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MULTIWAVELENGTH OBSERVATIONS OF QUASARS AND THEIR
ENVIRONMENTS

by
Eric Jon Hooper

A Dissertation Submitted to the Faculty of the
DEPARTMENT OF ASTRONOMY
In Partial Fulfillment of the Requirements
For the Degree of
DOCTOR OF PHILOSOPHY
In the Graduate College
THE UNIVERSITY OF ARIZONA

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GRADUATE COLLEGE

As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Eric Jon Hooper entitled Multiwavelength Observations of Quasars and their Environments

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SIGNED:

A handwritten signature in black ink, appearing to read "Prof. J. Hooper", written over a horizontal line.

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DEDICATION

Dedicated to my parents and to Marsha Wolf.

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ABSTRACT

The relationship between the radio and optical properties of quasars and the connection between these properties and the quasar host galaxies are investigated. Radio data have been analyzed for 359 of the 1055 quasars in the Large Bright Quasar Survey (LBQS). A major result of this work is that the radio-loud fraction is mostly insensitive to redshift and quasar optical luminosity, remaining at $\approx 10\%$ over the absolute magnitude range $-28 \leq M_B \leq -23$ and from redshifts $z = 0.2$ to $z \sim 5$. Two deviations from these flat distributions occur at $z \sim 1$, where there is a modest increase in the radio-loud fraction, and for absolute magnitudes brighter than $M_B = -28$, where the fraction climbs to 20-30%. The rise in radio-loud fraction at $z \sim 1$ is reproduced by a model based on the optical and radio quasar luminosity functions. The increase at high optical luminosities is consistent with the existence of two radio emission mechanisms, one correlated with optical luminosity, the other independent. The nearly flat distributions in the LBQS differ markedly from those of the optically selected Palomar-Green Bright Quasar Survey and the X-ray selected Extended Medium Sensitivity Survey. A subset of 16 LBQS quasars was imaged with the Hubble Space Telescope to study the dependence of radio and optical luminosity on the absolute magnitudes and morphologies of the host galaxies. There is no distinction in host galaxy magnitude between radio-loud and radio-quiet quasars, assuming they are all of the same galaxy type. The magnitudes of the hosts are $\gtrsim L^*$, and the optical luminosities of the hosts and nuclear components are positively correlated. Many of the host galaxies have small axial ratios, which may indicate that they are inclined disk systems; or else they have bright elongated features which are visible while the bulk of the underlying lower surface brightness components of the host galaxy are not.

CHAPTER 1

INTRODUCTION

The research for this dissertation has already been published in the *Astrophysical Journal* and is presented here in reprint form as three appendices. The copyright for these papers is held by the American Astronomical Society, but the copyright agreement explicitly grants the authors republication rights. The author of this dissertation is also the principal author of each of these papers. Each of the appendices contains its own introduction and reference list relevant to the topic at hand. The reference section for the main body of the dissertation contains references for the introduction and the conclusion. The dissertation introduction presents a wider and generally earlier historical overview of the field than is contained in the following appendices, and it provides context specific to the detailed results which follow.

Chapter 2 contains a synopsis of the results presented in each appendix, as well as a synthesis of the results for the dissertation as a whole. Appendix A contains a paper on the radio properties of optically selected quasars, Appendix B is a follow-up paper to the first, and Appendix C is a paper discussing imaging of

quasar host galaxies with the Hubble Space Telescope.

1.1. Overview of the Field

This work concerns quasars and the galaxies with which they are associated. Quasars are energetic compact objects which produce copious amounts of electromagnetic radiation and can accelerate particles close to the speed of light. They reside at the cores of some galaxies, which are gravitationally bound concentrations of gas and billions of stars.

Quasar and galaxy studies are major subfields of astronomical research and have captivated many professional astronomers for decades. The number of papers in the refereed literature on these two broad topics exceeds 50,000. Numerous compelling issues and questions drive this fascination. Earth's sun formed within a galaxy, and the heavy elements essential to our existence were forged in previous generations of galactic stars. Galaxies are the most numerous discrete parcels of luminous matter discernable at any great distance beyond our galaxy, as individual stars are far too small and faint. This property makes galaxies critically important for studying the structure and evolution of the known universe. Quasars are exotic objects which provide an opportunity to examine physics in extreme gravitational, energy density, and velocity environments. The most widely held theory of their nature is that they are powered by the consumption of material by a gigantic (millions to billions of times the mass of the sun) black hole. Quasars and their host galaxies exist in symbiosis; material in the galaxy surrenders its gravitational potential energy to power the quasar mechanism, and the near light-speed jets emitted by the central engine can induce the formation of stars in the surrounding galaxy. The vast luminosity generated by some quasars, coupled with their compact

size, makes them effective identifiers of distant galaxies and probes of intergalactic gas clouds.

1.2. Early History of Galaxies

Nearby galaxies visible to the naked eye, such as our own Milky Way and the Large and Small Magellenic Clouds, were noted and recorded by early civilizations (Urton 1988; White 1997, personal communication). It is not clear whether some of these people speculated that these objects were vast collections of stars, the interpretation later revealed by telescopes. Published speculations that faint patches of light in the night sky were distant stellar conglomerations appeared as early as the mid eighteenth century (Wright 1750; Kant 1755).

Nearly 200 years of debate followed about the nature of these objects, often referred to as “nebulae.” Part of the difficulty arose because what are now known as very different objects, gas clouds in our own galaxy and separate galaxies at great distances, had been lumped together. The controversy became more focused in the first quarter of this century, with new data enabling a more quantitative discussion (Curtis 1921; Shapley 1921). The resolution came during the 1920s with the identification and measurement of Cepheid variable stars in nearby galaxies (e.g., Hubble 1926). Cepheids were known to possess a relationship between their period of variation and luminosity (Leavitt 1912), which enabled the star’s distance to be calculated once its apparent brightness was measured (Hertzsprung 1913; Shapley 1918). This technique placed several of the nebulae millions of light years away from Earth, a massive increase in the accepted size of the known universe.

Spectroscopic data revealed that the light from most measureable galaxies was predominantly redshifted (Slipher 1917). The Doppler effect provided a

ready explanation if most galaxies were moving away from us. However, this initially seemed to contradict the well-established philosophical principle that Earth is not at a special location in the universe, and it was expected that equal numbers would be blueshifted (Hubble 1936). Attempts to reduce the relative motions to a distribution centered on zero velocity by introduction of an additional somewhat arbitrary constant (Wirtz 1918; see also Seitter & Duerbeck 1990) became increasingly more complicated with the ever growing body of data (Wirtz 1922). Hubble (1929) demonstrated that the redshifts of galaxies in the relatively nearby universe are approximately linearly related to distance from the observer. The connection between distance and apparent recession velocity is a keystone of modern cosmology.

Two major models for the known universe based on Einstein's general theory of relativity emerged at about the same time as the early results on galaxy redshifts, but the observers and theoreticians apparently were initially unaware of each other's work. This early theoretical work was influenced by a philosophical predilection that the global structure of the universe is static, although objects within that structure certainly move. Einstein's initial solution to the field equations of general relativity produced a model universe which was expanding, and he introduced an additional term to prevent this (Einstein 1917; Kragh 1996). De Sitter's (1917) alternate model also had features of expansion, but he interpreted the equations in terms of a static universe (Kragh 1996). The first model to directly incorporate evolution into the structure of the universe (Friedmann 1922) was initially largely ignored or misunderstood (Kerszberg 1989). However, by the early 1930s the empirical and theoretical foundations of an expanding universe became more widely known (Ellis 1990), a framework which is still cogent today. The apparent velocities of galaxies and other distant objects have two components. The dominant one in

all but the closest galaxies arises from the expansion of the universe, producing a redshift in galaxy spectra which increases with distance of the galaxy from the observer. Motions of the individual galaxies within the structure of the universe are superimposed upon the cosmic expansion. The observations are consistent with a model of the universe which flows naturally from general relativity and predicts that a similar redshift phenomenon would be seen from any point in the universe, thereby avoiding the objectionable inference that the Earth is in a privileged location.

1.3. Early History of Quasars

It is generally accepted that quasars were discovered in 1960 (see Burbidge 1967 for a review). However, objects such as radio galaxies and Seyfert galaxies, which are now thought to contain mechanisms similar to those of quasars, were known prior to this date.

Seyfert (1943) examined a sample of unusual spiral galaxies which have very bright unresolved nuclei and emission lines from highly ionized atomic species. The lines in some of the galaxies are quite broad, which was attributed to high speed motion of the emitting plasma. This class of galaxies, later called Seyferts, was largely ignored until near the time of the discovery of quasars (Pacholczyk & Weymann 1968). Quasars, while generally much more luminous than Seyfert galaxies, have similar spectral and other characteristics. Many studies have probed the relationship between Seyferts and quasars, beginning with Burbidge, Burbidge, & Sandage (1963).

Studies of radio galaxies and improvements in the technology and techniques of radio astronomy led directly to the discovery of quasars. Relatively poor positional

accuracy had been a central problem in radio astronomy, making it difficult or impossible to identify a visible counterpart to a radio source in all but the most obvious cases such as bright galactic sources or nearby external galaxies. Mills (1952) found that the radio sources in his survey appeared to represent two distinct distributions in space, one associated with the plane of our galaxy and the other isotropic, possibly extragalactic. As the number of identifications of radio sources with external galaxies increased, it became apparent that some of these galaxies were extraordinarily luminous radio emitters with respect to typical nearby galaxies (Minkowski 1958).

Improvement in the positional accuracy of radio sources led to optical identifications with objects which were not particularly large, bright or otherwise conspicuous. One of these had a star-like appearance, but its spectrum was unlike any known star, containing unknown broad emission lines (Matthews et al. 1961). Eventually the mysterious spectral features in this and similar objects were recognized as highly redshifted lines of known ionic species (Schmidt 1963; Greenstein & Matthews 1963; Oke 1963). The redshifts came as a strong surprise (Schmidt 1983), despite the fact that radio galaxies with higher redshifts were known (Minkowski 1960). It had been believed that the star-like radio sources were part of a long-sought class of radio stars (Greenstein 1963; Sullivan 1990), which were not expected to have such large redshifts. The quasar redshifts, if assumed to result from cosmological expansion, implied that these objects were billions of light years away and had luminosities many times those of the brightest known galaxies. The extreme luminosities were particularly unusual, as variations in the brightnesses of some quasars (Matthews & Sandage 1963; Smith & Haffleit 1963; Sharov & Efremov 1963) implied that the emitting volume is more than a trillion times smaller than a typical galaxy.

Quasars were known as a class of radio emitting objects for several years following their discovery. However, star-like objects having optical properties similar to radio-selected quasars were discovered at locations which didn't correspond to any known radio sources (Sandage 1965). This meant that the definition of a quasar had to be changed to include strictly optical criteria, with strong radio emission a feature of some members of the class. The taxonomy of quasars has grown increasingly complex with observations at many different wavelengths and the discovery of new features, but the core of the classification is still the optical properties.

1.4. The Quasar-Galaxy Connection

Extended optical nebulosity was found in the immediate vicinity of the first quasar discovered (Matthews & Sandage 1963). The possibility that this was a galaxy associated with the quasar was considered and rejected as unlikely because the size would have been much larger than any known galaxy, and the quasar was not centered on the extended emission. Nevertheless, the large redshifts plus the suspected similarities between the mechanisms powering quasars and the active nuclei of Seyfert and radio galaxies gave rise to speculation that quasars might also reside at the centers of galaxies. Concentric extended emission observed around a few quasars (Arp 1970) provided some observational support for this view. It was understood that the ratio of the luminosity of an active nucleus to the surrounding star light, as well as the distance to the object, could have a significant effect on the object's classification (Sandage 1971). Kristian (1973) estimated the detectability of a host galaxy on deep photographic plates based on the distances and brightnesses of several known quasars and found non-stellar morphologies in

many cases where it was expected.

Observations of quasar host galaxies are very difficult because the surface brightness of the quasar is much larger than the underlying galaxy. This is exacerbated by atmospheric seeing, which smears out the light from the quasar regardless of the size or quality of the telescope, effectively hiding the galaxy in many cases (Greenstein & Schmidt 1964). Even when extended flux was visible, its interpretation was complicated by the fact that in some cases the source of the emission was line-emitting gas clouds rather than stars (Wampler et al. 1975; Stockton 1976). However, possible stellar features were found in low signal-to-noise spectra of extended emission around a small number of low-redshift quasars (Morton, Williams, & Green 1978; Wyckoff et al. 1980). The quantity of data supporting the existence of host galaxies continued to grow, as moderately sized imaging samples provided evidence that extended emission around many quasars was consistent with the morphologies, sizes, and brightnesses of galaxies (Hutchings et al. 1981; Wyckoff, Wehinger, & Gehren 1981). More and better quantitative estimates of host galaxy parameters became possible with the advent of CCD detectors (e.g., Smith et al. 1986; Véron-Cetty & Woltjer 1990), but nevertheless the results often had large uncertainties and/or were contradictory. Recent technological advances are driving substantial progress in host galaxy research. The refurbished Hubble Space Telescope is providing unprecedentedly high resolution images of quasar systems, and similar capabilities are expected from the ground in the near future using adaptive optics systems. In addition, the Keck telescopes are obtaining high quality spectra of the stellar component of the host galaxies.

1.5. Overview of the Present Work

This dissertation explores the connection between the radio and optical emission components of quasars and their relationship with the host galaxies. Quasars have been studied extensively in these two wavebands, both for the historical reasons outlined earlier and because the bulk of the radiation in each spectral region is generated by different physical mechanisms. It is generally accepted that radiation at radio frequencies is predominantly due to synchrotron processes, which depend on the energy distribution of relativistic particles and magnetic field strength. The source of the optical continuum and broad lines is an accretion disk and centrally concentrated hot gas clouds, respectively. Therefore the optical luminosity is closely tied to the accretion rate and the mass of the central engine. The ultimate goal of research in this area is to produce a comprehensive model of the quasar mechanism, including the connection between the fueling of the black hole, the gas and dust in the vicinity of the central engine, the method of particle acceleration, and the host galaxy and surrounding cluster environment.

