alignment (or lack thereof) in the UV continuum. The component \(a\) is the reddest object (with an optical-to-IR flux ratio of 0.3) among the nearby companions or semi-discrete components that we measured in any of our 10 sources, while component \(c\) is among the bluest (optical-to-IR ratio = 8.7, but the error in the \(K'\) image is high). This is unexpected from the appearance of the HST image, in which the two companions look fairly symmetric and aligned with the rest of the galaxy. If they are both at the redshift of 3C 217, they must be quite different in nature, or in environment.
5.6. 3CR 237

5.6.1. Morphology

This radio galaxy is a compact steep spectrum source, with an angular size of 1\textquoteleft3, with an unresolved, flat-spectrum core (van Breugel et al. 1992). We display the HST and Keck K\textquoteleft images of the galaxy in Fig. 9 A and B; in panel C we show a magnified version of the HST image, with the fairly symmetric radio lobes of van Breugel et al. marked with white crosses in an inset. As can be seen in Fig. 9B, the HST image shows a slightly oblong galaxy with several close companion galaxies. Our Keck K\textquoteleft band image shows a fairly round galaxy (axial ratio \sim 1.07) whose center coincides with the optical peak within 0\textquoteleft05. Despite its roundness, the IR position angle is stable and aligned to the radio axis within 1\textdegree at the lower contour levels. (We exclude the nearest discrete companion galaxy in our magnitude and moment analyses; it is at a distance of 3\textquoteleft9.)

The optical image has a fairly dominant optical nucleus, with two lobes in a morphology similar to that of the radio. If we align the radio and optical cores, the E lobe radio and optical peaks are fairly well aligned; however, the western radio lobe peaks past the optical emission.

5.6.2. Discussion

Despite the fairly close correspondence in scale between the radio and optical morphologies, there does not seem to be a close point-to-point correspondence. This may be because the scale of the object is small enough that it is challenging (even with VLBI and HST data) to resolve the kind of detailed structure that we see in the northern lobe of 3C 2 (for example). We therefore do not find in this object a need
to ascribe the morphology to optical synchrotron radiation as is likely the source of the aligned radiation in 3CR 2.

5.7. 3CR 245

5.7.1. Morphology

We show in Fig. 10 A and B our PSF-subtracted HST and Keck images of the quasar 3C 245. (The two subtraction limits were the same for this quasar; any extension in the outer annulus was insufficient to change the scaling significantly). This quasar had the brightest nucleus in our sample, making detection of underlying extension more difficult. We were also hampered in our $K'$ imaging by an unfortunate period of poor seeing ($\sim 1\text{''}3$). Clear, nonetheless, in both images is the companion galaxy $2\text{''}3$ southeast of the quasar nucleus, studied by LeFèvre & Hammer (1992). Their spectra show this to be a fairly normal elliptical at $z = 1.013$.

In the HST image, other than this elliptical galaxy, the highest surface brightness extension is a linear feature (containing components $a$ and $b$) to the west of the nucleus. If we align the quasar with the core of the 5-cm map of Laing (1989), this optical feature coincides exactly with the radio jet. The direct correspondence, even in the position and relative brightnesses of the radio and optical hotspots, is shown in Fig. 10C. The inset at the lower right shows the central $3\text{''} \times 4\text{''}$ region of the PSF-subtracted quasar image, with contours from the 5-cm map of Laing (1989) superimposed. The radio map contours are offset vertically by $1\text{''}$ so that the optical image is visible for comparison.

In addition, there is low-surface-brightness extended flux to the east of the nucleus (including a peak at $d$ and extending down to the elliptical galaxy $e$); this
lies in the diffuse, extended eastern radio lobe of 3C 245; the very approximate center of this lobe is indicated by a cross (Laing 1989; Liu, Pooley, & Miley 1992). The 5-cm map of Laing shows 3 faint peaks centered around the cross position; we see a corresponding 3 peaked structure in the optical emission. This structure could be due to [Ne V] emission in our HST bandpass; however our [OIII] image (Fig. 10D; continuum subtracted) is of insufficient signal-to-noise to show whether there is [O II] at a correspondingly low surface brightness level at this location. However, we do see resolved [O II] emission line flux extending for about 3\" to the north, and at the location of the elliptical galaxy. In fact, the position angle of the [O II] emission line region is \( \sim 3^\circ \) (measured in a 2\" radius aperture, but excluding the elliptical); this orientation is within 2\° of perpendicular to the radio axis (as defined by the lobes; the jet direction is rotated by 10\°).

5.7.2. Analysis and Discussion

We give fluxes for the components seen in the HST image in Table 6; the \( K' \) image has far too low resolution to allow us to get colors (or even useful limits) for the extensions near to the quasar, other than the bright elliptical.

The linear feature containing components \( a \) and \( b \) is certainly associated with the radio jet, and the small-scale correspondence between the radio and the optical makes it very likely that the optical emission is synchrotron radiation. From the Laing (1989) contour map, we find the approximate surface brightness ratio (at 6 cm) of component \( a \) to component \( b \) is 2:1. In our optical image, \( a \) has a surface brightness \( \sim 3 \) times that of \( b \). From the radio spectral index data of Liu et al. (1992), in which they plot the spectral index (between 5 cm and 2 cm) along the jet, we estimate that \( a \) has \( \alpha \sim 0.8 \) and \( b \) has \( \alpha \sim 0.9 \). If there is no high-frequency turnover to the spectral
energy distribution, the surface brightness ratio between the two components would increase by a factor of 3 from observations at 6 cm to 6700\AA. This is a greater increase in the surface brightness ratio than we observe; however, high-frequency turnovers are the norm in synchrotron spectra where optical synchrotron has been observed.

5.8. 3CR 280

5.8.1. Morphology

Under ground-based seeing conditions, the radio source 3C 280 has been observed to be associated with an elongated galaxy that is well-aligned with the radio axis (within 1°: McCarthy et al. 1987; within 20°: Rigler et al. 1992). As seems to be the norm, with HST’s resolution this elongated galaxy separates into several discrete components. However, even by the standard of previous HST images of high-redshift galaxies, 3C 280 is unique. As shown in Fig. 11A and C, the elongated, aligned UV component is resolved into a two-component central region (peaks a and b), connected to a narrow, possibly disk-like structure (c) by a semi-circular arc (d). We see no similar structures in the rest of our sample, nor are we aware any similar features found in any other high-redshift sources. While the objects a, b, and c are well aligned along the radio axis, object c is elongated almost perpendicularly to this axis, and the arc d of course also deviates from the axis. In the HST image, the dominant elongation (if the arc is excluded) is at a position angle of 80°; this is within 10° of the radio axis. Inclusion of the peak of the arc rotates the derived position angle up to 90° (the details of the alignment analysis presented in Chapter 6).

The arc can also be seen in our CFHT [OII] image (continuum-subtracted, deconvolved with the Lucy restoration algorithm, then reconvolved with a Gaussian; shown as the inset in Fig. 11D). Despite this unusual morphology at rest-frame
0.33\(\mu\)m, in the near-infrared (rest-frame 1\(\mu\)m) the galaxy is seemingly quite round (but see below); no obvious sign of these discrete components is seen, other than a red companion galaxy.

The length of the arc is \(~1''\); at the redshift of the quasar this corresponds to \(~6\) kpc. What are possible origins for this curved structure, along with the rest of the aligned morphology? First, the arc could be a tidal tail, drawn from \(c\) (seen as a nearly edge-on galaxy in this view), and resulting from the interaction of the central component \((a\) and \(b)\), with \(c\). This is a straightforward way to explain the association of the discrete objects, and the arc-like structure. However, on most conventional views, the alignment of \(c\) with the radio axis would then be fortuitous. Second, the fact that the arc appears to be nearly semi-circular leaves open the possibility that it could be a gravitational arc, or possibly a bubble associated with a shock propagating from a point near its center. In order to evaluate these options, we need to consider more closely the nature of the radiation dominating the components seen on our HST image.

5.8.2. Details of Analysis

Although we have tried to use essentially line-free filter bandpasses, some weaker emission lines inevitably fall within our bands. For our HST imaging, which covers the rest-frame region near 3300Å, the most serious likely contaminants are [Ne V] \(\lambda3346,3326\). Especially in regions of weak emission, we cannot be certain that what we are seeing is dominated by continuum emission, unless we have supporting evidence from other bandpasses. For 3C 280, we see in our HST image a relatively fainter echo of the [O II] emission-line morphology associated with the eastern radio lobe (Rigler et al. 1992; Fig. 10D); this is likely to be largely due to [Ne V] contamination of
our continuum filter. As remarked by Dunlop & Peacock (1993), the fact that the emission line morphology is edge-brightened, and brighter in association with the radio lobe nearer the center, is behavior consistent with that of most other radio galaxies with emission-line regions (McCarthy et al. 1991). We assume that the emission in the eastern lobe boundary in our HST image is almost entirely [Ne V] and that the [Ne V]:[O II] ratio is relatively constant throughout the object. From the relative ratios between components in the [O II] image, we can see that there is likely to be a significant contribution from the continuum in components a, b, c, and d in our HST image. In the HST image, the peak in the arc is 1.5–3 times the average peak in the extended lobe flux; in the [O II] image, the arc peak is less than half the peak fluxes in the extension knots. Component c, in the [O II] image, is 1.3–2.2 times the surface brightness of the knots; in the HST image, these same ratios are 2.4–4.2. Our assumption that the [Ne V]:[O II] ratio is constant is actually conservative, because, other things being equal, the ionization will be lower in regions of higher gas density. In general, therefore, it seems reasonable to suppose that at least half the light in the arc, and in components b and c, are continuum (the component a is many factors brighter in the HST image, and has probably little line contribution).

We will assume, then, that we have both line and continuum radiation tracing this unusual morphology. In addition, in the HST image, components c and d display edge brightening, along the width of each feature, and well aligned with the radio jet direction. The brightened region in the edge of the arc has about 2× the surface brightness of the rest of the curve and extends out to a position angle of about 30° from the radio axis, or 40° from the optical axis. This is consistent with the probable opening angle derived by Barthel (1989) and Saikia & Kulkarni (1994); it seems likely that this edge brightening is related in some way to the radio source, and could be the result of illumination by the active nucleus. There is no way of knowing whether this
brightening originates in the emission-line or not, as our [O II] image has insufficient resolution. If the arc is of tidal origin, then we need to explain the existence of both the UV continuum and the line-emission.

The main peak in the $K$ band image looks like an elliptical galaxy, whose center is coincident with the brightest HST peak, object $a$, to within 0'06. Object $a$ has an intrinsic width of 0'20 on the HST image, and is therefore resolved (a nearby star has FWHM 0'15). The $K'$ image has an intrinsic seeing of $\sim$0'58 (derived from the same star).

We fit the "elliptical galaxy" using the IRAF stsdas routine ellipse from the stsdas package, which fits elliptical isophotes using the interactive algorithm of Jedrzejewski (1987). If we let the P.A., ellipticity and center vary, we obtain the $r^{1/4}$ profile shown in Figure 16. This is well-fit by a de Vaucouleurs profile between 0'5 and 1'46 (the radial region in which the elliptical isophotes were good fits, and outside of the inner, flattened region). This gives an effective radius $r_e = 0'84 \approx 5$ kpc. The position angle of the elliptical isophotes vary from about 65° to 90°; we show the position angle as a function of the semi-major axis in the lower panel of Figure 16. It is interesting to note how this kind of elliptical fitting compares with the position angles that result from the moment analysis discussed in Section 6.2. The dependence on radius translates to something like isophotal cutoff and smallness of the aperture used in the moment analysis; the results look similar, particularly when we fit the ellipses holding the center fixed at the HST image center. We find that the $K'$ light is aligned with the radio position angle within 20° at all isophotal levels; the best alignment seems to lie roughly in the same axis as that defined by the $a + b$ component.

We fix the ellipticity ($b/a = 0.9$) and position angle ($\sim 70°$), derive a profile, and use this to make a 2 dimensional model of the galaxy. We subtract the model from
the radio galaxy, varying the center and scaling slightly to reduce the residuals. There is evidence from the best-fit residual for some flux at the position of the component c in the HST image, and maybe a little extension at b. However, discrete contributions like these cannot have caused the elongations along PA~ 70–80° that we observe, since the elliptical isophotal fits have relatively consistent PAs and axial ratios through all the isophotes. To further verify this, we subtract the galaxy's azimuthal average from itself, and find the obvious bimodal, large-scale residuals, (along the axis defined by the best position angle of the elliptical isophotes), that are consistent with a non-circular morphology. (We also see again the extra flux at the position of the component c). We note, also, in the subtracting of the fit from the observed elliptical, that if the PA of the elliptical is varied (using the same profile and axial ratio), we can rotate the elliptical about 20° in either direction from the fixed PA of 70° without getting significant residuals. In addition, to make sure this elongation we see is not the result of an elongation in the observed PSF, we have checked the position angle and axial ratio of the star on the K' frame and seen no preferential elongation. (The stellar image is very circular; position angle determinations vary randomly over various apertures and isophotes). This best-fit elliptical galaxy has a total K' magnitude of 17.0 with an aperture of 8'', consistent with the 17.1 ± 0.3 K magnitude found by Dunlop & Peacock (1993).

We now use the elliptical model to scale and subtract from the a smoothed version of the HST image to determine probable extinction to the elliptical galaxy. We smooth the HST image with a gaussian until the star that falls in both the K frame and the HST frame matches in FWHM; we then determine the colors of any shared components. We subtract off the K elliptical galaxy model in steps until we have started to over-subtract the wings; this defines the upper limit to how much of the elliptical flux could be present in the HST λ0 = 3300Å image. We make this
estimate from the unsmoothed HST image as well, as the wings of the elliptical outside of $r=0'5$ should not be affected by the seeing, and the unsmoothed image will provide better contrast against the nucleus. We find consistently in the the smoothed and unsmoothed image that the ratio of the HST to $K$ envelope is $0.2 < \text{ratio} < 0.4$, with 0.3 providing the best apparent fit.

We can do additional photometry with these elliptical-subtracted images. (We will not attempt to subtract the line-emission contribution from the HST image, as we have insufficient information to do so; the fluxes presented will therefore include any line emission). We mask the HST image with the scaled elliptical subtracted and make isophotal apertures for the components labelled in Fig. 11A; our isophotal cutoff level is about $3-4 \sigma_{\text{sky}}$ comparable to the lowest grey level in the upper-right inset in Fig. 11C. We give the results of this photometry in Table 6.

5.8.3. Discussion

The most intriguing feature of our HST image of 3C280 is the arc between components $b$ and $c$. We consider three of the possible interpretations: (1) that it is a distant object gravitationally lensed by some mass associated with 3C280; (2) that it is a component in 3C280 gravitationally lensed by an intervening mass; and (3) that it is a tidal resulting from an interaction between component $c$ and the central mass of 3C280, presumably component $a$.

We think it extremely unlikely that the arc ($d$) is a gravitational image of a distant object for several reasons: first, the presence of line emission tracing the arc morphology at the redshift of the quasar; second, the edge brightening (plausibly associated with the radio axis) and some other lumps in the overall morphology; third, the fact that the $K$ elliptical galaxy is centered at the peak of the optical
emission (component $a$) rather than somewhere near the center of curvature of the arc, and there is no other likely candidate for the lensing mass. The second possibility, that of an intervening lensing mass lensing some feature associated with 3C280, would remove the first objection, but not the second and third. Indeed, the lack of detection of a plausible lens mass becomes more acute as it is moved to lower redshifts.

We favor the third interpretation: that the arc is the result of a tidal interaction. Tidal tails in several nearby interacting galaxies show both star formation and strong [O II] emission; in the case of 3C280, the latter may be enhanced by photoionization from a hidden quasar nucleus. A simulation by Mihos (1995) of the detectability with WFPC2 of tidal tails resulting from disk galaxy mergers indicate that from normal spirals, tidal merger remnants such as tails would only be visible at $z \sim 1$ for about 200 Myr after the initial interaction. (Mihos assumes a total exposure time with the WFC of 10,000 s similar to our 3C 280 exposure of 8800s. While it has to be admitted that the arc in 3C280 is not only detected, but could have been detected in a considerably shorter exposure, its relatively high surface brightness is likely to be at least partly due to enhancement from external ionization and scattering, as we have mentioned above). The main difficulty with interpreting the arc as a tidal tail is that in brings to the fore once again the problem of understanding how an actual galaxy can participate in the alignment effect.

There appears to be a cluster around 3C 280; we see some objects which seem to have [O II] emission at the redshift of the quasar. We also see some very linear features in the HST images, some of which are also present in our $K'$ image. 3C 280 was observed by ROSAT and found to have a $L_x \sim 1.3 \times 10^{44}$ erg s$^{-1}$; the radial profile is well-fit by a unresolved point source + extended cluster emission (Worral et al. 1994), evidence for a nuclear x-ray emitting jet or for an unresolved cooling flow (Worral et al. 1994, Crawford & Fabian 1995).
5.9. 3CR 289

We show in 12A and B our HST and Keck $K'$ images of the radio galaxy 3C 289. This galaxy is unusual for our sample, in that it shows some discrete, elongated structure that is severely misaligned with the radio axis ($\Delta PA=75^\circ$). The components $a$, $b$ and the central component are colinear, at a position angle of 0°. This colinear feature looks superficially similar to the “chain” of components seen in 3C 212, but that feature lies directly on the radio axis. At higher isophotal levels the central component has a position angle within 20° of the radio axis. In the infrared, this galaxy looks morphologically similar to its appearance in the optical. There is a dominant central elliptical galaxy component; its position angle is within 10° of the position angle of the elliptical component in the optical (30° from the radio axis). These position angles are close, as well, to that of extension c. The [O II] image shows a bright extension that matches c well; this is then a case in which the emission line morphology is better aligned with the radio axis than is the optical or infrared continuum.

3C 289 is the brightest radio galaxy in the infrared in our sample by a factor of 2, and the elliptical central component dominates the components $a$, $b$, and $d$, though $a$ and $d$ are detected in the infrared.

5.10. 3CR 336

5.10.1. Morphology

We show in 13A and B our HST and Keck $K'$ images of the quasar 3C 336. The radio structure of this quasar has been well-studied by Bridle et al. (1994); this is the source with the largest angular size in the radio of any in our sample (28''). We
give the directions toward each radio lobe as lines in panel A. In the HST image, we have resolved low-surface brightness extension near to the nucleus; this can be seen well in panel C where we display a magnified version of the HST image, slightly Gaussian-smoothed. Also seen are PSF subtraction residuals: this quasar had the worst match between PSF and nucleus, particularly in the diffraction spikes. (We chose the subtraction scaling we display here by requiring approximate monotonicity in regions which exclude these diffraction spike residuals.)

Bridle et al. detect a radio jet to the south-west; the knot nearest to the nucleus in this jet is at a radius of 0.97 and position angle $-162^\circ$. The brightest extension we have resolved around 3C 336 in the HST image is at a similar radius, on the jet-side of the nucleus, but is not aligned. In fact, this radio knot position corresponds to a break in the extension to the south of the quasar, to the west of extension a, giving a “channel” effect similar to that seen in Cygnus A (Stockton, Ridgway & Lilly 1994). 3C 336 is therefore the only quasar in our sample which shows no evidence of any direct alignment or correspondence of optical and radio structures (though 3C 196 has only one knot which corresponds, and is not nearly so straightforward an example as the jet-like and lobe-like structures in 3C 2, 3C 245, and 3C 212).