Efforts to reach this goal generally follow one of two approaches: observe and model individual objects in detail; or study statistical trends in subsets of the quasar population. The present work is of the latter type. Quasar surveys based on a particular set of observed characteristics provide the raw material for this analysis. Many surveys have been conducted in a variety of wavebands, from radio to X-rays. The product desired from many such surveys is a catalog of all quasars which conform to a precise set of selection criteria. This is not possible in practice (Weedman 1986), but an achievable and very useful alternative is to determine a quantitative estimate of the degree of incompleteness, from which the intrinsic distribution of quasar properties can be inferred (Hewett & Foltz 1994).

Optical surveys conducted within the past decade have the advantages of machine analysis of the data and computer selection algorithms, which make it possible to calculate the probability of including any observed or modeled quasar based on its brightness, redshift, and spectrum. A particularly effective and relatively recent survey is the Large Bright Quasar Survey (LBQS; Hewett, Foltz, & Chaffee 1995), which contains more than 1000 quasars selected by quantifiable and well-defined optical criteria. The LBQS is the backbone of this dissertation, as all observations conducted by the author are of LBQS quasars.

Many of the questions addressed in this dissertation involve the fraction of optically selected quasars which are strong radio emitters, called radio-loud quasars. The relative frequency of radio-loud quasars has been an area of ongoing research since Sandage (1965) first discovered that the fraction is less than one. It has been difficult to obtain reliable values for the radio-loud fraction and its dependence on quasar optical luminosity and redshift. This, coupled with a close similarity in the optical properties of radio-loud and radio-quiet quasars, makes the connection between the two emission mechanisms difficult to model. In particular, this dissertation investigates the evolution of the radio-loud fraction and its dependence on optical luminosity, correlation between radio and optical fluxes, and the distribution of radio luminosity.

The connection between quasar radio and optical fluxes and the nature of the host galaxy is also explored, including the distribution of host luminosity and its correlation with the luminosity of the nuclear component. The question of whether the host galaxy morphologies in the LBQS sample are consistent with the conventional wisdom that radio-loud and radio-quiet quasars reside in elliptical and spiral galaxies, respectively, is addressed.

CHAPTER 2

PRESENT STUDY

The methods, results, and conclusions of this study are presented in the papers appended to this dissertation. The most important findings in each of these papers are summarized below. A global summary of the dissertation follows, including commentary and future plans.

2.1. Summary of Appendix A

Approximately one quarter (255 objects) of the Large Bright Quasar Survey has been observed at 8.4 GHz with the VLA in C configuration. The median 3 sigma noise limit was 0.29 mJy, and 45 objects (18%) were detected. The radio-loud (8.4 GHz luminosity $> 10^{25} \text{ W Hz}^{-1}$) fraction remains constant at $\sim 10\%$ from $z = 0.5$ to $z > 3.5$, and there is some evidence that this holds for $z < 0.5$. There is no correlation between radio luminosity and absolute blue magnitude for $M_B < -24$, and the radio-loud fraction does not depend on blue magnitude. However, the number of powerful radio sources with $M_B > -24$ drops precipitously; among 20 objects, none had detectable radio luminosity above $10^{23} \text{ W Hz}^{-1}$. The distribution

of $\log R$ (ratio of radio to optical luminosity) appears to be bimodal, with a gap at $\log R \sim 1$ for all redshifts and absolute magnitudes.

2.2. Summary of Appendix B

A sample of 103 quasars from the Large Bright Quasar Survey (LBQS) has been observed with the VLA at 8.4 GHz to study the evolution of the radio luminosity distribution and its dependence on absolute magnitude. Radio data from pointed observations are now available for 359 of the 1055 LBQS quasars. The radio-loud fraction is constant at $\approx 10\%$ over the absolute magnitude range $-28 \lesssim M_B \lesssim -23$, and it rises to $\sim 20\%$ ($\log R_{8.4} > 1$) or $\sim 35\%$ ($\log L_{8.4} > 25$) at the brightest absolute magnitudes in the sample. This nearly flat distribution differs markedly from those of the optically selected Palomar-Green (PG) Bright Quasar Survey and the X-ray selected Extended Medium Sensitivity Survey (EMSS), both of which have lower radio-loud fractions for absolute magnitudes fainter than $M_B = -24$ and higher fractions at brighter magnitudes. The reason for the high radio-loud fraction at bright absolute magnitudes in the PG, compared to the LBQS and other optically selected quasar surveys, is unknown. The trend of increasing radio-loud fraction with absolute magnitude in the EMSS is due at least in part to a correlation between X-ray and radio luminosity. Combining the LBQS data with radio studies of high-redshift quasars leads to the conclusion that the radio-loud fraction in optically selected quasars does not appear to evolve significantly, aside from a modest increase at $z \sim 1$, from $z = 0.2$ to redshifts approaching 5, a result that is contrary to previous studies which found a decrease in radio-loud fraction with increasing redshift by comparing the low- z fraction in the PG to higher redshift samples.

2.3. Summary of Appendix C

A sample of 16 quasars selected from the Large Bright Quasar Survey in the redshift range $0.4 < z < 0.5$ has been imaged in the R band with the Planetary Camera on the WFPC2 instrument of the Hubble Space Telescope. The host galaxy magnitudes are mostly similar to or brighter than L^* , and the host luminosity is positively correlated with the luminosity of the quasar nuclear component. There is no distinction in host galaxy magnitude between radio-loud and radio-quiet quasars, assuming they are all of the same galaxy type. Many of the host galaxies in the sample have small axial ratios, which may indicate that they are inclined disk systems. Alternatively, this elongated appearance may be due to bars or other distinctive morphological features which are visible while the bulk of the underlying lower surface brightness components of the host galaxy are not.

2.4. Summary of the Dissertation

Significant new results regarding the radio and optical properties of quasars and the connection between quasar emission and the host galaxy are presented in this dissertation. The foundation of the research is a large data set of radio and optical fluxes for close to 400 quasars chosen from the Large Bright Quasar Survey, a well-defined homogeneous sample. This subsample covers a redshift range that spans more than half of cosmic time and an absolute magnitude interval which includes most quasars. There are sufficient numbers of quasars in the sample to make meaningful statements about trends across these large ranges. In addition to standing on their own as a self-contained study, the LBQS data provide a good comparison for smaller, higher redshift samples. The combined data sets probe the behavior of the radio and optical properties over almost the entire period in which

quasars are known to exist.

The conventional picture of the distribution of radio-loud quasars at the onset of the research for this dissertation was somewhat complex. The radio-loud fraction was thought to evolve strongly from around 10% at high redshift to values as large as 50% for $z < 0.5$ (e.g., Schneider et al. 1992; Visnovsky et al. 1992). The proportion of radio-loud quasars was found to be greatest at very bright absolute magnitudes (absolute blue magnitude $M_B \lesssim -28$), decreasing among fainter quasars, particularly for $M_B \gtrsim -24$ (e.g., Peacock 1986). Some of the earlier results were based on LBQS data which have been incorporated into the sample used in the present work. Visnovsky et al. (1992) obtained radio fluxes for a sample of LBQS quasars at $z > 1$ to compare to the predominantly low redshift Palomar-Green (PG) optical quasar survey (Schmidt & Green 1983; radio data for the PG are in Kellermann et al. 1989). The radio-loud fraction in that LBQS sample was much lower than among the PG quasars, and like other workers who found similar values, they concluded that the radio properties of quasars have undergone significant evolution. No single survey had sufficient numbers of objects to independently determine the evolution of the radio-loud fraction over the full range of accessible redshifts, and all of the current studies at the time used the PG as a low redshift anchor point.

While a few of the results which emerged from the expanded LBQS sample are consistent with these earlier studies, many are quite different. No evolution is seen in the radio-loud fraction except for a moderate rise at $z \approx 1$, and the dependence of the radio-loud fraction on absolute magnitude is nearly flat except among the brightest quasars in the survey. There is no detectable correlation between radio and optical luminosity among the radio-loud quasars. The source of

this discrepancy with previous results is a fundamental difference between the radio properties of the PG and the LBQS plus virtually every other optically selected survey. La Franca et al. (1994) studied a composite sample comprised of several optically selected quasar surveys of small to moderate size, and they noted that evolution of the radio-loud fraction was apparent only if the PG was included. The remaining surveys provided no independent evidence for evolution.

Several arguments suggest that the LBQS results are more complete and accurate than previous studies, which did not have the advantage of a large modern survey with which to work: (1) the LBQS spans much of the relevant parameter space in a single homogeneous survey, which is well defined and effective at finding almost all known types of quasars; (2) the La Franca et al. (1994) results suggest that the radio-loud fraction in the PG is anomalously high; (3) an independent study using very different selection techniques (Bischof & Becker 1997) found similar results. The consistency of the LBQS findings with those of Bischof & Becker (1997) is particularly compelling, since the sample they used was quite large (4079 quasars) but was very heterogeneous, with sources selected by a wide variety of surveys at different wavelengths. This sample is likely rife with unknown biases, yet it still produced conclusions similar to those from the LBQS.

The reason for the uniqueness of the PG sample is an important question, especially given the large numbers of studies which have utilized PG quasars. However, the more fundamental issue is the somewhat counter-intuitive insensitivity of the radio-loud fraction to redshift and optical luminosity found in the LBQS and the Bischof & Becker (1997) samples. The same gravitational engine is presumably the ultimate power source for both radio and optical emission. A positive correlation between radio and optical luminosity would seem to be a natural

consequence of this mutual origin, yet this is not apparent among the radio-loud quasars. There is indirect evidence that such a correlation is present among the radio-quiet quasars in the LBQS sample. Two radio emission mechanisms may be in operation. One is driven by optical/UV radiation pressure (Stocke et al. 1992) and is present in many quasars. This process does not produce sufficient luminosity to exceed the radio-loud threshold except for quasars with the highest optical luminosities, which would account for the upturn in radio-loud fraction at $M_B \lesssim -28$. The other mechanism, which is responsible for the radio-loud quasars with $M_B > -28$, is decoupled from the optical luminosity and hence the mass accretion rate onto the central black hole (see e.g., Wilson & Colbert 1995). The lack of strong evolution must also be incorporated into any models used to explain the observed radio properties. The radio emission mechanisms must be mostly insensitive to the factors which have effected large changes in the luminosity functions of quasars over cosmic time.

While the consistency between the LBQS results and the Bischof & Becker (1997) study may indicate convergence on the radio properties of optically selected quasars, many refinements are needed, and the proposed models need to be tested against the data in detail. The next stage of this research will use the vast new radio surveys, National Radio Astronomy Observatory Very Large Array Sky Survey (NVSS; Condon et al. 1995) and Faint Images of the Radio Sky at Twenty-centimeters (FIRST; Becker, White, & Helfand 1995), to obtain radio fluxes or upper limits for the remaining quasars in the LBQS. The three-fold increase in sample size will reduce the errors on derived parameters. It is particularly important for models of the radio emission mechanisms to determine whether the increase in radio-loud fraction at bright absolute magnitudes is as strong as currently indicated. Bischof & Becker (1997) noted a downturn in the radio-loud

fraction for $z < 0.5$. The redshift range of the LBQS extends only to $z = 0.2$, but there may be enough overlap to test for this decrease in the full sample. The extended data base will also help to address the question of whether the distribution of radio luminosity is bimodal. Indications of a bimodal distribution led to the quantitative distinction between radio-loud and radio-quiet quasars, but the current LBQS radio sample is too small to rigorously test the existence of two modes. Subsequent research will include deeper radio observations of some LBQS quasars which currently have only upper limits in order to better constrain the nature of the radio-quiet quasars. This will be particularly important for evaluating the model which connects low-level radio emission to the optical luminosity of the quasar.

A subset of 16 LBQS quasars with radio data was selected for a study of the host galaxies using high-resolution Hubble Space Telescope (HST) imaging. The sample size necessarily had to be small, due to the demanding nature of the observations and the scarcity of HST time. This restriction placed a premium on careful sample selection. The targets were chosen based on three criteria: (1) a radio luminosity span typical of optically selected quasars; (2) nearly identical redshifts to avoid problems of interpretation due to evolution and to provide a uniform rest-frame spatial resolution scale; and (3) quasar absolute magnitudes bright enough to exclude Seyfert galaxies, yet not so bright that the nucleus completely obscures the host galaxy.

Research on quasar host galaxies has entered a new era after the refurbishment of HST, which has triggered rapid evolution in our understanding of this important aspect of the quasar phenomenon. The initial research programs after the repair mission examined a wide variety of quasars in an attempt to establish the range of

host galaxy properties and reveal rough trends with quasar type. This was a crucial first step, but it is difficult to determine the distribution of the host parameters from such a heterogeneous mix. The LBQS data are the first homogeneous sample and therefore will be quite valuable for statistical analysis. The work presented in this dissertation is helping to shape the new views by confirming some trends seen in earlier studies and pointing out new features of host galaxies.

Quasar host galaxies in the LBQS and other studies are rather luminous; most have luminosities near or above the level at which the space density of galaxies begins to decline exponentially. It is likely that the high luminosities reflect large stellar mass, suggesting that large black holes either cannot form or are not adequately fueled in small galaxies. However, the optical brightness can be strongly affected by star formation, so it is conceivable that some quasars could reside in relatively small galaxies which are actively forming stars. This concern led McLeod & Rieke (1995a,b) to examine low redshift quasars in the near infrared, which is less sensitive to star formation and more closely traces the mass-bearing older stellar population. They found that the host galaxies have a minimum infrared luminosity which is positively correlated with quasar luminosity, suggesting a connection between galaxy mass and quasar power. A similar trend is present in the LBQS sample after adjusting for the difference in observing passband.

Differentiation of host galaxy type by quasar radio luminosity was a major tenet of pre-HST work in this area. Radio-loud and radio-quiet quasars were thought to reside in elliptical and spiral galaxies, respectively (e.g., Smith et al. 1986). Most hosts examined to date with HST appear to be early type galaxies (Disney et al. 1995; Bahcall et al. 1997), including some radio-quiet quasars. It is very difficult to accurately determine the morphological type of a quasar host

galaxy, even with HST data, and this has not yet been done for the LBQS sample. However, the apparent shapes of the hosts in the LBQS sample provide important clues about the nature of the galaxies. Most of them appear highly elongated, to the point that they are inconsistent with being drawn from the standard population of elliptical galaxies. The galaxies could be inclined disk systems, which would run counter not only to the prevalence of ellipticals seen by other workers, but also to the high incidence of face-on systems in cases where spirals were found (McLeod & Rieke 1994). The elongated features could be bars, which would also indicate a large proportion of spiral hosts in the sample. Other possibilities include tidal distortions or gas ionized by the quasar. The observed features are unusual compared to other studies and represent new aspects of quasar host galaxies which need to be further explored.

Future work related to the HST study will include a more detailed analysis of the current data, high-resolution infrared imaging, and a study of the surrounding galaxy cluster environment. The current HST images will be further analyzed to determine the morphological type of each host galaxy, calculate uncertainties for the measured parameters, and look for nearby companion galaxies. Infrared data will be obtained in order to estimate the mass of the host galaxies and the nature of the stellar population. In particular, the new data may help determine whether the elongated features seen in the current sample are present in the older stellar population, are areas of strong star formation, or are gas clouds ionized by the quasar. A proposal to use the new NICMOS infrared camera on HST to observe the current sample has been submitted. Ground-based adaptive optics systems have also been used, but the difficulties of the project exceed the current capabilities of this technology. It is expected that the project will be feasible with adaptive optics in the relatively near future, as more advanced systems come on

line. Lower technology instruments also have a role. A wide field seeing-limited imaging program in both the optical and infrared passbands is ongoing. These data will be used to study the effect of the surrounding galaxy cluster environment on the quasar. This will be followed by spectroscopy of the companion galaxies to determine their individual redshifts and the velocity dispersion of the cluster.

In summary, this dissertation has significantly advanced our understanding of the radio properties of quasars. The picture has changed from one in which the radio-loud fraction undergoes substantial evolution and varies strongly with absolute magnitude to a population which is much less prone to change. In addition, major results on quasar host galaxies have been corroborated by a sample which is well suited to statistical analysis, and new features of host galaxy morphology have been revealed.

APPENDIX A.

RADIO PROPERTIES OF OPTICALLY SELECTED QUASARS

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RADIO PROPERTIES OF OPTICALLY SELECTED QUASARS

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ABSTRACT

Approximately one-quarter (256 objects) of the Large Bright Quasar Survey (LBQS) has been observed with the VLA at 8.4 GHz, resulting in 44 detections (17%) with a median 3σ noise limit of 0.29 mJy. Quasars with radio luminosity detectable at this limit are underrepresented at faint absolute blue magnitudes ($M_B \geq -24$), an effect which cannot be explained by a potential LBQS selection bias against quasars which have large radio luminosities and small optical luminosities. The radio-loud (8 GHz luminosity $> 10^{25}$ W Hz⁻¹) fraction is observed to change as a function of redshift and M_B , for $M_B < -24$, although the causal variable is ambiguous. The description most consistent with the available data is that radio-loud fraction is approximately constant over the range $-27.5 \leq M_B \leq -24$ and increases at brighter absolute magnitudes. The radio-loud fraction as a function of redshift reaches a local maximum at $z \approx 1$, and, aside from the effects of increased radio-loud fraction at bright M_B , remains roughly constant to redshifts approaching 5. The log $R_{8.4}$ distribution (radio-to-optical luminosity ratio) of the current LBQS sample may be bimodal, but the results of statistical tests are ambiguous, requiring a larger sample size to become definite.

Subject headings: quasars: general — radio continuum: galaxies — surveys

1. INTRODUCTION

A long-standing problem central to understanding the quasar phenomenon is the lack of a simple scaling between quasar radio and optical luminosity, the presence of which would result in a constant ratio of the luminosities in the two spectral regimes. The observed ratios of radio to optical luminosity, R , span several orders of magnitude. It is important to explain such a large spread, given that the radio and optical emission mechanisms are believed to be driven ultimately by the same central engine. The wide range of observed radio luminosity was once thought to arise from the orientation of a beamed relativistic jet (Scheuer & Readhead 1979), resulting in a spread in R if the optical emission is unbeamed or emitted in a jet with a different opening angle. However, a range in the luminosity of large-scale, nonbeamed radio emission indicates an intrinsic spread in radio power (Orr & Browne 1982). Coleman & Dopita (1992) hypothesized that quasar radio luminosity may depend on the angle of the accretion disk with respect to the rotation axis of the central supermassive black hole. The fundamental mechanism regulating radio emission may be connected in some way to the host galaxies of quasars, as is the case with radio galaxies and Seyfert galaxies. The results of some studies of quasar host galaxies are consistent with the stronger radio emitters residing in ellipticals and the radio-weak quasars existing in spirals, but these conclusions are not definitive (e.g., Smith et al. 1986; Véron-Cetty & Woltjer 1990).

Much of the basic data on the radio and optical properties of quasars has come from optical follow-up of radio surveys, such as the 2 CR (Spinrad et al. 1985), the 2 Jy survey of Wall & Peacock (1985), the 1 Jy survey (Kühr et al. 1981b), the S4 (Pauliny-Toth et al. 1978) and S5 (Kühr et al. 1981a) surveys to

a limiting flux of 0.5 Jy, and the 100 mJy Parkes Selected Regions (Dunlop et al. 1989). Optically derived redshifts have enabled the determination of a quasar radio luminosity function and its evolution to redshifts $z > 3$ (Dunlop & Peacock 1990).

Since the initial realization that not all quasars are strong radio emitters (Sandage 1965), several optically selected quasar samples have been observed at radio frequencies (e.g., Sramek & Weedman 1980; Condon et al. 1981; Marshall 1987; Miller, Peacock, & Mead 1990, hereafter MPM). Typically only 10%–40% of the quasars were detected, even in relatively deep radio observations, and the radio luminosities of most of these detections lie below the luminosity range sampled by the radio surveys. The Very Large Array¹ (VLA) observations of the Palomar-Green (Schmidt & Green 1983) Bright Quasar Survey by Kellerman et al. (1989, hereafter PG), which detected more than 80% of the 114 quasars in the survey, are a notable exception to the low detection rates. The PG sample is consistent with two simple models of the joint optical and radio luminosity function, in which the radio luminosity function is either independent of optical luminosity or, as hypothesized by Schmidt (1970), is parameterized by R , i.e., a function of the ratio of radio to optical luminosity. MPM found that the R parameterization is inconsistent with the radio luminosities of quasars with faint absolute magnitudes.

Quasars have been designated either radio-loud or radio-quiet based on a division in R (e.g., PG) or radio luminosity, L (e.g., Peacock, Miller, & Longair 1986; Stocke et al. (1992)

¹ The Very Large Array (VLA) of the National Radio Astronomy Observatory is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation

found statistical support for bimodal distributions in both $\log R$ and $\log L$. Recently, La Franca et al. (1994) have analyzed the redshift and absolute magnitude dependence of the fraction of radio-loud quasars using a data set consisting of most of the available optically selected samples with radio observations. They determined that the radio-loud fraction is substantially higher for quasars with $z < 1$, a result due to the fact that the predominantly low redshift PG sample has a high overall radio-loud fraction; evolution is not required for $z > 1$ if the PG is excluded. The radio-loud fraction was found to be higher at bright absolute magnitudes, regardless of whether or not the PG sample was included in the analysis.

The Large Bright Quasar Survey (LBQS) (Hewett, Foltz, & Chaffee 1995) consists of more than 1050 quasars with magnitudes $16.0 \leq m_B \leq 18.85$ and redshifts $0.2 \leq z \leq 3.4$. Positions, magnitudes, redshifts, and spectra for the entire sample are now published (Hewett et al. 1995, and references therein). The LBQS was compiled using well-defined selection criteria, applied to objective-prism spectra of a broadband flux-limited catalog of objects. Quasar candidates were selected from among the objective-prism spectra according to a number of color and spectral feature-based criteria. The aim was to identify essentially all known types of quasars or active galactic nuclei whose broadband fluxes placed them within the magnitude limits of the LBQS.

Hewett et al. (1995) discuss the properties of the LBQS in some detail. The smooth number-redshift relation and high surface density of objects demonstrate that the LBQS is as effective as any existing optical survey of quasars. Direct comparison of the LBQS catalog with other surveys undertaken using a broad range of techniques shows that the only class of known active galactic nuclei to which the survey is not sensitive is featureless objects with red spectral energy distributions, e.g., some radio-selected BL Lac objects. Important advantages of the survey relative to other samples include (a) the very low percentage of objects that remain spectroscopically unidentified; only eight objects compared to the total of 1055 confirmed quasars (<1%) remain unclassified, and (b) the inclusion of quasars whose direct images are resolved due to the presence of an underlying galaxy. The very small percentage of candidates that remain unidentified ensures that bias against objects with weak emission lines is negligible, while the inclusion of objects with nonstellar morphology is important when the properties of quasars with low redshifts $z < 0.5$ are considered. The probability of selecting a candidate is a function of its intrinsic spectral energy distribution, a property common to all quasar surveys based on observed-frame, magnitude-limited samples (see Hewett & Foltz 1994). However, with the exception of red featureless active galactic nuclei (AGNs) and large amplitude photometrically variable objects such as optically violent variable quasars, the LBQS appears to be free of significant variations in the probability of detecting quasars whose magnitudes place them within the broadband flux limits.

The initial radio observations of the LBQS (Visnovsky et al. 1992, hereafter Paper I) consisted of 124 quasars in the redshift range $1.0 < z < 3.0$, chosen to complement the predominantly low redshift PG. The present work presents the radio data for an additional 132 LBQS quasars, which, together with the data from Paper I, span the full redshift range of the LBQS. The enlarged sample enables an independent and self-contained analysis of the evolution of the distribution of radio strength and its dependence on optical luminosity. Optical spectral

properties, including broad absorption lines, of the LBQS radio sample are discussed in Francis, Hooper, & Impey (1993). Section 2 summarizes the observations and presents an analysis of the noise properties of the radio maps and the criteria for detection. Section 3 examines evidence for a bimodal distribution of radio strength and discusses evolution, correlation of radio strength with absolute magnitude, and potential selection effects. Section 4 summarizes the results. Details of a statistical test for a bimodal distribution and an examination of the impact of selection effects are presented in Appendices A and B, respectively.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Summary of Observations

VLA observations at 8.4 GHz of 124 LBQS quasars in the redshift range $1.0 < z < 3.0$ were presented in Paper I. Subsequent observations at the same frequency of 132 additional LBQS quasars extended the redshift range to $0.2 < z < 3.4$. Table 1 summarizes each observing run, listing the date, number of quasars observed, VLA array configuration, pixel size of the maps, and the average angular extent of the major and minor axes of the beams at half-maximum intensity. All of the observations were snapshots, with exposure times ranging from 7.5 to 11 minutes. Table 2 lists the objects in the combined sample as follows.

Column (1): object name, listed in order of increasing right ascension.

Column (2): apparent B magnitude, calculated as described in § 2.3.

Column (3): redshift from Hewett et al. (1995).

Column (4): absolute B magnitude, calculated as described in § 2.3.

Column (5): flux density (mJy) at 8.4 GHz and 1σ error, or 3σ upper limit, measured as described in § 2.2.

Column (6): logarithm of the ratio of 8.4 GHz luminosity (W Hz^{-1}) to optical luminosity (W Hz^{-1}) averaged over the B passband; $R_{8.4} = L_{8.4}/L_B$. See § 2.3.

Column (7): logarithm of 8.4 GHz luminosity (W Hz^{-1}), $\log L_{8.4}$. See § 2.3.

Standard AIPS software was employed to produce dirty total-intensity (Stokes I) maps for all fields. Those containing a strong source were subsequently CLEANed, with the exception of three previously catalogued sources: 1148–0007, a VLA calibrator; 1215+1121 (Bennett et al. 1986); and 1229–0207 (Kühr et al. 1981b). A noise analysis was performed on the VLA maps of the quasars listed in Paper I and the more recent sample of 132 objects. Quasars with measured radio flux above a preset multiple of the noise were considered to be detected, as described below.

TABLE 1
SUMMARY OF VLA OBSERVATIONS

Date	Number Observed	VLA Array Configuration	Pixel Size	FWHM Major ^a	FWHM Minor ^b
1989 May ^c	97	B,C	0.25	2.5	0.9
1989 Oct ^c	27	C,D	0.25	5.8	2.9
1990 Oct.....	50	C	0.60	3.7	2.7
1991 Jan.....	82	C	0.60	4.5	2.5