We display in panel D the PSF-subtracted, continuum-subtracted [O II] image. The emission line region is very asymmetric with respect to the nucleus, and has low surface brightness structure to the northwest that is approximately perpendicular to the radio axis. There are relative peaks in the emission at the positions of the components b (part of this low surface-brightness extension) and a. The [O II] peak near a is at a radius of 1.0 and position angle $-172^\circ$; though the [O II] is at lower resolution than both the HST image and the radio map, this [O II] knot seems to be better associated with the peak a in the HST image (PA $-176^\circ$) than with the position of the radio jet knot.
This field of this quasar has been quite well-studied from the ground. Bremer et al. (1992) made a spectroscopic study of the [O II] extension and detected extended line emission out to 5" north and 3" south. This is qualitatively quite consistent with our [O II] image. Hintzen, Romanishin, & Valdes (1991) found an over-density of field objects, and suggested that 3C 336 was likely in a rich cluster. However, the 3C 336 spectrum is very rich in Mg II absorption line systems, having three. A spectroscopic survey of the field by Steidel & Dickinson (1992) identified a galaxy to the southwest of the quasar 5.7" (visible in Fig. 26) as responsible for the $z = 0.4722$ absorption line system; they also find marginal evidence for a foreground cluster at $z = 0.66$, the redshift of another of the Mg II absorbers. This then is the probable source of the overdensity observed by Hintzen et al., and there is no evidence for a cluster at the QSO redshift (Bremer et al. 1991, Steidel & Dickinson 1992). Steidel & Dickinson attempt spectroscopy of our object d, and see no evidence of a [O II] line at any of the absorption redshifts or the quasar redshift (after subtraction of a scaled quasar spectrum, to account for locally scattered light). Its colors (according to Steidel & Dickinson) are consistent with its being a galaxy at $z \sim 0.66$. Our optical-to-infrared color is consistent with such an interpretation.
Fig. 4.— 3C2 (quasar). (A) PSF-subtracted HST WFC image (inset shows the same image prior to PSF subtraction). The white cross shows the position of the southern radio hotspot. (B) PSF-subtracted CFHT Redeye $K'$ image. Again, the inset shows the unsubtracted version. (C) HST image, enlarged $2\times$. The inset shows the unsubtracted version with radio contours (2 and 32 mJy beam$^{-1}$) from the 2-cm VLA map of Saikia et al. 1987. This does not include the peak of the core flux. (D) Same as (C), but higher contrast. For this and following illustrations, N is at the top and E to the left. Tick marks are at 1" intervals, and long tick marks indicate the source center (optical peak for quasars, $K'$ peak for radio galaxies).
Fig. 5.— 3C175.1 (galaxy). (A) HST WFC image. The crosses indicate the positions of the radio hotspots. (B) Keck NIRC $K'$ image. (C) HST image, enlarged 2×, and slightly smoothed to show low-surface-brightness features better. Inset shows lower-contrast image without smoothing. (D) Same as (A), but smoothed and overlayed with contours from the 6 cm VLA map of Neff et al. (1995). The levels shown are 0.07, 0.2, 2, and 7 mJy beam$^{-1}$. 
Fig. 6.— 3C196 (quasar). (A) PSF-subtracted HST WFC image. The spiral galaxy is in the foreground, at $z = 0.437$ (Boisse & Boulade 1990). The crosses indicate the positions of the hotspots, and the inset shows the unsubtracted image. (B) PSF-subtracted Keck NIRC $K'$ image, with the inset showing the unsubtracted version. (C) HST image, enlarged 2x. The inset shows the same, with lower contrast. (D) Image obtained with the CFHT SIS fast guider through a $\sim 30$ Å interference filter centered on the [O II] $\lambda 3727$ line. The image has been continuum subtracted. The inset shows the same image at lower contrast.
Fig. 7.— 3C212 (quasar). (A) PSF-subtracted HST WFC image. Note the alignment of objects \(a, b, c, f,\) and \(g\) with the radio axis, indicated by the crosses on the radio hotspot positions. Note also the linear galaxy \(h.\) The inset shows the unsubtracted version. (B) PSF-subtracted Keck NIRC \(K'\) image. (C) HST image, enlarged 2x. (D) Same as (C), but smoothed and at higher contrast.
Fig. 8.— 3C217 (galaxy). (A) HST WFC image. The cross indicates the approximate position of the E radio hotspot, and the arrow shows the direction to the W hotspot, which lies outside the frame. 3C217 is the only source in our sample that does not have a detected radio core component, so we have assumed the optical position given by Pedelty et al. (1989). (B) Keck NIRC $K'$ image. (C) HST image, enlarged $2\times$, and at lower contrast than (A). The inset shows the image at even lower contrast, to show the faint, almost stellar, nucleus. (D) Same as (C), but smoothed and at higher contrast.
Fig. 9.—3C237 (galaxy). (A) HST WFC image. (B) Keck NIRC $K'$ image. (C) HST image, enlarged 2x, and at lower contrast than (A). The inset shows the positions of the radio hotspots. (D) Same as (C), but higher contrast.
Fig. 10.—3C245 (quasar). (A) PSF-subtracted HST WFC image. The crosses show the positions of the radio hotspots, although the E lobe is very diffuse, covering much of the region over which low-surface-brightness optical emission is seen. The inset shows the unsubtracted version of the image. (B) PSF-subtracted Keck NIRC $K'$ image, with the inset giving the unsubtracted version. (C) HST image, enlarged 2x and smoothed. The inset shows the enlarged, unsmoothed version at lower contrast. It also shows, displaced 1" N, radio contours from the 6 cm map of Laing (1989). Contour levels are 5, 10, 15, 20, 25, 50, 100, 125, 250, and 375 mJy beam$^{-1}$. Note the close correspondence between the optical and radio jet structures. (D) Continuum-subtracted [O II] $\lambda 3727$ image through a $\sim 30$ Â interference filter at the UH 2.2m Telescope.
Fig. 11.—3C280 (galaxy). (A) HST WFC image. The cross shows the position of the E radio hotspot, and the arrow shows the direction to the W radio hotspot, which lies outside the frame. The inset shows the same image, smoothed and at higher contrast, in order to show better the low-surface-brightness material in the direction of the E radio lobe. (B) Keck NIRC $K'$ image. The inset shows the same image at lower contrast. (C) HST image, enlarged 2x. The inset shows the same at lower contrast. (D) Image obtained with the CFHT SIS fast guider through a $\sim 30$ Å interference filter centered on the [O II] $\lambda 3727$ line. The image has been continuum subtracted and slightly deconvolved. The inset shows the same image at lower contrast.
Fig. 12.—3C289 (galaxy). (A) HST WFC image. The crosses show the position of the radio hotspots. (B) Keck NIRC $K'$ image. (C) HST image, enlarged 2×. The inset shows the same at lower contrast. (D) Image obtained with the UH 88-inch Telescope through a ~30 Å interference filter centered on the [O II] $\lambda 3727$ line. The image has been continuum subtracted.
Fig. 13.— 3C336 (quasar). (A) PSF-subtracted HST WFC image. The arrows show the directions to the radio hotspots, both of which lie outside the frame. The inset shows the unsubtracted image. (B) PSF-subtracted Keck NIRC $K'$ image, with the unsubtracted image shown in the inset. (C) HST image, enlarged 2× and smoothed. (D) Image obtained with the CFHT SIS fast guider through a $\sim 30$ Å interference filter centered on the [O II] $\lambda$3727 line. The image has been continuum subtracted. The inset shows the same image at lower contrast.
<table>
<thead>
<tr>
<th>Component</th>
<th>ΔRA</th>
<th>ΔDEC</th>
<th>Aperture*</th>
<th>λd(Å)b</th>
<th>Unsubtractedc</th>
<th>Flux densities (ergs cm⁻² s⁻¹ Å⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (NE “lobe”)</td>
<td>0'17</td>
<td>0'80</td>
<td>C(0.75)</td>
<td>3299</td>
<td>101.3</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4401</td>
<td>69.2</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8100</td>
<td>57.5</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10309</td>
<td>48.4</td>
<td>5</td>
</tr>
<tr>
<td>b (NW Extension)</td>
<td>-0'53</td>
<td>0'13</td>
<td>R(0.75,0.75)</td>
<td>3299</td>
<td>15.6</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4401</td>
<td>6.7</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8100</td>
<td>3.1</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10309</td>
<td>10.7</td>
<td>2.7</td>
</tr>
<tr>
<td>c (SE Companion)</td>
<td>0'80</td>
<td>-1'06</td>
<td>C(0.75)</td>
<td>3299</td>
<td>21.0</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4401</td>
<td>45.6</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8100</td>
<td>57.5</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10309</td>
<td>55.7</td>
<td>4.6</td>
</tr>
<tr>
<td>Symmetric Nebulosity</td>
<td>...</td>
<td>...</td>
<td>A(1.75,3.0)</td>
<td>3299</td>
<td>76.6</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4401</td>
<td>95.8</td>
<td>31.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8100</td>
<td>147.8</td>
<td>41.1</td>
</tr>
<tr>
<td>QSO (without extensions)</td>
<td>0 0</td>
<td>C(4)</td>
<td>...</td>
<td>3299</td>
<td>1579.4</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4401</td>
<td>1367</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8100</td>
<td>609.5</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10309</td>
<td>514</td>
<td>27</td>
</tr>
</tbody>
</table>

*Aperture type; i.e., C(r) is circular with radius r; A(r1,r2) is annular with inner radius r1 and outer radius r2; R(x, y) is rectangular with dimensions x and y; and r, r1, r2, x, and y are all in arcseconds.

b This is the rest wavelength in Å, assuming each component has the same redshift as the narrow-line 3C 2 redshift of 1.037.

For the components a, b, and c, these fluxes have had the best estimate of the local background due to the nebula subtracted; see the text for details. For the QSO itself, all extensions have been subtracted. Flux densities are in units of 10⁻²⁰ ergs cm⁻² s⁻¹ Å⁻¹ and have been corrected for galactic extinction.

d These fluxes have had no local background subtracted (other than standard sky subtraction). Flux densities are in units of 10⁻²⁰ ergs cm⁻² s⁻¹ Å⁻¹ and have been corrected for galactic extinction.
Fig. 14.— Photometry in $F_{\lambda}$ of the various components of 3C 2 versus $\lambda_0$, normalized by $F_{\lambda}(3300\text{Å})$. Filled circles are the QSO nucleus, asterisks are the nebulosity in an annulus from 1"5 to 3", unfilled squares are the companion c, filled triangles are the northern lobe a, and unfilled circles are the faint extension b. In panel A, the components a, b, and c do not have the local background subtracted; in panel B, a, b and c photometry is given minus an estimated local background contribution. The QSO nucleus and nebulosity photometry are identical in the two panels. In panel B, we plot models: at the top middle of the figure, we show the SED of M31 from Coleman, Wu & Weedman (1984) with the alternately short- and long-dashed line; the bluer model (with the same line pattern) is their S0 SED. Dotted lines are Bruzual & Charlot models: the upper model is a 4 Gyr stellar population, while the next two (in order of brightness at 1μm) are 2 Gyr and 1 Gyr old. A short-dashed line is a power-law with $\alpha = 1.36$. 

79
Fig. 15.— We plot our photometry of the northern lobe (component a) with the radio photometry of Saikia et al. (1987) of the same component (crosses). The error bars shown on our data are 2σ errors. We plot a linear fit to our data (weighted instrumentally); this gives a power-law with $\alpha=1.36$, where $S_{\nu} \sim \nu^{-\alpha}$. A linear fit to the Saikia et al. points gives $\alpha=0.83$. 