^a Average angular extent of the major axis of the beam profile at FWHM

^b Average angular extent of the minor axis of the beam profile at FWHM

^c These observations were also reported in Paper I

TABLE 2
RADIO AND OPTICAL OBSERVATIONS OF LBQS QUASARS

Source (1)	B (2)	z (3)	M_B (4)	$S_{8.4}$ (mJy) (5)	$\log R_{8.4}$ (6)	$\log L_{8.4}$ (WHz^{-1}) (7)
0006+0230	18.06	2.098	-27.11 ± 0.76	< 0.24	< 0.07	< 24.62
0006+0200	17.89	2.336	-27.39 ± 0.81	< 0.28	< 0.11	< 24.78
0009+0219	18.02	2.642	-27.69 ± 0.86	< 0.24	< 0.04	< 24.82
0013-0029	18.24	2.083	-26.92 ± 0.76	< 3.54	< 1.31	< 25.78
0018-0220	17.46	2.596	-28.19 ± 0.85	< 0.18	< -0.30	< 24.68
0019+0107	18.17	2.130	-27.03 ± 0.77	< 0.19	< 0.03	< 24.55
0025-0151	18.11	2.076	-27.03 ± 0.76	< 0.34	< 0.25	< 24.77
0027+0149	17.73	2.328	-27.55 ± 0.80	< 0.23	< -0.02	< 24.70
0028+0236	17.91	2.007	-27.17 ± 0.74	< 0.24	< 0.01	< 24.59
0040-2917	17.85	2.087	-27.31 ± 0.76	< 0.48	< 0.28	< 24.92
0041-2638	18.50	3.053	-27.88 ± 0.93	< 0.30	< 0.17	< 25.03
0041-2707	13.04	2.786	-27.89 ± 0.88	< 0.22	< -0.02	< 24.83
0041-2807	17.17	2.505	-28.35 ± 0.83	< 0.26	< -0.23	< 24.81
0041-2859	18.13	2.134	-27.08 ± 0.77	< 0.22	< 0.06	< 24.60
0042-2930	17.84	2.388	-27.51 ± 0.81	< 0.26	< 0.05	< 24.77
0045-3002	18.29	2.021	-26.80 ± 0.75	< 0.25	< 0.19	< 24.62
0047-2759	18.37	2.130	-26.83 ± 0.77	< 0.23	< 0.17	< 24.62
0048-2545	18.28	2.082	-26.88 ± 0.76	< 0.22	< 0.12	< 24.58
0049+0045	17.50	2.265	-27.70 ± 0.79	< 0.43	< 0.15	< 24.94
0050-2523	17.86	2.159	-27.38 ± 0.77	< 0.24	< -0.00	< 24.65
0052-0058	17.93	2.212	-27.24 ± 0.78	< 0.40	< 0.29	< 24.89
0053-0134	18.31	2.062	-26.82 ± 0.76	< 0.34	< 0.33	< 24.76
0100-3105	18.32	2.641	-27.39 ± 0.86	< 0.30	< 0.24	< 24.91
0105-2649	17.70	2.463	-27.75 ± 0.83	0.92 ± 0.07	0.53 ± 0.39	25.34 ± 0.21
0109+0213	17.66	2.343	-27.63 ± 0.81	0.31 ± 0.06	0.07 ± 0.39	24.83 ± 0.22
0252+0136	17.87	2.465	-27.58 ± 0.83	< 0.36	< 0.19	< 24.93
0254+0000	18.16	2.247	-27.03 ± 0.79	< 0.21	< 0.11	< 24.64
0256-0000	18.54	3.364	-28.43 ± 0.97	6.25 ± 0.19	1.34 ± 0.46	26.42 ± 0.25
0258+0210	17.99	2.524	-27.56 ± 0.84	< 1.47	< 0.83	< 25.56
0302-0019	18.13	3.281	-28.66 ± 0.96	0.63 ± 0.08	0.23 ± 0.46	25.41 ± 0.25
0307-0058	17.93	2.106	-27.25 ± 0.76	< 0.28	< 0.09	< 24.69
1009-0252	17.69	2.746	-28.18 ± 0.87	< 0.29	< -0.04	< 24.93
1010+0219	17.68	0.222	-22.83 ± 0.35	< 0.37	< 0.06	< 22.90
1011-0144	17.91	2.236	-27.27 ± 0.79	< 0.22	< 0.03	< 24.65
1013+0124	16.68	0.779	-26.44 ± 0.43	137.0 ± 5.6	2.26 ± 0.20	26.54 ± 0.10
1014+0023	18.22	2.291	-27.01 ± 0.80	< 0.26	< 0.21	< 24.73
1019+0147	17.36	0.791	-25.79 ± 0.44	< 0.29	< -0.13	< 23.88
1021-0250	17.44	0.496	-24.70 ± 0.37	< 0.29	< -0.09	< 23.49
1021-0118	17.93	0.743	-25.08 ± 0.44	< 0.29	< 0.09	< 23.83
1026-0144	17.13	0.217	-23.33 ± 0.34	< 0.32	< -0.22	< 22.81
1027-0114	17.62	0.958	-25.93 ± 0.49	< 0.32	< 0.01	< 24.09
1128+0022	18.02	1.379	-26.24 ± 0.60	< 0.23	< 0.06	< 24.26
1129-0218	17.43	1.247	-26.64 ± 0.57	< 0.22	< -0.21	< 24.15
1129-0229	17.74	0.333	-23.59 ± 0.36	< 0.23	< -0.09	< 23.05
1130+0018	18.20	1.255	-25.87 ± 0.58	< 0.31	< 0.25	< 24.31
1131-0039	17.91	0.268	-22.98 ± 0.36	< 0.40	< 0.18	< 23.09
1132-0302	17.01	0.237	-23.63 ± 0.34	< 0.40	< -0.17	< 22.98
1132-0054	18.11	2.753	-27.77 ± 0.88	< 0.21	< -0.01	< 24.79
1132-0013	17.77	0.955	-25.78 ± 0.49	< 0.52	< 0.28	< 24.30
1135+0044	17.52	0.803	-25.67 ± 0.45	< 0.30	< -0.05	< 23.92
1135-0255	18.30	2.407	-27.08 ± 0.82	< 0.27	< 0.24	< 24.78
1137+0110	18.24	1.138	-25.64 ± 0.55	70.19 ± 2.37	2.61 ± 0.25	26.57 ± 0.13
1138-0107	18.17	2.754	-27.72 ± 0.88	< 0.23	< 0.03	< 24.83
1138+0003	17.93	0.500	-24.23 ± 0.39	37.73 ± 0.81	2.20 ± 0.17	25.60 ± 0.07
1138+0204	17.64	0.383	-23.97 ± 0.36	< 5.14	< 1.20	< 24.50
1139-0257	18.09	1.028	-25.59 ± 0.52	< 0.22	< 0.05	< 24.00
1141-0222	18.09	1.394	-26.19 ± 0.61	< 0.19	< 0.01	< 24.20
1141+0227	17.72	0.216	-22.73 ± 0.36	< 0.24	< -0.10	< 22.69
1145-0039	18.14	1.941	-26.87 ± 0.73	< 0.22	< 0.06	< 24.52
1145-0216	17.78	0.566	-24.63 ± 0.40	< 0.73	< 0.43	< 23.99
1145+0235	17.92	1.217	-26.10 ± 0.56	0.27 ± 0.07	0.07 ± 0.29	24.22 ± 0.18
1146+0207	18.34	2.054	-26.79 ± 0.75	< 0.26	< 0.22	< 24.64

TABLE 2—Continued

Source (1)	B (2)	z (3)	M_B (4)	$S_{8.4}$ (mJy) (5)	$\log R_{8.4}$ (6)	$\log L_{8.4}$ (WHz^{-1}) (7)
1148-0128	16.67	0.460	-25.32 ± 0.36	< 0.40	< -0.26	< 23.56
1148-0007	17.29	1.976	-27.75 ± 0.73	1201 ± 27	3.46 ± 0.35	28.27 ± 0.18
1148-0033	17.76	0.800	-25.42 ± 0.45	4.14 ± 0.12	1.17 ± 0.21	25.04 ± 0.10
1148+0055	18.19	1.885	-26.75 ± 0.72	< 0.25	< 0.14	< 24.55
1149+0043	17.07	0.466	-24.94 ± 0.36	< 0.49	< -0.02	< 23.66
1150+0127	17.80	1.636	-26.82 ± 0.66	< 0.20	< -0.08	< 24.35
1150+0041	17.65	0.781	-25.47 ± 0.45	< 0.28	< -0.03	< 23.86
1203+1043	17.96	1.333	-26.23 ± 0.60	< 0.45	< 0.31	< 24.51
1204+0935	17.88	1.559	-26.63 ± 0.65	< 0.23	< 0.00	< 24.36
1204+1136	18.08	1.010	-25.58 ± 0.52	< 0.38	< 0.27	< 24.21
1205+1729	17.12	0.548	-25.22 ± 0.40	< 0.30	< -0.20	< 23.59
1206+1318	17.94	1.334	-26.26 ± 0.60	< 0.21	< -0.01	< 24.19
1206+1500	18.07	2.595	-27.58 ± 0.85	< 0.33	< 0.20	< 24.94
1206+1716	18.13	1.012	-25.53 ± 0.52	< 0.35	< 0.26	< 24.18
1208+1250	16.88	1.002	-26.75 ± 0.50	0.26 ± 0.07	-0.36 ± 0.26	24.04 ± 0.16
1208+1535	17.97	1.961	-27.06 ± 0.74	< 0.20	< -0.02	< 24.50
1209+1046	17.73	2.187	-27.54 ± 0.78	< 0.48	< 0.24	< 24.96
1209+1524	18.50	3.059	-27.88 ± 0.93	< 0.34	< 0.22	< 25.09
1210+1731	17.44	2.543	-28.14 ± 0.84	< 0.24	< -0.16	< 24.79
1210+1507	17.29	1.613	-27.29 ± 0.66	0.23 ± 0.073	-0.23 ± 0.34	24.39 ± 0.21
1210+1425	17.95	0.723	-24.99 ± 0.45	< 0.21	< -0.03	< 23.67
1210+1324	17.62	1.141	-26.27 ± 0.55	429.8 ± 4.9	3.14 ± 0.25	27.36 ± 0.13
1211+0848	17.87	0.810	-25.33 ± 0.47	7.06 ± 0.15	1.44 ± 0.21	25.29 ± 0.10
1211+1106	17.73	1.337	-26.47 ± 0.60	< 0.38	< 0.14	< 24.44
1211+0841	17.65	0.585	-24.83 ± 0.41	< 0.96	< 0.50	< 24.14
1212+1445	17.94	1.656	-26.70 ± 0.67	0.45 ± 0.07	0.31 ± 0.32	24.70 ± 0.18
1212+0830	18.12	1.664	-26.53 ± 0.67	< 0.29	< 0.19	< 24.51
1212+1045	17.79	1.970	-27.25 ± 0.74	< 0.34	< 0.12	< 24.73
1212+0854	18.22	2.344	-27.07 ± 0.81	< 0.67	< 0.62	< 25.15
1212+1411	18.03	0.847	-25.27 ± 0.48	< 0.25	< 0.07	< 23.89
1213+1015	18.28	2.513	-27.25 ± 0.84	< 0.34	< 0.31	< 24.92
1213+0922	18.15	2.714	-27.67 ± 0.87	30.61 ± 1.13	2.16 ± 0.41	26.94 ± 0.22
1213+1208	17.31	1.486	-27.09 ± 0.63	< 0.41	< 0.03	< 24.57
1213+1722	18.08	1.205	-25.91 ± 0.57	< 0.35	< 0.25	< 24.33
1213+1709	17.75	1.196	-26.23 ± 0.56	< 0.21	< -0.10	< 24.09
1214+1804	16.73	0.374	-24.84 ± 0.36	< 0.31	< -0.36	< 23.27
1214+1753	17.68	0.679	-25.12 ± 0.43	< 0.21	< -0.12	< 23.62
1214+0826	17.30	0.343	-24.09 ± 0.37	< 0.26	< -0.22	< 23.12
1215+1202	18.28	2.841	-27.73 ± 0.89	< 0.23	< 0.06	< 24.86
1215+1121	16.62	1.398	-27.66 ± 0.60	133.9 ± 6.6	2.25 ± 0.28	27.03 ± 0.15
1216+1754	18.13	1.810	-26.72 ± 0.71	49.76 ± 2.62	2.42 ± 0.33	26.81 ± 0.18
1216+1032	17.62	0.542	-24.70 ± 0.40	< 0.31	< 0.00	< 23.58
1216+1656	18.26	2.818	-27.72 ± 0.89	< 0.25	< 0.09	< 24.89
1218+1611	17.78	0.231	-22.81 ± 0.38	< 0.21	< -0.13	< 22.69
1220+0939	17.62	0.681	-25.18 ± 0.43	0.50 ± 0.11	0.21 ± 0.22	23.99 ± 0.13
1222+1640	17.78	0.549	-24.57 ± 0.41	< 0.25	< -0.02	< 23.50
1222+1433	17.02	1.337	-27.18 ± 0.59	< 0.24	< -0.33	< 24.25
1222+1235	17.45	0.412	-24.31 ± 0.38	21.80 ± 0.43	1.76 ± 0.16	25.19 ± 0.06
1222+0901	17.89	0.535	-24.40 ± 0.41	< 0.28	< 0.07	< 23.54
1222+1334	17.99	1.796	-26.84 ± 0.70	< 0.20	< -0.02	< 24.42
1223+1723	18.14	2.402	-27.23 ± 0.82	< 0.47	< 0.42	< 25.03
1224+1244	18.39	2.156	-26.84 ± 0.78	< 0.44	< 0.46	< 24.91
1224+1538	18.05	1.771	-26.75 ± 0.70	< 0.23	< 0.07	< 24.48
1225+1502	17.88	0.856	-25.45 ± 0.48	< 0.24	< -0.01	< 23.87
1225+0836	17.85	1.471	-26.53 ± 0.63	< 0.35	< 0.17	< 24.49
1225+1512	18.10	1.990	-26.96 ± 0.74	< 0.23	< 0.08	< 24.57
1226+1526	18.22	1.122	-25.63 ± 0.55	< 0.28	< 0.21	< 24.17
1228+1642	17.59	0.841	-25.70 ± 0.47	< 0.31	< -0.01	< 23.97
1228+1116	17.42	0.237	-23.22 ± 0.37	< 0.39	< -0.02	< 22.97
1228+1808	18.17	2.649	-27.55 ± 0.86	< 0.32	< 0.21	< 24.94
1228+1216	17.55	1.408	-26.74 ± 0.61	< 0.55	< 0.25	< 24.65
1228+1602	17.76	0.511	-24.45 ± 0.40	< 0.28	< 0.00	< 23.49

TABLE 2—Continued

Source (1)	B (2)	z (3)	M_B (4)	$S_{0.4}$ (mJy) (5)	$\log R_{0.4}$ (6)	$\log L_{0.4}$ ($W\text{Hz}^{-1}$) (7)
1229+1133	18.39	1.028	-25.29 ± 0.53	< 0.32	< 0.32	< 24.14
1229-0207	17.69	1.045	-26.03 ± 0.52	283.9 ± 23.9	2.59 ± 0.24	27.11 ± 0.12
1229+0106	18.02	0.477	-24.04 ± 0.40	< 0.26	< 0.08	< 23.41
1229+1250	17.95	1.246	-26.12 ± 0.58	< 0.32	< 0.15	< 24.31
1230+1042	18.37	2.420	-27.03 ± 0.82	< 0.33	< 0.36	< 24.88
1230+1430	17.67	0.332	-23.66 ± 0.38	< 0.35	< 0.04	< 23.21
1230-0015	17.03	0.470	-25.00 ± 0.38	63.33 ± 1.91	2.06 ± 0.16	25.77 ± 0.06
1230+1627B	17.79	2.700	-28.02 ± 0.87	< 0.24	< -0.07	< 24.84
1230+1052	17.64	1.377	-26.62 ± 0.60	< 0.26	< -0.03	< 24.31
1230+0947	18.17	0.415	-25.61 ± 0.35	< 0.30	< -0.59	< 23.35
1231+0816	18.30	1.510	-26.13 ± 0.64	< 0.25	< 0.21	< 24.38
1231+0813	18.09	1.190	-25.89 ± 0.56	< 0.26	< 0.13	< 24.19
1233+1524	18.11	1.544	-26.38 ± 0.65	< 0.26	< 0.14	< 24.40
1234+0209	17.80	1.620	-26.79 ± 0.66	< 0.34	< 0.14	< 24.56
1234+0122	18.04	2.025	-27.05 ± 0.75	< 1.06	< 0.71	< 25.24
1235+0857	18.32	2.898	-27.79 ± 0.90	0.41 ± 0.08	0.29 ± 0.44	25.12 ± 0.25
1235+0216	17.68	0.672	-25.09 ± 0.43	< 0.20	< -0.16	< 23.58
1235+1807B	18.89	0.449	-25.05 ± 0.37	1.68 ± 0.26	0.43 ± 0.17	24.16 ± 0.09
1236+1543	17.64	0.315	-23.58 ± 0.37	< 0.31	< -0.01	< 23.12
1236+1308	18.14	1.303	-26.01 ± 0.59	< 0.26	< 0.15	< 24.26
1236+0128	17.66	1.262	-26.43 ± 0.58	< 0.43	< 0.17	< 24.45
1236+0903	17.58	0.498	-24.57 ± 0.39	< 0.39	< 0.08	< 23.62
1236+1103	17.85	1.304	-26.30 ± 0.59	< 0.28	< 0.07	< 24.29
1236-0207	18.21	2.244	-26.98 ± 0.79	< 0.32	< 0.30	< 24.80
1237+1752	17.63	0.913	-25.82 ± 0.49	< 0.31	< 0.00	< 24.04
1237+0834	18.25	1.075	-25.52 ± 0.54	< 0.23	< 0.14	< 24.06
1237+1042	18.23	1.030	-25.46 ± 0.53	< 0.23	< 0.12	< 24.01
1237+1325	17.95	1.727	-26.79 ± 0.69	< 0.28	< 0.11	< 24.53
1237+0950	17.93	0.736	-25.05 ± 0.45	< 0.30	< 0.10	< 23.83
1237+0204	17.53	0.665	-25.22 ± 0.43	< 0.37	< 0.05	< 23.84
1238+1006	18.11	1.046	-25.61 ± 0.53	< 0.22	< 0.06	< 24.01
1238+0039	18.24	1.361	-26.00 ± 0.61	< 0.35	< 0.32	< 24.43
1238+1013	18.21	1.184	-25.76 ± 0.56	< 0.20	< 0.07	< 24.08
1239-0231	17.75	1.234	-26.30 ± 0.57	< 0.32	< 0.07	< 24.30
1239+0028	17.49	1.214	-26.52 ± 0.56	0.38 ± 0.09	0.05 ± 0.28	24.37 ± 0.17
1239+1435	17.91	1.948	-27.11 ± 0.73	< 0.33	< 0.15	< 24.71
1240+0224	17.98	0.790	-25.16 ± 0.46	0.47 ± 0.11	0.41 ± 0.31	24.63 ± 0.18
1240+1754	17.64	0.458	-24.54 ± 0.38	< 0.33	< -0.05	< 23.47
1240+0728	18.02	1.861	-26.89 ± 0.71	< 0.22	< 0.02	< 24.49
1241+1228	17.86	0.320	-23.39 ± 0.38	< 0.27	< 0.01	< 23.08
1242-0173	17.26	0.491	-24.76 ± 0.39	< 0.28	< -0.14	< 23.47
1242+1749	17.70	0.264	-23.16 ± 0.37	< 0.30	< -0.02	< 22.95
1242+0006	17.78	2.075	-27.27 ± 0.76	< 0.31	< 0.06	< 24.72
1243+1737	17.85	1.863	-27.06 ± 0.71	< 0.21	< -0.04	< 24.48
1243+1456	17.63	0.582	-24.84 ± 0.41	< 0.36	< 0.08	< 23.72
1243-0011	18.26	1.683	-26.42 ± 0.68	< 0.33	< 0.30	< 24.58
1243+1701	17.64	0.459	-24.34 ± 0.39	< 0.28	< -0.03	< 23.41
1244+1703	17.53	1.588	-27.02 ± 0.65	< 0.22	< -0.14	< 24.37
1244+0240	17.94	0.934	-25.57 ± 0.50	< 0.26	< 0.04	< 23.98
1244+1329	17.10	0.512	-25.11 ± 0.38	< 0.39	< -0.10	< 23.64
1245+0126	17.58	0.346	-23.83 ± 0.37	< 0.30	< -0.04	< 23.19
1245+1719	17.79	0.752	-25.25 ± 0.45	< 0.29	< 0.03	< 23.84
1246-0059	17.90	2.442	-27.53 ± 0.83	< 0.29	< 0.11	< 24.83
1246+0032	18.16	2.305	-27.06 ± 0.80	< 0.25	< 0.32	< 24.87
1246-0217	18.14	2.106	-27.04 ± 0.76	< 0.25	< 0.12	< 24.64
1247-0213	18.05	1.313	-26.11 ± 0.59	< 0.30	< 0.17	< 24.33
1308-0104	18.10	2.584	-27.53 ± 0.82	< 0.30	< 0.16	< 24.89
1308+0109	18.11	1.075	-25.66 ± 0.52	32.93 ± 0.72	2.22 ± 0.24	26.19 ± 0.12
1311+0217	16.99	0.306	-24.17 ± 0.31	< 0.45	< -0.11	< 23.25
1313+0111	18.28	1.569	-26.24 ± 0.64	< 0.35	< 0.34	< 24.54
1313-0138	17.72	0.406	-24.00 ± 0.34	< 0.41	< 0.15	< 23.47

TABLE 2—Continued

Source (1)	B (2)	z (3)	M_B (4)	$S_{8.4}$ (mJy) (5)	$\log R_{8.4}$ (6)	$\log L_{8.4}$ (WHz^{-1}) (7)
1313+0107	18.16	2.393	-27.20 ± 0.81	3.91 ± 0.11	1.35 ± 0.39	25.94 ± 0.21
1314-0008	18.22	1.747	-26.55 ± 0.68	< 0.31	< 0.26	< 24.59
1315+0127	17.93	1.628	-26.68 ± 0.66	< 0.29	< 0.12	< 24.50
1315+0140	17.99	0.689	-24.84 ± 0.42	0.34 ± 0.08	0.19 ± 0.22	23.83 ± 0.14
1316+0023	17.91	0.492	-24.22 ± 0.37	< 0.26	< 0.04	< 23.44
1317-0142	17.26	0.225	-23.27 ± 0.31	0.41 ± 0.11	-0.06 ± 0.17	22.95 ± 0.12
1317-0018	17.76	0.354	-23.69 ± 0.34	< 0.23	< -0.07	< 23.10
1319+0039	17.95	1.619	-26.64 ± 0.65	53.29 ± 1.07	2.38 ± 0.31	26.75 ± 0.16
1319+0033	18.01	0.530	-24.26 ± 0.38	< 0.40	< 0.27	< 23.68
1320+0048	18.25	1.954	-26.78 ± 0.73	< 0.31	< 0.26	< 24.68
1320-0006	18.22	1.388	-26.05 ± 0.60	< 0.35	< 0.31	< 24.44
1320+0103	18.15	1.776	-26.66 ± 0.69	0.33 ± 0.08	0.26 ± 0.34	24.63 ± 0.20
1321-0145	17.71	0.224	-22.81 ± 0.32	< 0.27	< -0.06	< 22.77
1323-0248	17.44	2.120	-27.76 ± 0.76	15.96 ± 0.29	1.64 ± 0.36	26.45 ± 0.19
1324+0039	18.26	1.061	-25.48 ± 0.52	53.99 ± 1.80	2.50 ± 0.24	26.40 ± 0.12
1326+0206	17.35	1.416	-26.95 ± 0.60	< 0.39	< 0.02	< 24.51
1329+0242	17.82	1.583	-26.72 ± 0.65	< 0.24	< 0.00	< 24.40
1329+0018	18.24	2.351	-27.07 ± 0.81	< 0.31	< 0.30	< 24.83
1330+0113	18.13	1.511	-26.30 ± 0.63	< 0.24	< 0.12	< 24.35
1331-0108	17.92	1.881	-27.02 ± 0.71	0.68 ± 0.08	0.47 ± 0.34	24.99 ± 0.19
1332-0045	17.44	0.672	-25.33 ± 0.41	< 0.33	< -0.03	< 23.80
1333+0133	17.95	1.577	-26.59 ± 0.65	0.26 ± 0.08	0.07 ± 0.33	24.42 ± 0.21
1334-0033	17.52	2.801	-28.43 ± 0.88	0.20 ± 0.06	-0.29 ± 0.44	24.78 ± 0.27
1334+0212	17.85	2.382	-27.50 ± 0.81	< 0.30	< 0.11	< 24.82
1334-0232	17.66	0.722	-25.28 ± 0.43	< 0.40	< 0.13	< 23.95
1337-0146	17.54	1.014	-26.12 ± 0.51	< 0.24	< -0.13	< 24.01
1338-0030	17.25	0.385	-24.37 ± 0.35	< 0.30	< -0.17	< 23.28
1340-0038	16.98	0.326	-24.31 ± 0.33	< 0.17	< -0.52	< 22.90
1340+0107	18.15	1.067	-25.61 ± 0.52	< 0.26	< 0.13	< 24.09
1342-0000	17.77	0.244	-22.93 ± 0.35	< 0.26	< -0.05	< 22.82
1343-0221	17.99	0.509	-24.21 ± 0.38	0.72 ± 0.21	0.51 ± 0.21	23.90 ± 0.14
1344+0137	17.42	1.913	-27.56 ± 0.72	< 0.27	< -0.12	< 24.61
1344-0105	17.70	1.737	-27.05 ± 0.68	< 0.26	< -0.02	< 24.50
1345-0137	18.30	1.929	-26.70 ± 0.73	< 0.33	< 0.30	< 24.69
1346+0007	18.16	1.128	-25.70 ± 0.54	< 0.23	< 0.10	< 24.09
1346-0251	17.75	1.715	-26.97 ± 0.68	< 0.27	< 0.01	< 24.51
1347-0026	17.68	0.515	-24.54 ± 0.38	< 0.33	< 0.04	< 23.57
1348-0054	18.15	1.474	-26.23 ± 0.63	< 0.30	< 0.23	< 24.43
1348+0118	17.09	1.089	-26.71 ± 0.52	< 0.28	< -0.25	< 24.14
1349+0057	17.71	1.144	-26.18 ± 0.54	< 0.29	< 0.01	< 24.20
1428+0202	17.90	2.106	-27.28 ± 0.76	< 0.24	< 0.00	< 24.62
1429-0100	17.06	0.659	-25.67 ± 0.41	< 0.44	< -0.06	< 23.91
1429-0036	17.80	1.180	-26.16 ± 0.56	< 0.76	< 0.47	< 24.64
1429+0127	18.14	1.092	-25.66 ± 0.54	< 0.26	< 0.13	< 24.11
1429-0053	17.74	2.078	-27.41 ± 0.76	< 1.15	< 0.62	< 25.29
1429+0137	17.80	1.533	-26.67 ± 0.64	< 0.27	< 0.03	< 24.41
1430-0046	17.79	1.023	-25.88 ± 0.52	14.97 ± 0.31	1.75 ± 0.24	25.81 ± 0.12
1430-0041	16.40	1.116	-27.44 ± 0.53	0.27 ± 0.09	-0.53 ± 0.28	24.15 ± 0.19
1433+0223	18.27	2.140	-26.95 ± 0.77	< 0.83	< 0.69	< 25.17
1435-0134	16.01	1.310	-28.15 ± 0.57	67.75 ± 0.98	1.71 ± 0.27	26.68 ± 0.14
1435+0228	18.16	1.676	-26.51 ± 0.68	< 0.25	< 0.15	< 24.46
1437+0224	17.66	0.821	-25.57 ± 0.46	< 0.31	< 0.01	< 23.95
1438+0002	17.84	1.446	-26.50 ± 0.62	< 0.32	< 0.12	< 24.43
1440+0149	18.20	1.169	-25.74 ± 0.56	< 0.46	< 0.41	< 24.42
1440-0024	17.88	1.815	-26.97 ± 0.70	< 0.24	< 0.01	< 24.51
1440+0154	17.18	1.359	-27.05 ± 0.60	< 0.27	< -0.21	< 24.31
1440-0234	17.30	0.678	-25.49 ± 0.42	< 0.26	< -0.19	< 23.71
1441+0142	17.19	0.296	-23.91 ± 0.36	< 0.29	< -0.22	< 23.04
1442-0011	18.24	2.226	-26.94 ± 0.79	< 0.41	< 0.42	< 24.90
1443+0141	18.22	2.451	-27.21 ± 0.83	0.49 ± 0.14	0.47 ± 0.41	25.06 ± 0.25
1445-0231	18.09	1.734	-26.66 ± 0.69	< 0.23	< 0.07	< 24.44
2206-1958A	17.56	2.558	-28.04 ± 0.85	< 0.27	< -0.08	< 24.84
2209-1842	17.74	2.092	-27.42 ± 0.76	< 0.25	< -0.03	< 24.63
2212-1759	17.94	2.217	-27.23 ± 0.79	< 0.27	< 0.12	< 24.72
2230+0232	18.14	2.147	-27.08 ± 0.77	< 0.35	< 0.27	< 24.81
2231-0015	17.74	3.015	-28.57 ± 0.92	0.51 ± 0.09	0.11 ± 0.44	25.25 ± 0.25
2241+0014	17.65	2.131	-27.55 ± 0.76	< 0.20	< -0.16	< 24.56
2243+0141	18.26	2.314	-26.99 ± 0.80	< 0.23	< 0.18	< 24.69
2244-0105	17.99	2.030	-27.11 ± 0.75	< 0.26	< 0.09	< 24.64
2248+0127	18.23	2.559	-27.37 ± 0.85	< 0.26	< 0.17	< 24.83

2.2. Noise Analysis and Source Detection

A procedure was developed in Paper I to fit the core of each beam to various regions of the associated map. The core is chosen to extend to approximately the first minimum of the beam profile. To fit this core to a region centered on an arbitrary pixel in the map, the beam is translated without rotation to the desired location, and a least-squares fit is performed by minimizing

$$X = \sum_{i=1}^n (m_i - fb_i)^2, \quad (1)$$

where m_i and b_i are the intensity values of the i th pixel in the overlap of the map and the beam core, respectively. The number of pixels in the fitted region is n , and f is a scale factor for the beam, which is adjusted to minimize the value of X . The value of f at a minimum X is the flux in Jy assigned to the map pixel, since the beam represents the intensity distribution of a 1 Jy point source.