80
Fig. 16.— We show the results of fitting elliptical isophotes to the $K'$ 3C 280 image, with companion objects removed from the fit. In the upper panel, we give the mean surface brightness of each isophote versus the semi-major axis. If a deVaucouleurs profile is fit to the linear portion of the data, the effective radius is $r_e = 0'84 \approx 5kpc$ corresponding to $r_{1/2} = 0.96$. The inner portion of the profile is smoothed by atmospheric seeing, with seeing FWHM $\approx 0'6$. In the lower panel, we show the PAs of the fit ellipses.
### TABLE 6

**OPTICAL AND NEAR-INFRARED COMPONENT PHOTOMETRY**

<table>
<thead>
<tr>
<th>Name</th>
<th>Component</th>
<th>Aperture Type&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Aperture Area&lt;sup&gt;b&lt;/sup&gt;</th>
<th>$F_\lambda(0.33\mu m)$&lt;sup&gt;c&lt;/sup&gt;</th>
<th>$F_\lambda(1\mu m)$&lt;sup&gt;d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C 175.1</td>
<td>a</td>
<td>I(2.7)</td>
<td>0.77</td>
<td>47.8±2.3</td>
<td>...</td>
</tr>
<tr>
<td>3C 196</td>
<td>QSO</td>
<td>C(5)</td>
<td>80.1</td>
<td>17649±350</td>
<td>4285±70</td>
</tr>
<tr>
<td></td>
<td>a</td>
<td>R(3.2,1.65)</td>
<td>5.3</td>
<td>270.2±2.5</td>
<td>115.4±2.5</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>C(0.25)</td>
<td>0.20</td>
<td>40.4±2</td>
<td>...</td>
</tr>
<tr>
<td>3C 212</td>
<td>QSO</td>
<td>C(4)</td>
<td>50.3</td>
<td>472±60</td>
<td>2365±30</td>
</tr>
<tr>
<td></td>
<td>a</td>
<td>C(0.25)</td>
<td>0.20</td>
<td>11.4±1.9</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>C(0.35)</td>
<td>0.38</td>
<td>20.1±3.5</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>C(0.20)</td>
<td>0.26</td>
<td>8.3±3.1</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>b+c</td>
<td>R(1.55,1.7)</td>
<td>26.4</td>
<td>48.5±1.8</td>
<td>25±6</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>R(2.05,1.2)</td>
<td>2.46</td>
<td>39.6±3.5</td>
<td>18.8±2.7</td>
</tr>
<tr>
<td></td>
<td>e</td>
<td>C(0.45)</td>
<td>0.64</td>
<td>8.9±1.8</td>
<td>12.1±1.8</td>
</tr>
<tr>
<td></td>
<td>f</td>
<td>R(2.65,3.5)</td>
<td>9.54</td>
<td>240.7±10.5</td>
<td>146.6±20.9</td>
</tr>
<tr>
<td></td>
<td>g</td>
<td>C(1.5)</td>
<td>7.1</td>
<td>37.6±3</td>
<td>71.2±4.2</td>
</tr>
<tr>
<td></td>
<td>a</td>
<td>I(0.4)&lt;sup&gt;e&lt;/sup&gt;</td>
<td>2.5</td>
<td>40.7±2</td>
<td>8.6±0.9</td>
</tr>
<tr>
<td>Extension</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>A(1.2,65)</td>
<td>18.9</td>
<td>182.2±10</td>
<td>128.6±20</td>
</tr>
<tr>
<td>3C 217</td>
<td>a</td>
<td>C(1.0)</td>
<td>3.1</td>
<td>16.1±1.3</td>
<td>52.7±4.3</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>C(1.0)</td>
<td>3.1</td>
<td>22.2±6.5</td>
<td>2.6±1.9</td>
</tr>
<tr>
<td>3C 245</td>
<td>QSO</td>
<td>C(4)</td>
<td>50.3</td>
<td>21229±140</td>
<td>3468±200</td>
</tr>
<tr>
<td></td>
<td>a</td>
<td>C(0.25)</td>
<td>0.20</td>
<td>22.3±1.1</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>C(0.25)</td>
<td>0.20</td>
<td>8.7±1.1</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>a+b</td>
<td>I(3.6)</td>
<td>0.42</td>
<td>46.1±1.9</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>I(3.6)</td>
<td>0.22</td>
<td>10.9±1</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>I(3.6)</td>
<td>0.79</td>
<td>38.2±2.8</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>e</td>
<td>C(3.5)</td>
<td>15.9</td>
<td>423.2±2.9</td>
<td>879±47</td>
</tr>
<tr>
<td>3C 280</td>
<td>a+b</td>
<td>I(5.2)</td>
<td>0.56</td>
<td>197.2±2</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>I(5.2)</td>
<td>0.56</td>
<td>96.6±2</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>I(5.2)</td>
<td>0.78</td>
<td>96.7±2</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Elliptical C(4)</td>
<td>50.3</td>
<td>191±40</td>
<td>608±30</td>
</tr>
<tr>
<td>3C 289</td>
<td>a</td>
<td>C(0.35)</td>
<td>0.38</td>
<td>9.6±2</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>C(0.35)</td>
<td>0.38</td>
<td>7.4±2</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>I(5.2)</td>
<td>0.42</td>
<td>17.2±1.6</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>C(1)</td>
<td>3.1</td>
<td>11.8±3</td>
<td>22.6±5.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Elliptical C(3.2)</td>
<td>32.2</td>
<td>376±50</td>
<td>694±50</td>
</tr>
<tr>
<td>3C 336</td>
<td>QSO</td>
<td>C(4)</td>
<td>50.3</td>
<td>2070±414</td>
<td>2216±60</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>R(1.4,2.95)</td>
<td>4.1</td>
<td>79.6±6.6</td>
<td>63.7±9.6</td>
</tr>
<tr>
<td></td>
<td>a</td>
<td>R(1.15,0.75)</td>
<td>0.86</td>
<td>44.1±4.8</td>
<td>10.4±1.4</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>C(0.6)</td>
<td>1.1</td>
<td>26.3±3.6</td>
<td>11.4±1.2</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>C(0.6)</td>
<td>1.1</td>
<td>36.1±4.8</td>
<td>13.2±1.8</td>
</tr>
</tbody>
</table>

<sup>a</sup> Aperture areas in square arcseconds.

<sup>b</sup> Aperture type: i.e., C(r) is circular with radius r; A(r1,r2) is annular with inner radius r1 and outer radius r2; R(x, y) is rectangular with dimensions x and y; and I(JL) is an isophotal aperture with surface brightness cutoff level JL; r, r1, r2, x, y, and r are all in arcseconds and JL is in 10⁻¹⁹ ergs cm⁻² s⁻¹ A⁻¹ arcsec⁻², at the wavelength of the HST image. This value is normalized by the correction to $z = 1$ factor, to enable comparison to the $\sigma_{sys}$ given in Table 2.

<sup>c</sup> Flux densities from the HST image; in units of 10⁻²⁰ ergs cm⁻² s⁻¹ A⁻¹. The exact HST rest wavelength for each object is given in Table 2. Fluxes have local background subtracted; errors are derived from background statistics and sky level determination errors, and may not include possible systematic contributions.

<sup>d</sup> Flux densities from the $K'$ image; in units of 10⁻²⁰ ergs cm⁻² s⁻¹ A⁻¹. The exact $K'$ rest wavelength for each object is given in Table 5. Fluxes have not been normalized to $z = 1$.

<sup>e</sup> Cutoff level is in Gaussian-smoothed HST image.
Chapter 6

Magnitude and Moment Analysis of the Images

6.1. Magnitudes

We discussed in 4.3 how we create isophotal masks from the images (with flux densities normalized to $z = 1$) in order to allow us to compare the imaging results for our objects less biased by the details of our observations. Here we will give a few more details, and the differences in the way we treated the ground-based data from the HST images.

For the WFPC2 images, we first define a single set of isophotal levels; these are chosen based on our knowledge of the average normalized $1 \sigma$ sky in our observed frames, given in Table 2. For each image, multiplied by the $z = 1$ correction factor, we create masks at these isophotal levels. We then smooth the mask contours slightly by convolving with a Gaussian with a sigma of 1 rebinned pixel ($0.05$) and excluding any pixels whose "smoothed" values are less than 0.5. This smoothing tends to eliminate any isolated sky pixels which might have been picked up in the mask and gives continuous contours; it therefore allows us to consider magnitudes to slightly lower flux limits than would have been otherwise possible. Otherwise, choosing a flux level at which all images will not have noise-dominated profiles would exclude much of the interesting features in the quasars. (As it is, we still will not include in the objective magnitude comparison some low-level nebulosity which falls below our best "common" isophotal level).

We then calculate the flux densities in the unsmoothed image after multiplication by these smoothed masks (in a series of apertures). We find this smoothing process works well on radio galaxies, but is dangerous for the linear features seen in 3C 212 and 3C 245. For this reason we reduced the smoothing as much as possible and check the
smoothed lowest isophotal masks visually to see how much of the structure of interest we are preserving. From this visual inspection, we also select the lowest isophotal level at which all of our normalized image masks have little or no sky contribution. We take the lowest common level to be $4.56 \times 10^{-19}$ ergs cm$^{-2}$s$^{-1}$ Å$^{-1}$ arcsec$^{-2}$, about 2.5 times the average normalized sky $\sigma$. For the $K'$ data, we follow a very similar procedure, except that we don’t need to smooth the masks, prior to applying them to the images. Our adopted “common” isophotal level for the $K'$ data is $1.4 \times 10^{-19}$ ergs cm$^{-2}$s$^{-1}$ Å$^{-1}$ arcsec$^{-2}$.

This magnitude calculation procedure is straightforward for the radio galaxies; for the quasars we must deal with the interior region of the subtracted image which are dominated by residuals from the profile subtraction. As a first pass at this question, we mask out the profile subtraction region in the quasars to exclude them from our moment and magnitude calculations; a circular region with radius $0.45$ arcsec is generally necessary to remove the region dominated by PSF subtraction residuals. We also mask out an identical region in the radio galaxies to make an accurate comparison, and to understand how this subtraction process affects the final magnitudes we calculate. We follow the entire masking and magnitude- and moment-determination procedure for both subtraction limits for those quasars in which the monotonic limit differed significantly from the $\chi^2$ minimum fit. These $\chi^2$ minimum subtractions give us a probable lower-limit to the flux we observe around the quasars, and an idea of whether changing our PSF-subtraction technique would affect our results significantly.

Another major variable is whether to include discrete companions. (This is particularly important for the moment calculations). The HST data provides much greater resolution than ground-based data, and therefore much more structure will appear discrete. In 3C 212, for example, we see aligned structure within a few arcseconds of the nucleus that is almost certainly directly associated with the quasar,
yet these objects appear quite discrete. For this reason, we include companions within 3" for our objective comparison; however, in some cases (like those of 3C 280 and 3C 289) it will be instructive to consider the central component alone. We also exclude from our moment and magnitude analyses known foreground objects, such as the probable $z = 0.437$ absorbing spiral galaxy in front of 3C 196 (BB 1990), the star in the 3C 175.1 field, the probable foreground galaxy in the 3C 280 field, and (for some purposes) the $z = 1.013$ elliptical galaxy companion to 3CR 245 (LeFevre & Hammer 1992).

We show the photometric results for the radio galaxies and quasars in Tables 7–8; we give both the flux densities in the isophotal level masks and in circular and annular apertures. The values given here are normalized to $z = 1$.

6.2. Position Angle Determination

The “alignment effect” observed statistically in samples of radio galaxies is probably the result of several contributing physical processes, as we have discussed in the introduction. It therefore shouldn’t be too great a surprise that the morphology of an “aligned” object should not necessarily be of a consistent type; this variation causes problems, however, when trying to define an objective criterion to measure the degree of alignment in any one object (or small sample of objects). In our sample alone, we see in our HST images several types of “alignment”. We have objects in which the “aligned component” consists of a number of seemingly discrete objects, that are aligned along the radio axis, objects with direct point-to-point correspondence from the optical to the radio structure, and objects that are elongated cohesive structures, but aligned at an angle <30° from the radio position angles. With the high resolution of HST, we can resolve components and discrete structures to a much greater degree.
than possible with groundbased data. In one sense, therefore, the whole procedure of trying to use a single number ($\Delta P.A.$) to correlate a complicated optical morphology with a sometimes similarly convoluted radio structure may be somewhat futile; we need some way, however, to quantify the alignments in our sample, both to compare them with each other and to compare them with previous work.

We discuss first how some other quantitative measurements of the alignment effect have been made. The most common technique consists of calculating the second moments of the intensity distribution around some center, in some aperture, sometimes reducing noise by excluding noisy pixels or introducing a flux cutoff level for including pixels in the moment calculation. In a survey of $z \sim 1$ 3C radio galaxies, Rigler et al. (1992) set a specified aperture (4 $''$), and do not vary it from object to object. They make moment calculations of the sky-subtracted flux in this aperture, excluding noisy pixels (by hand). In the interests of objectivity, they do not exclude companion or foreground objects; they rely upon their small aperture to reduce such contributions.

Dunlop & Peacock (1993), on the other hand, vary their apertures in accordance with the size of the radio source, with some limitations: if the radio source diameter is $>8''$, they adopt 8$''$; if less than 5$, they use 5$''$; otherwise they use an aperture equal to the largest angular size of the radio source. The rationale of this choice of aperture size is that continuum radio galaxy light rarely, if ever, extends beyond the radio lobes. This choice of aperture should then minimize contributions from foreground objects and companions, while retaining as much extended flux information as seems useful. In order to avoid skewing their moments with noisy pixels, they have set a lower flux threshhold of 30% of the peak value. They show convincingly the need for a lower threshhold, and varying the size of the aperture depending on the expected size of the galaxy seems reasonable.
Our technique is similar to theirs, with some exceptions. First, we explicitly mask out any known foreground or companion objects, particularly those for which likely redshifts exist. We then make our moment calculations in the isophotal masks we have generated, with a common range of apertures (from 1" up to 5" radius) that should span the probable range of physical scales of interest for all of the objects.

To find the principal axes of the flux distribution, we calculate the first and second flux-weighted moments. Where $\mu_i$ is the sky-subtracted intensity of the $i$'th pixel at position $(x,y)$, we calculate $\sum_i(\mu_i)$ and the first moments $\sum_i(x\mu_i)/\sum_i(\mu_i)$ and $\sum_i(y\mu_i)/\sum_i(\mu_i)$. We then calculate the second moments around the center that most closely matches a probable AGN location. For our quasars, this is simply the quasar center; for our radio galaxies, we detect unresolved optical contributions in all of the HST images which match the best infrared centers. We therefore use in all cases the WFPC2-determined "nuclear" center. (In all of our objects the optical and near-IR cores match well, thus we use the higher resolution HST data to determine the best center. Such small shifts in centering affect the moments little). We derive the second moments $I_{xx} = \sum_i(x^2\mu_i)/\sum_i(\mu_i)$, $I_{yy} = \sum_i(y^2\mu_i)/\sum_i(\mu_i)$, $I_{xy} = \sum_i(xy\mu_i)/\sum_i(\mu_i)$, where $(x,y)$ is the position of the $i$'th pixel relative to the best determined center.

We use these to determine (see Appendix A) the position angle $\theta$ and the eccentricity $e$, for which $\sqrt{1-e^2}$ is equal to the ratio of the major axis to the minor axis of the ellipse. (For an ellipse, $0 < e < 1$). We have tested our routines with a simple rectangular noiseless model of various rectangular aspect ratios; we rotated it to non-zero position angles and verified that our routines recover the input position angles and aspect ratios.

It is straightforward to plot the dependence of the axial ratio and position angle on the isophotal cutoff and aperture; the difficult (and subjective) part of this
procedure is in choosing what aperture and isophotal cutoff (and resultant position angle) one will select.

To choose one position angle to represent the overall alignment of a complex source may not be possible in many cases. We thus endeavor to understand any dependence of position angle on the aperture and isophotal cutoff on a case-by-case basis. Adopting a single aperture and cutoff level is perhaps the most objective criterion, but will also introduce a greater level of dispersion into the measurement of alignment; moments will still be skewed by included foreground or unrelated companion objects, and unexcluded noisy sky pixels. We have a small sample, and cannot afford this increase in dispersion. In addition, our primary goal in this moment analysis is to compare the alignment properties between the our radio galaxy and quasar samples. An isophotal cutoff that is based on the peak value of an object would introduce a bias between these two samples, and indeed would probably not be possible; the structure in the quasars or in the masked-off radio galaxies is close to the sky background.

For the purposes of our objective comparison, we make the following observations: in many cases, there is a “dominant” position angle associated with an isophotal-cutoff vs. position angle plot. For the HST images, once the isophotal cutoff is above the value chosen for our magnitude analysis, the sky noise contribution is much reduced. This can be seen in these plots as a stabilization of the position angle with respect to changes in isophotal cutoff or aperture size. After such stabilization, the position angle in some cases will remain quite constant with aperture size and increasing isophotal cutoff. In these cases, the dominant position angle is fairly clear, and we adopt this value, generally an average over a range in which the position angle is relatively flat. In other cases, the determination is not so simple: discrete companions may skew the position angle at larger apertures/lower isophotal levels,
a primary object may itself have different dominant position angles at low and high isophotal levels, and in at least one case once above the sky noise the isophotes twist smoothly and there doesn't appear to be any dominant position angle. We adopt an aperture criterion similar to that of Dunlop & Peacock to remove ambiguity in a few cases; in the others, we record both a "high" and "low" isophotal position angle; we generally use the low isophotal cutoff level we use for our magnitude calculation, and a level about 5 times this. The existence of this "high" and "low" position angle is particularly important in light of our need to compare results between the radio galaxies and quasars; in some cases, the removal of the center of the source removes any "high" isophotal level. We will give approximate errors for the position angles based on how stable they seem to be with variables such as isophotal cutoff and aperture.

The $K'$ data are of lower resolution, and the radio galaxies have fairly round central components. We find that in most cases the variation in position angle are related to inclusion or exclusion of companions. We therefore use a aperture criterion similar to DP, and a moderate isophotal cutoff level of about 2 times our magnitude isophotal cutoff level for $K'$.

In addition, we are interested in the behaviour of the most central component (or extension) alone. For example, we see in Section 5.8 that the central elliptical component in 3C 280 seems to have elliptical isophotes that are aligned preferentially with the radio axis. A similar moment analysis of the central component will be more clear if we exclude the bright red companion. For this reason, we also give position angles excluding all companions that we interpret as possibly discrete from our high-resolution HST images.
## Table 7