The noise estimate for maps without strong sources was obtained by performing the fitting routine on pixels randomly distributed across the map. The number of random points was chosen to keep the coincidence rate $\leq 5\%$.

All but a few of the maps produced noise distributions which closely approximated a Gaussian with a mean of zero. The cumulative distributions of fluxes from the random sampling of apparently empty maps indicate that the probability of obtaining a 3σ or greater positive fluctuation is 1.8 times greater than the value expected for a Gaussian noise model: $1.8(1.35 \times 10^{-3}) = 2.4 \times 10^{-3}$. The excess of positive fluctuations may be due to weak sources in the maps, or it may be due to part of the sidelobe patterns from unknown off-map sources. A few of the nondetections have 3σ upper limits much higher than the typical values (see Table 2). Most of these high limits are due to observed nearby strong sources.

The beam was fitted to each pixel whose center was within $2''$ of the center of the map to determine whether a source is present, and, if so, to measure its position. If the maximum flux assigned to any pixel within this area, $f_{\max}$, equaled or exceeded 3 times the rms noise of the map (3σ), then a detection of $f_{\max}$ Jy was adopted for the object. Table 2 contains the results of this analysis for both the sample from Paper I and the new observations: fluxes with 1σ noise values for 44 detections and 3σ upper limits for the remaining quasars. The pointing accuracy of the VLA is generally much better than the astrometric accuracy of the LBQS; the latter is estimated to be $\leq 2''$ for the original quasar positions (Morris et al. 1991, and references therein), which were the coordinates used in the VLA observations. An internal consistency check of the positional accuracy was performed by analyzing the data using a $4.5''$ search radius. Every strong source ($f_{\max} > 7\sigma$) discovered in this test, with the exception of one, lay within $2''$ of the map center. The exception, 1229-0207, is located $\approx 8''$ from the center of the map. Since the LBQS coordinates differ by less than $3''$ from the position of a VLBI source (Wehrle, Morabito, & Preston 1984), it is assumed that the VLA was misaligned and the radio source is associated with the quasar. It is possible that the VLA was mispointed for other LBQS quasars with detectable radio flux, which would be difficult to determine if the radio source were faint or displaced by a large angle from the center of the map. There is a noticeable source within $1'$ of the map center for three quasars listed as upper limits in Table 2: 0049+0045, 1429-0036, and 2244-0105, located $26''$, $47''$, and $29''$, respectively, from the map center.

The number of independent sampling points within the search region of each map was approximated by the ratio of the area of the $2''$ search disk to the area of the beam at half-maximum. Table 1 lists the average FWHM of the beam major and minor axes. When this area ratio was less than 1, the number of independent points was assumed to be 1. The average of the number of independent sample points per search disk for all of the maps in the snapshot survey is 3.9. The expected total number of spurious 3σ or greater detections is the product of the total number of objects, the probability of a spurious source, and the number of independent sample points per search region: $256(2.4 \times 10^{-3})(3.9) \approx 2.4$.

The detection method is optimized for point sources. Given the resolution of the maps (Table 1) and the redshifts of the quasars, hot spots in jets and the gross features of extended emission are expected to be the only structures present in these maps, in addition to the core sources. Only seven of the 44 detections have noticeable multiple structure, and all of these are core-dominated, with flux from other features amounting to no more than 50% of the core flux. Table 2 lists only the detections of, and upper limits to, the unresolved core fluxes of the quasars.

There are discrepancies between Table 2 and seven quasars listed in Paper I. The flux density for 1229-0207 listed in Paper I was measured at the center of the map, but, as noted above, the radio source is offset by $8''$, and the flux density measured at the position of the source is listed in Table 2. Slight changes in the noise analysis technique from Paper I resulted in the reclassification of a nondetection to a detection (1334-0033) and a detection to a nondetection (1237+1325). Upper limits instead of detected flux were listed for 1239+1118, 1320+0103, and 1333+0133 in Paper I due to typographical errors. A detection was listed for 1203+1043 in Paper I based on analysis of a CLEANed map which contained no obvious radio source. However, the quasar was not detected in the unCLEANed map; consequently it is listed as an upper limit in Table 2. All of the detections which were added or deleted have flux densities near the 3σ detection limit.

2.3. Derived Quantities

The optical magnitudes measured for objects in the LBQS are total B_J magnitudes, containing contributions from the quasar nucleus and any host galaxy. The B_J band is the natural system of the Kodak IIIa-J emulsion and GG 395 filter. Apparent B_J magnitudes of quasars with redshifts $z < 2.2$ were converted to rest-frame absolute Johnson B magnitudes (M_B) using k -corrections calculated from a composite LBQS spectral energy distribution (Francis et al. 1991). Since the B and B_J passbands can include Lyman α absorption systems for $z > 2.2$, the high redshift k -corrections were calculated (S. J. Warren 1994, private communication) using the mean Lyman α absorption as a function of wavelength and redshift from the model of Møller & Warren (1991) with parameters as given in Warren, Hewett, & Osmer (1994). A power-law continuum ($f_\nu \propto \nu^{-\alpha}$; $\alpha = -0.75$) and Ly α /N ν emission lines of 84 Å rest-frame equivalent width replaced the LBQS composite spectrum shortward of $\lambda = 1290$ Å. The conversion from B_J to Johnson B as a function of redshift is

$$(B - B_J)_{\text{observed}} = m_B - m_{B_J} = M_B - M_{B_J} + \Delta_{B-B_J}(z). \quad (2)$$

$$(B - B_J)_{\text{observed}} = -2.5[\log \bar{F}_B(\lambda) - \log \bar{F}_{B_J}(\lambda)] + \Delta_{B-B_J}(z) + C. \quad (3)$$

where $F_B(\lambda)$ and $F_{B'}(\lambda)$ are the flux densities of the LBQS composite spectrum averaged over the rest-frame B and B' passbands, respectively, $\Delta_{B-B'}k(z)$ is the difference in k -corrections between B and B' , and C is a constant depending only on the zero-point flux densities of the two passbands. The final expression for the conversion is

$$(B - B')_{\text{observed}} = \Delta_{B-B'}k(z) + 0.04. \quad (4)$$

Rest-frame absolute magnitudes and 8.4 GHz luminosities ($L_{8.4}$) were calculated assuming $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = 0.5$, a radio spectral index $\alpha = -0.5$ ($f \propto \nu^\alpha$), and the optical k -corrections described above. The derived quantities M_B , $L_{8.4}$, and $R_{8.4}$, the ratio of $L_{8.4}$ to the average optical luminosity over the B passband, are listed in columns (4), (7), and (6), respectively, of Table 2.

Errors in $\log L_{8.4}$ and M_B are due to measurement uncertainty, a dispersion in k -corrections, and source variability. Uncertainty in the measured radio flux values, along with an uncertainty in the 4.8–14.5 GHz spectral index of ≈ 0.4 (Aller, Aller, & Hughes 1992), lead to the error in the derived value of $\log L_{8.4}$ listed in Table 2 for each detection. Photometric imprecision in the LBQS B' magnitudes is $\approx 0.15 \text{ mag}$ (Hewett et al. 1995). The LBQS survey plates predate the VLA observations by 3–14 yr, which introduces an additional uncertainty due to variability of the quasars (e.g., Hawkins 1986). Variability uncertainties as a function of the difference in epoch between the optical and radio observations were calculated for each quasar in the sample using equation (20) of Hook et al. (1994). These magnitude uncertainties were combined in quadrature with a rather large assumed uncertainty due to a dispersion in rest-frame optical to near-UV spectral index of ≈ 0.6 among LBQS quasars (Francis 1993), resulting in the errors in M_B listed for each object in Table 2. Errors in $\log R_{8.4}$ for the detections are the quadrature sum of uncertainties in M_B and $L_{8.4}$.

3. RADIO AND OPTICAL PROPERTIES

3.1. The Subsample of the LBQS with Radio Measurements

The apparent magnitude range of the LBQS is constrained to $16.0 \leq B_j \leq 18.85$ (Hewett et al. 1995). The VLA sample was chosen to span the entire redshift range of the LBQS, but it excluded quasars with apparent magnitudes near the faint limit of the survey. These criteria are reflected in cumulative distributions of apparent and absolute magnitude and redshift for the radio sample and the LBQS quasars not observed at the VLA (Fig. 1). The cumulative distributions of the same properties for radio detections and nondetections within the VLA sample are compared in Figure 2. Kolmogorov-Smirnov (KS) tests on each pair of distributions in Figure 2 indicate that LBQS quasars with detectable radio fluxes have a marginally significantly different absolute magnitude distribution but are not found at significantly different redshifts than those which were not detected. The KS probability that the M_B , z , and B distribution pairs are drawn from the same parent population is 10%, 82%, and 29%, respectively. Figure 3 shows absolute magnitude plotted against redshift for the radio detections (filled circles), nondetections (crosses), and, for clarity, $\frac{1}{3}$ of the LBQS quasars without radio observations (Y-shaped symbol), selected without regard to redshift or absolute magnitude. The bias toward bright magnitudes in the radio sample is apparent, as is the strong correlation between M_B and redshift, which is responsible for the well-known difficulties in disentangling red-

shift evolution of radio properties from changes with optical luminosity in all flux-limited quasar samples of limited dynamic range.

3.2. The Relationship between Radio and Optical Luminosity

The distributions of $\log R_{8.4}$ and $\log L_{8.4}$ are plotted against M_B in Figure 4. There are no detections in the range $0.54 < \log R_{8.4} < 1.17$ for all values of M_B (Fig. 4a), which suggests a bimodal distribution. The luminosity of the corresponding division in the $\log L_{8.4}$ distribution increases with M_B (Fig. 4b) from $\log L_{8.4} \approx 24$ at $M_B = -24$ to $\log L_{8.4} \approx 26$ at $M_B = -28$.

3.2.1. Evidence for a Bimodal Distribution of $\log R_{8.4}$

The possible presence of a bimodal distribution in $\log R_{8.4}$ for the LBQS radio sample was tested quantitatively with the Lee statistic (Lee 1979; Fitchett 1988). For two-dimensional data (M_B and $\log R_{8.4}$ in the present case) the statistic is based on the clumpiness in the projection of the data points onto a line. The projected data with the maximum amount of clumping, determined by rotating the line, is tested for consistency with a bimodal distribution. Specifically, for each orientation of the projection line, a measure of the scatter of the data is calculated from the distances between the points along the line.

FIG. 1.—Cumulative distributions of (a) Johnson B magnitude, (b) redshift, and (c) M_B for the LBQS radio sample (dotted line) and the LBQS quasars not observed at the VLA (solid line).

FIG. 2.—Cumulative distributions of (a) Johnson B magnitude, (b) redshift, and (c) M_B within the subsample of the LBQS observed in the radio. The dotted line in each panel indicates the radio detections (44 objects), and the solid line represents the non-detections (212 objects).

FIG. 4.—The distribution of (a) $\log R_{44}$ and (b) $\log L_{44}$ against M_B . Filled circles represent detections, and horizontal lines are upper limits. Error bars ($\pm 1 \sigma$), calculated as described in § 2.3, are shown for representative points.

The data are then partitioned into two sections, and the scatter is calculated separately for each section. If the data are intrinsically clumped in two groups, the partition which corresponds to the division between these groups results in a small scatter within each section, relative to the dispersion of the entire data set. Therefore, the maximum, over all possible partitions, of the ratio of total scatter to the sum of the scatter in each of the two sections is a measure of the clumping of the data. This ratio is subsequently maximized over all rotations of the line to obtain

FIG. 3.—Distributions of M_B against redshift for the LBQS radio detections (filled circles) and upper limits (crosses). Y-shaped symbols represent LBQS quasars without radio observations, only $\frac{1}{3}$ of which are plotted for clarity.

the Lee statistic. Monte Carlo simulations based on an assumed unimodal comparison distribution are used to calibrate the statistic and evaluate the significance of the result. An analysis of three comparison distributions appropriate for the LBQS data is presented in Appendix A.

Stocke et al. (1992) applied the Lee statistic to the distributions of radio luminosity and $\log R$ at 5 GHz ($\log L_5$ and $\log R_5$, respectively), derived from Paper I, MPM, and PG, the major radio surveys of optically selected quasars available at the time. All of these samples have $\log L_5$ and $\log R_5$ distributions which were shown to be different from a single Gaussian function (incorporating upper limits) at or above the 98% confidence level, from which Stocke et al. (1992) concluded that the $\log R_5$ and $\log L_5$ distributions are bimodal. Della Ceca et al. (1994) applied the same test as Stocke et al. (1992) to a sample of 406 X-ray-selected quasars with radio data and found evidence for a bimodal distribution of the radio to optical luminosity ratios. The $\log R_{8.4}$ distribution of the current, enlarged, LBQS radio sample is also incompatible with a Gaussian distribution (point iii. in Appendix A) at a 99.8% confidence level. The confidence level of the result remains at or above 99% when either the mean or standard deviation are changed by a few tenths.

The results from the Gaussian comparison functions alone do not unequivocally demonstrate that the data have a bimodal distribution. The observed data would have to be inconsistent with all reasonable unimodal distributions to reach such a conclusion. Since testing all potential models is impractical, some of the most stringent tests were performed, using distributions which closely approximate the data, except that the models are unimodal. This has the effect of isolating the feature of interest, the hypothesized gap in the $\log R_{8.4}$ distribution, and reducing the influence of differences between the model and the data unrelated to testing for a local minimum. The observed $\log R_{8.4}$ data differ from one such model (point ii. in Appendix A) at only a 39% confidence level. Therefore, given the size of the current data set, a Gaussian model is ruled out, but it is not possible to use the Lee statistic to discriminate between a bimodal distribution and a unimodal distribution with an extended tail.

Regardless of whether the $\log R_{8.4}$ distribution is truly bimodal, in common with previous work, the high $\log R_{8.4}$ tail of the distribution is classified as "radio-loud." A dividing value of $\log R_{8.4} = 1$ was chosen to coincide with the apparent gap and for consistency with other studies. PG and Padovani (1993) used the same dividing value. Stocke et al. (1992) adopted $\log R_{8.4} = 1.2$, and La Franca et al. (1994) employed a radio to optical spectral index definition equivalent to a division at $\log R_{8.4} = 0.86$, assuming an 8.4 GHz to 5 GHz spectral index of -0.5 . A corresponding division between loud and quiet in terms of radio luminosity was chosen to be $\log L_{8.4} = 25$, close to the radio luminosity of an object with $\log R_{8.4} = 1$ and the median absolute magnitude of the sample. The two definitions of radio-loud are not equivalent, especially at low and high optical luminosities. The observed sample has no radio-loud quasars, by either definition, at low optical luminosities, and the only differences in classification of detections occur for $M_B < -27.2$: 0105–2649, 0302–0019, 1235+0857, 1443+0141, 2231–0015 have $\log L_{8.4} > 25$ but $\log R_{8.4} < 1$.

3.2.2. Distribution of Radio Luminosity as a Function of M_B

The radio-loud ($\log L_{8.4} > 25$) quasars are distributed relatively uniformly in M_B and $\log L_{8.4}$ for $M_B < -24$ (Fig. 4). A BHK correlation test, a Kendall's τ test modified to incorpo-

rate upper limits (Isobe, Feigelson, & Nelson 1986), of detections and upper limits with $\log L_{8.4} > 25$ showed no significant correlation between M_B and $\log L_{8.4}$, consistent with the results of MPM and Stocke et al. (1992).

MPM found evidence that the fraction of quasars with high radio luminosity increases with increasing optical luminosity, a result which is strengthened by combining the MPM sample with data from the first LBQS radio observations (Paper I). A similar result at a 99.6% confidence level is obtained if the test criteria from Paper I, which divided quasars in the redshift range $1 < z < 2.5$ into two absolute magnitude groups separated at $M_B = -27.5$, are applied to the enlarged LBQS sample alone.

Padovani (1993) found that the optical luminosity functions (OLFs) for the full PG sample and the radio-loud ($\log R_{8.4} > 1$) subsample have similar cosmological evolutions and a similar shape for bright absolute magnitudes, within the uncertainties of the data. At fainter absolute magnitudes the radio-loud OLF is flatter, resulting in a lower radio-loud fraction. The change in slope occurs at $M_B \approx -24$ for $z = 0$ and at higher optical luminosities with increasing redshift. Analogous results were obtained by Della Ceca et al. (1994) for the X-ray luminosity function (XLF) of X-ray-selected quasars: the radio-loud and radio-quiet XLFs have experienced similar luminosity evolution, and the radio-loud fraction decreases at low X-ray luminosities. The pure luminosity evolution and the local OLFs determined by Padovani (1993) were used to calculate expected radio-loud fractions in the LBQS. The results for high-redshift quasars are ambiguous, since the evolution is undetermined for $z > 2.2$, the redshift cutoff of the PG sample. Two extremes of high-redshift evolution were considered: no evolution for $z > 2.2$; and the same function used for lower redshifts. The predicted radio-loud fractions were not markedly different for these two choices, and both reproduced the overall trend in the data of higher radio-loud fraction at brighter absolute magnitudes. However, the total number of radio-loud quasars predicted is 2.5 times the number observed, and even after normalizing the model to match the observed total, the predicted radio-loud fraction as a function of absolute magnitude does not fit the data well. A χ^2 test for a series of absolute magnitude bins gives a 95% probability that the data and model are incompatible. A somewhat better fit (89%) is obtained by considering only LBQS quasars with $z < 2.2$, but the same qualitative differences between model and data remain.

La Franca et al. (1994) combined several published optically selected quasar samples with radio data and observations of their own for a study of the radio-loud ($\log R_{8.4} > 0.86$) fraction. One of the products of this analysis is a series of expected radio-loud fractions in redshift and absolute magnitude bins (their Table 5) based on derived radio-loud and total optical luminosity functions. The model radio-loud fractions increase with brighter absolute magnitudes in each of the redshift ranges. The full LBQS radio sample was found to be inconsistent at the 97% confidence level with these predictions, based on a χ^2 goodness-of-fit test, with some of the bins combined to obtain an expected number of radio-loud ($\log R_{8.4} > 0.86$) objects greater than two in each bin. The model predicts a substantially higher radio-loud fraction than is observed for the LBQS ($\approx 25\%$ compared to $\approx 10\%$) in the redshift range $0 < z < 1$, which is dominated by PG quasars in the La Franca et al. (1994) sample. If low redshifts are not considered, the LBQS data are more compatible (inconsistent at the 87% confidence level) with the expected fractions for $1 < z < 3$.

The fractions of detections with $\log L_{8.4} > 25$ and $\log R_{8.4} > 1$ are 27/256 (11%) and 22/256 (9%), respectively, for the LBQS sample. A χ^2 test for goodness of fit was used to determine whether the average radio-loud fraction for the sample is consistent with the radio-loud fractions in eight absolute magnitude bins chosen to each contain 32 quasars. The null hypothesis that the fraction of detections with $\log L_{8.4} > 25$ is independent of absolute magnitude can be rejected at the 99.6% confidence level. A similar test using the $\log R_{8.4} > 1$ definition of radio-loud gives rejection of the null hypothesis at an 88% confidence level. The only differences in the $\log L_{8.4}$ and $\log R_{8.4}$ distributions occur in the two brightest absolute magnitude bins, which contain a total of five more detections with $\log L_{8.4} > 25$ than with $\log R_{8.4} > 1$.

A graphical representation of the behavior of the radio-loud fraction as a function of M_B , shown in Figure 5, was constructed by calculating the radio-loud fraction of objects within a 1 mag range centered on the M_B value of each quasar in the sample, essentially a boxcar smoothing of the data. The error bars ($\pm 1 \sigma$) shown at selected values of M_B are the standard deviations of a fraction calculated from a binomial random variable: $\sigma = [f(1-f)/N]^{1/2}$, where f is the radio-loud fraction in a 1.0 mag bin centered on M_B containing N points. The salient features of the functions, namely a value of zero at faint magnitudes, rising to $\sim 15\%$ around $M_B = -25.5$, reaching a minimum for $M_B \sim -27$, climbing to the highest values at the brightest absolute magnitudes, and differences between the $\log R_{8.4} > 1$ and $\log L_{8.4} > 25$ fractions at bright absolute magnitudes, are present for smoothing scales ranging from 0.5 to 2.0 mag.

The sharp rise in smoothed radio-loud fraction ($\log L_{8.4} > 25$) at bright absolute magnitudes and the differences in the χ^2 goodness-of-fit results between $\log L_{8.4} > 25$ and $\log R_{8.4} > 1$ are suggestive of a greater proportion of luminous radio emitters among optically luminous quasars. The most optically luminous absolute magnitude bin contains 10/32 (31%) detec-

tions with $\log L_{8.4} > 25$. Given the average radio-loud fraction for the whole sample of 27/256 (11%), the binomial probability of obtaining at least this many radio-loud quasars in one bin is 0.0012. Since no a priori decision was made to test a particular bin, the probability was multiplied by the number of bins (8), for a final confidence level of 99.0%. The fraction of detections with $\log R_{8.4} > 1$ in the most optically luminous bin is not significantly different from the average, despite the fact that the smoothed fraction attains its highest value at bright absolute magnitudes.

The relatively high fraction of LBQS quasars with $\log L_{8.4} > 25$ at bright absolute magnitudes may be the result of a positive correlation between radio and optical luminosity among the radio-quiet population, as was found in the PG by Stocke et al. (1992). In this scenario, since the radio-loud quasars appear to have no such correlation, the two populations merge at high optical luminosity, resulting in an enhancement in the fraction of quasars with radio luminosity above the "radio-loud" threshold. Stocke et al. (1992) suggested that the radio-quiet correlation could arise if a large portion of the radio emission in these quasars comes from the kinetic energy of outflowing material, such as broad absorption line clouds, driven by optical/UV radiation pressure. There is indirect evidence that the above explanation holds in the LBQS, in that the fraction of radio detections among the radio-quiet quasars remains roughly constant at 5%–10% over the full range of absolute magnitude. If there were no correlation or a negative correlation between the luminosities among the radio-quiet objects, the fraction of detections would decline at higher redshifts (brighter M_B), since the radio luminosity of the 3σ detection limit increases with z (Fig. 4b).

3.2.3. Evidence for a Change in the Quasar Population at Faint Optical Luminosities

Peacock et al. (1986) presented evidence for an abrupt change in the radio properties of the quasar population at an

FIG. 5.—Smoothed radio-loud fraction as a function of M_B for a smoothing scale of 1.0 mag. The solid line is the fraction of detections with $\log L_{8.4} > 25$, and the dotted line represents the fraction with $\log R_{8.4} > 1$. Error bars ($\pm 1 \sigma$), calculated as described in § 3.2.2, are shown at selected absolute magnitudes.

absolute magnitude $M_B \sim -24$, based on the PG survey and a radio-selected sample from the Parkes catalog. In particular, they found a dramatic reduction in the fraction of quasars that were radio-loud at magnitudes $M_B > -24$. None of the PG quasars with $M_B > -24$ is radio-loud ($\log L_{8.4} > 25$), compared to a radio-loud fraction of 24/69 (35%) for the remainder of the survey, a change significant at more than the 99.99% confidence level. This change with absolute magnitude is clearly seen in the luminosity function of the radio-loud PG quasars (Padovani 1993). Although Della Ceca et al. (1994) find some radio-loud quasars with $M_B > -24$ in an X-ray-selected sample, the fraction (3%) is significantly less than for brighter absolute magnitudes (30%) at greater than 99.99% confidence level. Inspection of Figure 4 suggests that the radio properties of the LBQS quasars concur with these results.

The change in the radio distribution for quasars fainter than $M_B = -24$ could be an evolutionary effect. All of the low-luminosity ($M_B \geq -24$) quasars in the LBQS are in the redshift range $0.2 < z < 0.41$ (Table 3). For comparison, the radio-loud fraction is close to 10% for the higher luminosity quasars with $z < 0.5$, although most of these have $z > 0.41$. This suggests that the change in the radio distribution is likely to be caused by differences in M_B rather than z , but the confidence level of the result is only 90% due to the small number of objects involved. The PG sample also has limited overlap in redshift between the bright and faint quasars (Table 3). However, the bright PG quasars provide a closer redshift match for the LBQS quasars fainter than $M_B = -24$. The radio-loud fraction among the optically bright ($M_B < -24$) PG quasars in the range $0.2 < z < 0.41$ is 9/21 (43%), different from the optically faint LBQS sample at greater than 99% confidence level.

Statistical tests comparing the absence of radio-loud quasars at faint absolute magnitudes to the radio-loud fractions of brighter quasars have low confidence levels (91% for $\log L_{8.4} > 25$; 86% for $\log R_{8.4} > 1$). The relatively weak results are due to the small number (20) of LBQS quasars fainter than $M_B = -24$, combined with the low predicted occurrence of radio-loud quasars ($\sim 10\%$), determined from the brighter quasars. However, the VLA observations provide information on the incidence of quasars with radio luminosities considerably fainter than the canonical $\log L_{8.4} = 25$ limit. A significant number of detections for objects with luminosities as faint as $\log L_{8.4} = 23.8$ occur for $M_B < -24$. Upper limits to the radio luminosity are also present above $\log L_{8.4} = 23.8$, but the number of detections places a firm lower limit to the fraction of quasars with radio luminosities exceeding $\log L_{8.4} = 23.8$. At absolute magnitudes brighter than $M_B = -24$, 43/236 (18%) quasars are detected with $\log L_{8.4} > 23.8$. There are 20 quasars with $M_B \geq -24$, with no detections at $\log L_{8.4} > 23.8$ and only one upper limit exceeding this luminosity

(1138 + 0204). Based on the expected fraction of 0.18 from the bright sample for the admittedly a posteriori radio luminosity division $\log L_{8.4} = 23.8$, the binomial probability of observing one or fewer quasars more luminous than $\log L_{8.4} = 23.8$ (assuming the upper limit is detected at $\log L_{8.4} > 23.8$) is 0.098, and (assuming the object with the upper limit is not detected at $\log L_{8.4} > 23.8$) of zero quasars is 0.018.

If more sensitive observations confirm that 1138 + 0204 has a radio luminosity $\log L_{8.4} < 23.8$, the LBQS sample will provide further evidence of the discontinuity in the radio properties of quasars at $M_B \sim -24$ reported by Peacock et al. (1986).

A potential selection effect may be influencing the observed fraction of radio-loud quasars at faint optical luminosities. The M_B values used in the LBQS analysis include contributions from both quasar and host galaxy. Magnitudes of the quasar alone could be fainter by up to 0.75 mag (factor of 2), since the LBQS selected quasars at least as bright as their host galaxies. Shifts to fainter magnitudes for individual quasars will tend to be greater for fainter M_B , since the relative contribution of the host galaxy will be larger. If, as in the hypothesis of Peacock et al. (1986), the radio-loud quasars lie in elliptical galaxies, which may be intrinsically brighter than the spiral galaxies which host the radio-quiet quasars, then the luminosities of the radio-loud quasars may shift farther to the left in Figure 4 than the radio-quiet quasars. Conceivably, one or more of the three quasars with radio luminosities $\log L_{8.4} > 23.8$ and absolute magnitudes $-24.75 < M_B < -24.0$ could reside in a high-luminosity elliptical galaxy, in which case the nuclear luminosity of the quasar may be fainter than $M_B = -24$.