### Quasar HST Photometry

<table>
<thead>
<tr>
<th>Name</th>
<th>Aperture</th>
<th>Cutoff</th>
<th>$F_A$ (Monotonic)</th>
<th>$F_A$ ($\chi^2$ Minimum)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C 2</td>
<td>A(0.3,3.75)</td>
<td>I(4.56)</td>
<td>243.1</td>
<td>230.2</td>
<td>c included; $\Delta F = 23$</td>
</tr>
<tr>
<td>3C 2</td>
<td>A(0.3,3.75)</td>
<td>None</td>
<td>484.8</td>
<td>469.3</td>
<td>c included; $\Delta F = 21$</td>
</tr>
<tr>
<td>3C 2 (ext)</td>
<td>A(0.3,3.75)</td>
<td>I(4.56)</td>
<td>275.5</td>
<td>253.8</td>
<td>c included; $\Delta F = 21$</td>
</tr>
<tr>
<td>3C 2 (ext)</td>
<td>A(0.3,3.75)</td>
<td>None</td>
<td>528.7</td>
<td>505.2</td>
<td>c included; $\Delta F = 21$</td>
</tr>
<tr>
<td>3C 196</td>
<td>A(0.45,3.75)</td>
<td>I(4.56)</td>
<td>457.2</td>
<td>352.1</td>
<td>foreground c excluded</td>
</tr>
<tr>
<td>3C 196</td>
<td>A(0.45,3.75)</td>
<td>None</td>
<td>578.2</td>
<td>504.7</td>
<td>foreground c excluded</td>
</tr>
<tr>
<td>3C 196 (ext)</td>
<td>A(0.3,3.75)</td>
<td>I(4.56)</td>
<td>535.9</td>
<td>427.3</td>
<td>foreground c excluded</td>
</tr>
<tr>
<td>3C 196 (ext)</td>
<td>A(0.3,3.75)</td>
<td>None</td>
<td>699.5</td>
<td>579.9</td>
<td>foreground c excluded</td>
</tr>
<tr>
<td>3C 212</td>
<td>A(0.45,3.75)</td>
<td>I(4.56)</td>
<td>108.7</td>
<td>\ldots</td>
<td>h included; $\Delta F = 5$</td>
</tr>
<tr>
<td>3C 212</td>
<td>A(0.45,3.75)</td>
<td>None</td>
<td>338.2</td>
<td>\ldots</td>
<td>h included; $\Delta F = 5$</td>
</tr>
<tr>
<td>3C 212 (ext)</td>
<td>A(0.3,3.75)</td>
<td>I(4.56)</td>
<td>136.4</td>
<td>(86.9)$^g$</td>
<td>h included; $\Delta F = 5$</td>
</tr>
<tr>
<td>3C 212 (ext)</td>
<td>A(0.3,3.75)</td>
<td>None</td>
<td>371.1</td>
<td>(362.$^g$)</td>
<td>h included; $\Delta F = 21$</td>
</tr>
<tr>
<td>3C 245</td>
<td>A(0.45,3.75)</td>
<td>I(4.56)</td>
<td>138.0</td>
<td>(88.9)$^h$</td>
<td>e excluded</td>
</tr>
<tr>
<td>3C 245</td>
<td>A(0.45,3.75)</td>
<td>None</td>
<td>325.6</td>
<td>(272.1)$^h$</td>
<td>e excluded</td>
</tr>
<tr>
<td>3C 245 (ext)</td>
<td>A(0.3,3.75)</td>
<td>I(4.56)</td>
<td>202.4</td>
<td>\ldots</td>
<td>e excluded</td>
</tr>
<tr>
<td>3C 245 (ext)</td>
<td>A(0.3,3.75)</td>
<td>None</td>
<td>389.4</td>
<td>(313.5)$^f$</td>
<td>e excluded</td>
</tr>
<tr>
<td>3C 336</td>
<td>A(0.55,3.75)</td>
<td>I(4.56)</td>
<td>129.1</td>
<td>87.8</td>
<td>d included</td>
</tr>
<tr>
<td>3C 336</td>
<td>A(0.55,3.75)</td>
<td>None</td>
<td>348.2</td>
<td>237.0</td>
<td>d included</td>
</tr>
<tr>
<td>3C 336 (ext)</td>
<td>A(0.55,3.75)</td>
<td>None</td>
<td>376.4</td>
<td>\ldots</td>
<td>d included</td>
</tr>
</tbody>
</table>

---

*a* Quasar name; (ext) means that the central region of the quasar has been extrapolated with a low-order polynomial fit.

*b* Aperture size; A(r1,r2) signifies annular aperture with inner radius r1 and outer radius r2, where r1 and r2 are in arcseconds.

*c* Isophotal cutoff level; I(\(\mu\)) signifies a surface brightness cutoff level of \(\mu = 10^{-19} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \text{ arcsec}^{-2}\), at the wavelength of the HST image. This value is normalized by the correction to \(z = 1\) factor.

*d* Flux densities from the monotonic PSF subtraction limit, in units of \(10^{-20} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}\). Flux densities have been corrected for galactic extinction, and normalized to \(z = 1\) factor.

*e* Flux densities from the \(\chi^2\) minimum PSF subtraction limit, in units of \(10^{-20} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}\). Flux densities have been corrected for galactic extinction, and normalized to \(z = 1\). Where the \(\chi^2\) minimum and the monotonic subtraction limit agree, this value is placed in the monotonic-limit column only. Values in parentheses are “lower limit” flux densities calculated by another method, and are placed here for convenience.

*f* Notes associated with individual values.

*g* We note here whether nearby companions were included or not. We included all companions except the foreground spiral c in the field 3C 196 and the elliptical e in 3C 245. For those objects in which we included a nearby (perhaps discrete) companion, we give the change in flux density that would result from subtracting that companion’s contribution.

$h$ This lower-limit value was derived by replacing the central 1'25 \(\times 0'95\) region with a constant; this excluded high surface brightness regions immediately exterior to the PSF subtraction annulus.

This lower-limit value was derived by excluding the central 0'65 instead of the standard 0'45; this certainly excludes host galaxy, but may exclude PSF residuals near the edge of the PSF subtraction region.
<table>
<thead>
<tr>
<th>Name</th>
<th>Aperture\textsuperscript{a}</th>
<th>$F_\lambda$(isophotal)\textsuperscript{b}</th>
<th>$F_\lambda$(total)\textsuperscript{c}</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C 175.1</td>
<td>A(0,3)</td>
<td>154.5</td>
<td>355.3</td>
<td>d</td>
</tr>
<tr>
<td></td>
<td>A(0.45,3)</td>
<td>38.1</td>
<td>236.4</td>
<td>d</td>
</tr>
<tr>
<td>3C 217</td>
<td>A(0,3.75)</td>
<td>211.9</td>
<td>373.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A(0.45,3.75)</td>
<td>83.9</td>
<td>244.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A(0,3.75)</td>
<td>191.9</td>
<td>343.1</td>
<td>e</td>
</tr>
<tr>
<td></td>
<td>A(0.45,3.75)</td>
<td>63.8</td>
<td>215.0</td>
<td>e</td>
</tr>
<tr>
<td>3C 237</td>
<td>A(0,3.0)</td>
<td>472.5</td>
<td>607.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A(0.45,3.0)</td>
<td>183.6</td>
<td>316.5</td>
<td></td>
</tr>
<tr>
<td>3C 280</td>
<td>A(0,6.0)</td>
<td>581.9</td>
<td>915.9</td>
<td>f</td>
</tr>
<tr>
<td></td>
<td>A(0,4.75)</td>
<td>513.5</td>
<td>696</td>
<td>f</td>
</tr>
<tr>
<td>3C 289</td>
<td>A(0,3.75)</td>
<td>169.8</td>
<td>391.6</td>
<td>h</td>
</tr>
<tr>
<td></td>
<td>A(0.45,3.75)</td>
<td>36.1</td>
<td>247.4</td>
<td>h</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Aperture size; $A(r_1,r_2)$ signifies annular aperture with inner radius $r_1$ and outer radius $r_2$, where $r_1$ and $r_2$ are in arcseconds.

\textsuperscript{b} Flux densities above an isophotal cutoff level of $4.56 \times 10^{-19}$ ergs cm$^{-2}$s$^{-1}$\textsuperscript{A-1} arcsec$^{-2}$, at the wavelength of the HST image, normalized to E(B - V) = 0, $z = 1$.

\textsuperscript{c} Total flux densities in aperture, with no isophotal cutoff. Flux densities have been corrected for galactic extinction, and normalized to $z = 1$.

\textsuperscript{d} Foreground star removed

\textsuperscript{e} Components a and c excluded

\textsuperscript{f} Foreground galaxy removed

\textsuperscript{g} Companions, "lobe" emission excluded

\textsuperscript{h} Component d excluded
Fig. 17.— Method used to determine the position angle: example shown is the position angle on the sky for the Keck $K'$ image of 3C 175.1 ($y$ axis) given as function of the isophotal cutoff level ($x$ axis) and as a function of the aperture size used (proportional to the size of the circular points; radii vary from 1" to 5"). The bright foreground star has been excluded; all other companion objects are included. The two companion objects centered $\sim 3.5$ to the northeast contribute to the moment calculations at low isophotal levels and in apertures of 3" or more. We adopt $70^\circ$ for this position angle by choosing to exclude the companions; the position angle then flattens out at $\sim 70^\circ$, before rising again at higher isophotal level cutoffs.
Chapter 7

Modelling the Quasars with the Radio Galaxies

In order to understand how the radio galaxy properties compare to those of the quasars, we must address how the radio galaxies we have observed would appear if they lay under the quasar nuclei. Though we can estimate how much of the radio galaxy would certainly have been lost in a nuclear subtraction by simply excluding the central region as we have done in the magnitude and moment analyses discussed above, this does not include the considerable noise that may be introduced in the subtraction process. If the PSF is observed rather than modelled, as are the ones we use here, then subtraction adds sky noise (partially flat-fielding residuals, partially Poisson) and Poisson noise from the overlying bright nucleus. In addition, the details of any observation (jitter, positioning on the chip) will introduce PSF variations, so another potential source of noise are the PSF subtraction residuals.

To model as closely as possible the quasars as we observed them, we would like to have a PSF independent of the stellar PSFs to simulate the quasar nuclei. If we use the same stellar PSFs to subtract that we use to model the nuclei (with independent noise added, of course), we may succeed in simulating the effect of the Poisson noise, but will not be able to address the deviations caused by PSF mismatches. The modelled Tiny Tim PSFs show large residuals when subtracted from observed PSFs, and they are not an adequate representation of the actual PSFs on our fields. We have therefore tried to obtain an average PSF from the quasar nuclei themselves. We have first taken the best subtracted quasars (as seen in Figures 3–12) and extrapolated over the interior region that is dominated by noise and PSF subtraction residuals (generally the inner 0″25–0″35 radius). We then Gaussian smooth (with a σ of 0″05) this image, which should consist primarily of objects that we are identifying as extensions to the true quasar PSF. We mask this smoothed residual image off at a level (generally
\( \sim 0.06 \) that (with an additional smoothing of the mask) picks up little sky but most of the major extensions. The area included in the mask is \( \leq 10\% \) of the total area. We subtract this masked residual from the quasar, leaving us with a “mostly QSO only” image. This image basically uses information from the stellar PSFs to replace regions which we identify as mostly extension. By smoothing the extension image and reducing the area subtracted as much as possible, we also increase the independence of this quasar PSF from the stellar PSF. The noise is still linked in certain regions, and we will not have removed all contribution from the quasar extensions. The core regions, on the other hand, have only the original quasar information, since we extrapolated over the inner region, in most cases with a near-constant subtracted to simulate a host galaxy contribution that is continuous with the extension immediate exterior.

Therefore we must combine the 5 quasar PSFs with a clipping algorithm. We center and scale these images to each other, using the same scaling and centering procedures used to subtract the stellar PSFs from the quasars and discussed in Section 4.2. We mask out the saturated regions from each quasar, then average the 5 quasars with `gcombine` and the “rsigclip” clipping algorithm. The PSF that results from this looks very similar to the observed stellar PSFs. There will still be extension contributions in regions are not sufficiently subtracted and that are similar in the 5 quasars.

This PSF image still has noise associated with it; though we have reduced noise by averaging, there is an increase in sky noise associated with the extension subtraction process. The sky noise in the model quasar PSF is somewhat less than, but comparable to, the sky noise in our brightest quasar. We now use this model PSF with the observed radio galaxies to simulate the conditions under which we observed each quasar; depending primarily on the brightness of the quasar we are
modelling, this may require adding extra noise to the model to simulate the Poissonian contribution. This is definitely necessary for the faint quasar 3C 2 and for 3C 212. We scale the model quasar PSF to the brightness of each of our 5 quasars, then add each radio galaxy to each quasar, resulting in 5 separate models per quasar. We have not required that the primary radio galaxy peak land exactly on the same position as the quasar PSF; we have used the same 5 radio galaxy images to add to each of the quasars, but both the radio galaxy and quasar centers are constrained only to fall within the central pixel (0'05) of the simulated image. Thus the mismatch between radio galaxy primary center and quasar center will be at most 0'05; nonetheless, this is easily seen in some of our subtracted images.

Since we've added a radio galaxy that already has approximately the proper sky noise, though not, of course, the Poisson noise from the overlying quasar, we want to add extra Poisson noise only in the central region where that noise contribution will dominate over the sky noise. For 3C2 and 3C 212, we excise the inner 1″ central region from the scaled quasar PSF model, place it on a noiseless zero sky, add back the original sky background and add the proper Poisson noise (with IRAF task `mknoise`). These images now have similar noise characteristics to the original quasar observations; we subtract the non-noisy image to inspect the noise characteristics visually. If we calculate at what radius the Poisson noise is $\sim 2\sigma_{sky}$, and check this visually on the artificial images, we see that the inner 0″25 radius will probably be the major contributor. We then add the noise from this region alone to the sum of the quasars plus radio galaxies. Though this method is a little clumsy, it should give us approximately the proper noise behavior, with some discontinuity at $r = 0″25$.

We then run the same centering, scaling and monotonic subtraction technique described in Section 4.2 on these 25 images. These models are on the conservative side; some of the radio galaxy images had higher sky noise than the final quasar
image we were attempting to simulate. But they give a good impression of some of the effects of the Poisson noise and PSF mismatches. For the opposite, optimistic limit, we have already in essence simulated a near-perfect "noiseless" subtraction by simply removing the central region, as discussed in Section 6.2.

We display a montage of the subtracted images in Figure 18. The first row shows the observed radio galaxies; they are oriented as observed on the WFC CCD. The second row shows the unsubtracted models of 3C 245, consisting of an average PSF (scaled to the magnitude of the actual 3C 245 nucleus) with each of the observed radio galaxies added. 3C 245 is the brightest of our quasars, and this row shows therefore the case in which it is most difficult to recover the extensions. The next 5 rows show subtracted versions of the models of each of the 5 quasars, constructed in a similar fashion. In each case, we subtract the average stellar PSF appropriate for the filter in which the quasar was actually observed, to give an idea of the range of possible residuals. The distance between tickmarks represent 1".

It can be seen that the quasars 3C 212 and 3C 245 were slightly farther from the average radio galaxy center than the other QSOs, and thus a little more of the central radio galaxy peak emission is visible to one side.

Visual inspection of the models reveals some interesting points without further analysis, many of which are fairly obvious. It is easier to recover host galaxy structure from fainter QSOs like 3C 2 and 3C 212. 3C 2 also happens to have been fairly well observed, and therefore to have lower sky noise. We also see an extra feature to the upper right in the 3C 245 and 3C 336 simulations; this may correspond to a poor subtraction of the diffraction spike in this corner, but it is also visible in the difference between the average stellar F622W PSF and F675W PSF.
In general, we get an idea from these models out to what radius PSF residuals are likely to dominate our recovered data. We find that our adopted radius of 0'45 is supported by the results of our modelling.
Fig. 18.— We show simulations of the quasars, manufactured by adding a mean quasar “nuclear” PSF (scaled to each of the quasar magnitudes) to each of the observed radio galaxies.
8.1. Magnitudes and Alignment

Here we discuss the results from our isophotal and annular magnitude and moment analysis of all the objects in our sample. The first question is, can we distinguish with this small sample, no matter how carefully observed, between the radio galaxy and quasar subsamples? The answer to this is probably “no”, for the properties for which there is only one measure per object (i.e., total magnitude, color, ΔPA), as the intrinsic dispersion in the properties in each subsample is greater than any difference observed between the two samples. There is more hope with quantities such as the total number of galaxies in the field, for which the dispersion properties may not be so great.

We begin our discussion with the total flux densities in the extensions surrounding the quasars and in the radio galaxies. For the WFPC2 data, we find that the average flux density (all values in \(10^{-20} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}\)) in the annular aperture \(0'\,45-3'\,75\) above our fiducial isophotal cutoff level is 215±145 for the quasars, and 124±106 for the radio galaxies where the errors given represent the dispersion in the flux over the 5 objects. For the total annular flux density, without application of the isophotal cutoff level, the quasars have an average value of 415±112, and the radio galaxies have an average flux density of 301.5±96. We give histograms of the distributions of these two values in Fig. 19 and Fig. 20. We see marginal evidence that the quasar host galaxies are brighter than the radio galaxies, but systematic effects in the quasar subtraction process may dominate. In the \(K'\) data, we find that the average values and dispersions are very similar in the two samples: for the quasars, the average total isophotal flux density is 202 ±157, and the average total annular
flux density is $291\pm 165$; for the radio galaxies, the average isophotal flux density is $196\pm 148$, and the average total annular flux density is $296\pm 191$. These average values are perfectly consistent, Despite our marginal evidence for some difference in the total optical magnitudes between the radio galaxy and quasar subsamples, basically our results are consistent with the unification hypothesis of AGNs. If radio galaxies are unbeamed versions of quasars, the extensions (if host galaxy) should have about the same total flux densities.

We would also expect the radio galaxy UV continuum “alignment effect” to show itself in the quasars in some form, but at a reduced amplitude relative to that seen in the radio galaxies because of projection effects. The aligned component in quasars, for an opening angle of $45^\circ$, should be half of that seen in radio galaxies. We show in Figs. 22 and 24 the results of our alignment effect analysis for the HST images. We do see alignment in both of the samples, though, once again, our sample is too small to differentiate between the subsample properties. However, from the morphological information from the high-resolution HST data, we can tell that there are strong qualitative differences between the type of alignments we see in the quasar and radio galaxies. In the quasar sample, we have several cases in which we have direct correspondence between radio structure hot spots and discrete, optical “hot spots” in our HST imaging. The radio galaxies show alignment as well, but the alignment tends to be of a more global nature for the radio galaxies, and involve more total flux. When the central $0''45$ radius is removed from the radio galaxies, this in many cases removes the peaked portion of the galaxy distribution; however it rarely changes the derived alignment significantly, either quantitatively (i.e. position angle) or qualitatively, in that the fairly extended, bright material which dominates a second moment calculation, also give the radio galaxies their “globally” aligned appearance.
8.2. Linear Galaxies

Another method of assessing the sample properties is by studying the properties of the galaxies in each source's field. We display in Fig. 27 the result of a fairly qualitative analysis of the fields surrounding our sources. We have selected objects that fall above a certain magnitude limit and have the appearance of the "linear galaxies" seen by Cowie et al. (1995), and observed by us in the immediate vicinity of some of our sources; see Fig. 26. These linear or chain galaxies have a lumpy collinear structure that is reminiscent of the aligned portion of the quasars and radio galaxies, and seem truly linear (i.e., not spirals seen edge on). From spectroscopic surveys (Cowie et al. 1995) they are found in the field at redshifts from $z = 1$ to 1.5, and have been used as evidence that galaxy formation may sometimes occur in a one-dimensional form. Our figure shows the constant field background of these objects for the sum of the fields of our sources. There is moderate evidence for an overdensity of these galaxies in the vicinity of the radio sources; most of this overdensity comes from the quasar fields. If this overdensity is verified, it will be the first evidence of clustering for these "linear" galaxies; if the difference between the radio galaxies and quasar fields is real, this is evidence against the unification hypothesis of AGNs. Once again, our sample is too small to support a firm conclusion either way. This is likely, however, to be a fruitful area of future research, particularly with the large number of HST deep observations of radio sources that have been and are being made.

8.3. Optical Synchrotron Emission

We have found evidence in two of our sources for optical synchrotron emission. In one case, 3C 2, the emission comes from the north-eastern lobe; in another, we have evidence for an optical counterpart to the radio jet to the western side of the
core of 3C 245. Optical jets or hotspots that are probably synchrotron emission have
been detected in about 10 extragalactic objects. Optical counterparts to radio jets
have been found in M87, 3C 273, 3C66B, and PKS 0521−036 (Crane et al. 1993
and references therein); and in hotspots in lobes of 3C 20, 3C 33, Pictor A, 3C 111,
and 3C 123 (Meisenheimer & Roser 1989 and references therein). The synchrotron
nature of the optical emission in these objects has been confirmed in most cases by
radio-optical morphology correspondence, photometry and detections of strong linear
polarizations (Meisenheimer & Roser 1986, Sparks et al. 1990, Roser & Meisenheimer
synchrotron jets have been detected in 3C 264 with HST (Crane et al. 1993) and in
3C 120 (Hjorth et al. 1995), though the synchrotron nature of the emission in these
jets has not yet been verified with the detection of strong linear polarization.

These objects are at distances varying from very local (M 87) to a redshift of ~0.2.
Their radio/optical spectral properties have many similarities. The radio spectral
indices are consistent for the jets, with $\alpha = 0.5 \pm 0.1$ (radio) and $\alpha \sim 1.3-1.4$ for the
optical spectral index. Astrophysically observed synchrotron emission takes several
characteristic shapes; a common form is that of a power law with $\alpha \sim 0.5 - 0.8$ (where
$S_{\nu} \propto \nu^{-\alpha}$), with a steepening of the power law spectrum at higher frequencies above
a certain cutoff frequency $\nu_c$.

Synchrotron emission occurs as relativistic electrons circle in the influence of a
magnetic field. Cosmic ray electrons at the surface of the earth's atmosphere are
observed to have an energy spectrum that is well-described by a power law:

$$N(E)dE = \kappa E^{-x}dE$$  \hspace{1cm} (8.1)

in which $N(E)$ is the number of electrons per unit volume of energy $E$ in interval
d$E$, $\kappa$ and $x$ are constant, and the exponent $x$ is found to have the value $\sim 2.7$ in
the high energy regime (Longair 1980; we adopt much of the following discussion and equations from Longair 1980 and Pacholczyk 1970). Assuming a power-law distribution of relativistic electrons as the source of synchrotron radiation leads naturally to the power-law dependence of the observed flux density, where \( S_\nu \propto \nu^{-(x-1)/2} \), and therefore the observed \( \alpha = (x - 1)/2 \). The radiative energy losses due to the synchrotron mechanism are proportional to the energy of the electron squared, therefore the synchrotron lifetime of an individual electron of energy \( E \) is proportional to \( E^{-1} \). This energy dependence causes an initial, intrinsic power-law electron energy spectrum to steepen with time as the higher energy electrons lose energy first if the high energy electrons are not replaced. This effect steepens correspondingly the emitted synchrotron emission. Therefore the often-observed steepening of astrophysical synchrotron spectra can be explained either by an intrinsic high energy cutoff in the spectrum of the energetic particles, or by an age since the injection of the relativistic electrons into the plasma. This fact has been used to assess the ages of injected electrons in hot spots, jets, and lobes from multifrequency radio mapping of extragalactic radio sources (Alexander & Leahy 1987; Liu, Pooley & Riley 1992). Meisenheimer & Roser (1989) have modelled the optical synchrotron in a number of hotspots and jets very well as the result of in situ Fermi acceleration of the electrons from a strong shock.

The fact that the SED of the lobe in 3C 2 has a turnover in the region often observed in other optical synchrotron regions is evidence that its spectrum could be modelled in a similar fashion, and makes it less likely that the close morphological correspondence between the optical and the radio is due to another mechanism (such as thermal Bremsstrahlung, or inverse Compton scattering of microwave background photons).
Fig. 19.— We give histograms of the total isophotal flux densities at 3300 Å (HST images) for the radio galaxies and quasars combined (top panel), for the quasars alone (middle panel), and for the radio galaxies alone (bottom panel).
Fig. 20.— We give histograms of the total annular flux densities at 3300 Å (HST images) for the radio galaxies and quasars combined (top panel), for the quasars alone (middle panel), and for the radio galaxies alone (bottom panel).
Fig. 21.— We give histograms of the total annular flux densities at ~1μ m ($K'$ images) for the radio galaxies and quasars combined (top panel), for the quasars alone (middle panel), and for the radio galaxies alone (bottom panel).
Fig. 22.— We give histograms of the difference between the object position angle in the HST image (at a low isophotal level) and the radio axis. The top panel is the sum of the radio galaxy and quasars samples; the middle panel is the quasars alone, and the bottom panel is the radio galaxies alone.
Fig. 23.— We give histograms of the difference between the object position angle in the $K'$ image and the radio axis. The top panel is the sum of the radio galaxy and quasars samples; the middle panel is the quasars alone, and the bottom panel is the radio galaxies alone.
Fig. 24.— We give histograms of the difference between the HST orientation (at a high isophotal level, where possible) and the radio axis. The top panel is the sum of the radio galaxy and quasars samples; the middle panel is the quasars alone, and the bottom panel is the radio galaxies alone.
Fig. 25.— We give histograms of the optical–near-infrared spectral index $\alpha$ for the identifiable components whose photometry we present in Table 6. The top panel gives the values for the quasar nuclei (minus any extension); the middle panel gives the values for discrete companions, while the lower panel represents primarily nebulous material. Many objects (such as $d$ of 3C 212) are intermediate between these two classes and are included in both middle and lower histograms.
Fig. 26.— Examples of some of the "chain" or "linear" galaxies in the immediate vicinity of the radio sources.
Fig. 27.— We show the distribution of the linear galaxies in the WFC fields; the quasar field objects are shown with open circles, the galaxy field objects are filled circles. There is marginal evidence for a higher density of linear galaxies in the vicinity of the radio source.
Chapter 9

Summary

HST's improved resolution over ground-based observations makes a significant difference in the interpretation of the extensions observed around the quasars. Often structure that seems nebulous and galaxy-like with ground-based seeing is revealed to consist of discrete components that may have more to do with the quasar phenomenon than with stellar populations. An example of this are the discrete blobs seen in 3C 212. Though these can be seen in the ground-based optical image and some hint of the general extension is seen in the Keck image, any extension that does not appear clearly discrete is generally ascribed to host galaxy. In this case, these extensions fall directly on the radio axis and are entirely discrete from the quasar nucleus; there is no reason to associate them with a normal galaxy host. For the radio galaxies, on the other hand, this improvement in resolution in some cases forces an entirely new interpretation of the morphology, as for 3C 280, while in others simply confirms what could be surmised about the radio galaxy structure from lower-resolution data (an example is 3C 217 or 3C 289).

Our samples are small, but some results are clearcut: we find evidence for continuum structure around all of our quasars in the high resolution WFPC2 data, although generally the extension doesn't resemble a "normal" galaxy host. 3C 2 seems, however, to have a bright elliptical galaxy-like nebulosity.

We see morphological evidence of interactions in our objects, most strikingly in 3C 280, in which we may see a tidal tail. We also observe a high incidence of morphological oddities, all sometimes ascribed to interactions: a high incidence of nearby companion galaxies, lumpy morphology, and asymmetric emission-line gas.
We see morphological and color evidence for illumination effects from the active nucleus, i.e. scattered quasar light or photoionization. In 3C 196 and 3C 280, we see very blue and/or edge brightened structures that lie within the probable quasar opening angle.

We see evidence for the aligned emission commonly found in radio galaxies in at least 3, and possibly 4, of our quasars; this has not previously been observed and our recognition of the effect is probably primarily due to the increased resolution of HST. In 3C 212, we see an object that lies beyond the radio lobe that looks morphologically quite similar to a radio hotspot and tail; this object is bright in the infrared and has a steep spectral gradient across the tail. If this is truly a result of the radio jet, it is a unique object that may prove vital to understanding the relationship between the UV continuum alignment effect and the radio source. We have detected an optical counterpart to a radio jet in the quasar 3C 245, and an optical counterpart to a radio lobe in 3C 2. Both of these structures have such a detailed, high-resolution, point-to-point correspondence with the radio structures that they are very likely the result of optical synchrotron radiation. The spectral indices in 3C 2 are consistent with this hypothesis.

We may observe a significant alignment in the elliptical envelopes of the central components of the radio galaxies; this does not seem to be the result of skewing of the position angle by discrete components.

We find that the extension properties in the radio galaxy and quasar subsamples match fairly well. The optical and infrared extension magnitudes do not differ significantly between the radio galaxy and quasar samples; the small size of the sample means the dispersion in observed magnitude dominates. As a consequence, we find that the infrared magnitudes of the quasar extensions (after correction for the missing flux from the obscured central region) fall within the dispersion of the $K-z$ relation.
found for radio galaxies. The colors of the extended components around the quasars are in all cases of the same optical-infrared color as or redder than the quasar nucleus. In some cases at least, nearby companions or overall nebulosity have colors consistent with a stellar population of 4 Gyr or more.

Based on the correspondence between the total magnitudes in the radio galaxies and quasars, and the first detection of aligned components in quasars, we conclude that this study provides general support for the unification hypothesis of radio galaxies and quasars. However, there seem to be significant morphological differences between the aligned structure in the two samples. The extension around the quasars in some cases is likely due to stars, and in others is almost certainly optical synchrotron emission.
Appendix A
Determination of Principal Axes of an Ellipse

We wish to determine the principal axes of a two-dimensional intensity distribution; i.e., to give the axes which minimize the intensity-weighted second moments. Specifically, we will calculate the position angle $\theta$ of the major axis (relative to astronomical north) and the eccentricity $e$ in terms of the second moments in the original coordinate system.

We derive the second moments $I_{xx} = \sum_i(x^2\mu_i)/\sum_i(\mu_i)$, $I_{yy} = \sum_i(y^2\mu_i)/\sum_i(\mu_i)$, $I_{xy} = \sum_i(xy\mu_i)/\sum_i(\mu_i)$, where $(x,y)$ is the position of the $i$'th pixel relative to the best determined center. In analogy to the moment of inertia ellipsoid (Arfken 1985, p. 218), we can form an ellipse using the elements of moment matrix:

$$k = I_{xx}x^2 + I_{yy}y^2 + 2I_{xy}xy$$

By diagonalizing the matrix we can rotate to a coordinate system which lies along the principal axes of this ellipse; this is equivalent to solving for the eigenvectors of the matrix. To determine the position angle, we can derive the rotation directly by using the rotation transformation:

$$x = x' \cos \theta - y' \sin \theta, \quad y = x' \sin \theta + y' \cos \theta$$

Substituting these values into above ellipse formula, we find a formula of the form

$$Ax'^2 + Bx'y' + Cy'^2 = k$$

where $B = 2I_{xy} \cos 2\theta - (I_{xx} - I_{yy}) \sin 2\theta$. Setting $B$ to zero gives the rotation $\theta$ for which the matrix is diagonal; therefore

$$\tan 2\theta = \frac{2I_{xy}}{(I_{xx} - I_{yy})}. \quad (A.1)$$
We use the eccentricity $e$ and the axial ratio $(b/a)$, with $e = \sqrt{1 - \left(\frac{b}{a}\right)^2}$, and $a$ and $b$ are the major and minor axes of the ellipse. (For an ellipse, therefore, $0 < e < 1$).

The coefficients $A$ and $C$ in the equation of the ellipse in the rotated coordinate system are proportional to $(1/a^2)$ and $(1/b^2)$. To determine the values of the coefficients $A$ and $C$, we solve the characteristic equation of the matrix to obtain the roots

$$
\lambda = \frac{I_{xx} + I_{yy} \pm \sqrt{(I_{xx} - I_{yy})^2 + 4I_{xy}^2}}{2}
$$

Therefore $e = \sqrt{1 - \frac{\lambda_1}{\lambda_2}}$ and $(b/a) = \sqrt{\frac{\lambda_1}{\lambda_2}}$ for $\lambda_1 < \lambda_2$. 

117
References


Bennett, A.S. 1962, MmRAS, 68, 163


Boisse, P., & Boulade, O. 1990, AA, 236, 291 (BB)


119


Edge, D. O., Shakeshaft, J.R., McAdam, W. B., Baldwin, J. E., & Archer, S. 1957, MmRAS, 68, 7


Hill, G. et al. 1995


Hjorth et al. 1995


Jackson, N., & Browne, I.W.A. 1990, Nature, 343, 43


Laing, R. 1978

Laing, R. 1988, Nature, 331, 149


Longair, M. 1980,


McCarthy, P.J., & van Breugel, 1989,