Peacock et al. (1986) ascribed the origin of the apparent change in the radio-loud fraction at $M_B = -24$ to a systematic difference in the classification of active galactic nuclei, coupled with the existence of two distinct classes of object: radio-quiet quasars which exist primarily in spiral galaxies and radio-loud quasars which reside primarily in elliptical galaxies. In the analysis of quasars taken from radio surveys, they hypothesized that radio-loud quasars with faint optical luminosities are classified as radio galaxies, resulting in a deficiency of optically faint quasars where the elliptical galaxy host appears sufficiently prominent.

This explanation cannot be tested quantitatively with the PG quasars, as the effects of host galaxy type and magnitude on quasar selection probability are not accurately known for this survey. The significance of this selection effect for the identification of quasars in the LBQS was investigated in detail (see Appendix B), an analysis made possible by the survey's broad, well-defined, and consistently applied selection criteria, and the ability to accurately simulate the appearance of a test spectrum on the objective-prism plates. The simulations show that very few quasars residing in elliptical hosts would be missed by the

TABLE 3
RADIO-LOUD FRACTION ($\log L_{8.4} > 25$) AS A FUNCTION OF z AND M_B

Survey	M_B Range	$z < 0.2$	$0.2 < z < 0.41$	$0.41 < z < 0.5$	$0.5 < z < 1.0$	$z > 1.0$
LBQS	$M_B > -24$	...	0/20			
	$M_B < -24$	...	0/5	2/13 (15%)	5/41 (12%)	20/177 (11%)
PG	$M_B > -24$	0/45*	...			
	$M_B < -24$	1/17 (6%)	9/21 (43%)	3/5 (60%)	5/7 (71%)	6/19 (32%) ^b

* 0/24 for $M_B < -22.7$, the faint absolute magnitude limit of the LBQS

^b 1/9 (11%) for $M_B > -23.7$, the bright absolute magnitude limit of the LBQS.

FIG. 6.—Smoothed radio-loud fraction as a function of redshift with a smoothing scale of $\Delta z = 0.5$. The observed fraction of detections with $\log L_{8.4} > 25$, with $\log R_{8.4} > 1$, and predicted by the model derived from the radio luminosity functions of Dunlop & Peacock (1990) are indicated by the solid, dashed, and dotted lines, respectively. Error bars ($\pm 1\sigma$), calculated as described in § 3.2.2, are shown at selected redshifts.

LBQS selection algorithms. The revised significance calculation, taking into account the results of the simulation, ascribes a significance of 0.030 (cf. 0.018 above) to observing 0 radio-loud quasars among the 20 $M_B \geq -24$ objects. The simulations are based on a series of conservative (worst case) assumptions, and the results suggest that the hypothesis advanced by Peacock et al. (1986) to explain their own result does not provide a tenable explanation for the lack of optically faint, radio-loud quasars in the LBQS sample.

3.3. The Evolution of Radio and Optical Luminosity

The smoothed radio-loud fraction as a function of redshift (Fig. 6) was calculated using the method described in § 3.2.2 for a redshift interval of 0.5. The upturn in radio-loud ($\log L_{8.4} > 25$) fraction for the observed data at high- z and the apparent peak at $z \approx 1$ are present for larger smoothing scales, although the peak becomes broader and less prominent and is hardly visible for a redshift interval of 1.5. The increased fraction of detections with $\log R_{8.4} > 1$ is barely present with larger smoothing intervals. A χ^2 test found that the LBQS sample, divided into eight redshift bins with 32 quasars in each, is inconsistent with an unevolving radio-loud fraction at the 97.2% ($\log L_{8.4} > 25$) and 94% ($\log R_{8.4} > 1$) confidence levels. The only substantial departures from the average radio-loud fractions are overabundances of radio-loud objects in a bin consisting of the redshift interval $0.75 < z < 1.12$ and, for $\log L_{8.4} > 25$ only, the highest redshift bin, $2.41 < z < 3.36$, consistent with the redshifts at which the smoothed fraction is enhanced. A model based on Padovani's (1993) optical luminosity functions (see § 3.2.2) predicts that the radio-loud ($\log R_{8.4} > 1$) fraction rises slowly with increasing redshift, which, except for the peak around $z \approx 1$, is consistent with the observed data.

Many of the quasars in the two redshift ranges with increased radio-loud fraction have absolute magnitudes corresponding to the maxima in the radio-loud fraction as a func-

tion of M_B (Fig. 5), resulting in an ambiguity as to whether observed changes in radio-loud fraction are primarily evolutionary effects or a function of absolute magnitude. La Franca et al. (1994) found that the radio-loud fraction decreases with redshift for constant M_B (their Table 5). The MPM sample is well suited to resolve the ambiguity in the cause of the elevated radio-loud fraction at $z \approx 3$ and at $z \approx 1$, since that sample is confined to a redshift range ($1.8 < z < 2.5$) between the redshifts of these peaks and has an absolute magnitude coverage ($-28.4 < M_B < -25.0$) which includes the absolute magnitudes of the peaks. Absolute magnitudes for the MPM quasars were calculated in the same manner as for the LBQS, after apparent B magnitudes were derived from $m_{1.4-5}$ as described in La Franca et al. (1994). The smoothed radio-loud fraction for the MPM data, calculated with a 1.0 magnitude smoothing range, is flat within the error bars from $M_B = -25$ to -27 , at which point the fraction rises steeply, consistent with the rise at bright absolute magnitudes in the LBQS sample. Lack of a local maximum at $M_B \approx -25.5$ suggests that the peak observed at these absolute magnitudes in the LBQS is caused by an increase in radio-loud fraction for $z \approx 1$. In summary, the causal variable for the upturn in radio-loud fraction appears to be absolute magnitude at $z \approx 3$ and redshift at $z \approx 1$, although the current LBQS radio subsample is insufficient to resolve this issue conclusively.

An independent estimate of the evolution of the radio-loud fraction was obtained from the 2.7 GHz luminosity function models of Dunlop & Peacock (1990). The expected radio-loud fraction in any redshift interval, $z_1 < z < z_2$, is proportional to the double integral of the radio luminosity function (RLF) over (z_1, z_2) and the luminosity range $\log L_{8.4} > 25$ divided by the number of optically selected quasars in this redshift range. The lower luminosity limit is equivalent to a 2.7 GHz luminosity of $10^{24.15} \text{ W Hz}^{-1} \text{ sr}^{-1}$, assuming a spectral index of -0.5 and a factor of 4 π to convert to the luminosity units used in Dunlop & Peacock (1990). LBQS quasars in the apparent magnitude

range of the radio subsample, $16.0 < B < 18.5$ (Fig. 1), were used for the count of optically selected quasars. The same apparent magnitude criteria were incorporated into the RLF by multiplying the integral by the fraction of radio-selected quasars having apparent magnitudes in the above range and redshifts in (z_1, z_2) , determined from the more than 1100 radio-selected quasars with redshifts and apparent V magnitudes listed in the latest version of the Hewitt & Burbidge Catalog (1993). $B-V$ colors from Cristiani & Vio (1990) were used for the cataloged quasars without measured colors, as the LBQS composite spectrum does not extend sufficiently to the red to calculate $B-V$ colors. Model radio-loud fractions were normalized by requiring that the calculated fraction for the redshift range of the LBQS radio sample equal the observed average fraction.

Radio-loud fractions were calculated from the flat-spectrum MEAN- z model RLF1 of Dunlop & Peacock (1990) for the redshift intervals resulting from the division of the LBQS radio sample into eight redshift bins of 32 quasars each. Although a χ^2 test indicates that the model is inconsistent with the observed data for the eight bins at the 99.7% confidence level, the predicted numbers of radio-loud ($\log L_{8.4} > 25$) quasars are close to the observed values in all but the highest redshift bin ($2.41 < z < 3.36$), in which 1.6 are predicted, compared to seven observed. The discrepancy in the high-redshift range is responsible for the high confidence level from the χ^2 test; if only the first seven bins are used, the model is not rejected by the test. The model rather closely reproduces the local maximum at $z \approx 1$ seen, along with the discrepancy at high redshift, in the smoothed radio-loud fraction (dotted line in Fig. 6), calculated for the model in an analogous manner to that employed for the observed data.

The divergence of the model and data for $z > 2.5$ can be understood if optical luminosity is the causal variable for the enhanced radio-loud fraction at bright absolute magnitudes. In this case the increase in the fraction at high redshift results from the preponderance of optically luminous objects among the high-redshift quasars in the radio sample. Otherwise, the discrepancy between model and data is unexplained. The slight upturn in model smoothed fraction for $z > 3$ may arise from the change in the evolution of the luminosity function of optically selected quasars for $z \geq 3$: Hewitt, Foltz, & Chafee (1993) found that the few LBQS quasars with $z > 3$ are consistent with a constant space density at these redshifts, and Warren et al. (1994) concluded that the space density declines for $z > 3.3$. Sharp variations in the smoothed fraction at these redshifts result from small number statistics in the apparent magnitude correction factor to the RLF and in the number of LBQS quasars in the smoothing interval.

Radio luminosity and $\log R_{8.4}$ are plotted against redshift and lookback time in Figure 7. The radio-loud LBQS detections and upper limits show no significant correlation between redshift and $\log L_{8.4}$ or $\log R_{8.4}$. The LBQS was supplemented at high redshift with data from McMahon, Irwin, & Hazard (1992) and Schneider et al. (1992), also shown in Figure 7. McMahon et al. (1992) used the VLA to observe 29 optically selected quasars with $3.5 < z < 4.7$ and $M_B < -26$, detecting four of these quasars at 5 GHz. Individual redshifts and magnitudes were not published. Any biases in the sample selection are unknown. The four detections, which have $z < 4.25$, are indicated by lines of constant 8.4 GHz luminosity and $\log R_{8.4}$ in Figure 7. The published R values for the detections, defined as the ratio of 5 GHz to V -band flux, were converted to $R_{8.4}$

FIG. 7.—The distribution of (a) $\log L_{8.4}$ and (b) $\log R_{8.4}$ against redshift, and (c) $\log L_{8.4}$ against look-back time. Filled circles and short dashes represent LBQS detections and upper limits, respectively. The asterisk is the Schneider et al. (1992) high-redshift detection, and their 5σ upper limits are shown as crosses. The solid lines indicate the redshift range and the radio luminosity or $\log R_{8.4}$ value for the four detections in McMahon et al. (1992). The nondetections in McMahon et al. (1992) are displayed collectively by the dotted line as a range of upper limits in $\log L_{8.4}$ or $\log R_{8.4}$. Error bars ($\pm 1\sigma$) for $\log L_{8.4}$ and $\log R_{8.4}$, calculated as described in § 2.3, are shown for a representative high-redshift point in each panel. Low-redshift error bars are of order the size of the filled circles.

assuming an optical spectral index of 0.0 and a radio spectral index of -0.5 . The dotted line in each panel shows the 8.4 GHz luminosity and $\log R_{8.4}$ values corresponding to the 3σ upper limit of 0.5 mJy in McMahon et al. (1992) as a function of redshift. Schneider et al. (1992) state that their sample of 22 optically selected quasars in the absolute magnitude range $-27.3 < M_B < -24.9$ drawn from the literature is incomplete, but they believe that the radio properties are unbiased. They detected only one object at 5 GHz at a 5σ limit of ≈ 0.21 mJy. The detection and the individual upper limits, converted to 8.4 GHz, are represented in Figure 7 by an asterisk and crosses, respectively.

The radio-loud ($\log L_{8.4} > 25$) fraction in the combined McMahon et al. (1992) and Schneider et al. (1992) data sets is 5/51 (10%), consistent with the LBQS radio-loud fraction in the redshift range $1.5 < z < 2.5$. The absolute magnitude range of these lower redshift LBQS quasars (see Fig. 3) is similar to that of the Schneider et al. (1992) data, and there is overlap with the McMahon et al. (1992) objects, although some of the quasars in the latter sample may have substantially higher optical luminosities. The simplest interpretation of all of the observations is that the radio-loud fraction of quasars with $M_B \geq -28$ is 5%–10% from $z \approx 1.5$ to redshifts close to 5. A

direct test of this interpretation would require a larger sample of quasars with $z > 2.5$ and $M_B > -28$.

4. SUMMARY

The evolution of radio luminosity with cosmic epoch and its relationship with optical luminosity for optically selected quasars has been investigated, with the following principal results.

i. There is a significant deficit of optically faint ($M_B \geq -24$) quasars with radio luminosities detectable at the flux limits of the LBQS VLA study. This effect appears to be the result of a real physical change in the quasar population, since it cannot be accounted for by an LBQS selection bias against quasars which have large radio luminosities and small optical luminosities. The deficit of optically faint, radio-loud quasars does not appear to be an evolutionary effect, since the change is present among quasars of similar redshifts.

ii. The radio-loud fraction ($\log L_{8.4} > 25$) of LBQS quasars is approximately 10%, independent of absolute blue magnitude, in the range $-27.5 \leq M_B \leq -24$, and rises sharply for brighter absolute magnitudes. An observed increase in the fraction around $M_B \approx -25.5$ is more likely a manifestation of an enhanced radio-loud fraction at $z \approx 1$. No significant correlation between M_B and $\log L_{8.4}$ is present among the radio-loud quasars.

iii. The radio-loud fraction exhibits a peak around $z \approx 1$, is constant at $\approx 10\%$ until $z \approx 2.5$, and then increases substantially to $z = 3.4$, the highest redshift in the LBQS. A model based on radio luminosity functions produces a good match to the data for $z \leq 2.5$ but predicts too low a fraction at higher redshifts. The radio-loud fraction at $z > 3.5$, based on data from the literature, is $\approx 10\%$, similar to that in the range $1.5 \leq z \leq 2.5$. There is evidence that the enhanced observed radio-loud fraction at $z \approx 3$ may be a result of increased radio-loud fraction at bright absolute magnitudes (see point ii. above), which would explain the discrepancy between the data and the

model and indicate that the radio-loud fraction is roughly constant from $z \approx 1.5$ to redshifts approaching 5. No significant correlation between z and $\log L_{8.4}$ is present among the radio-loud quasars.

iv. The $\log R_{8.4}$ distribution may be bimodal. A Gaussian model is clearly not consistent with the observed data, but the sample size is insufficient to determine the applicability of other classes of unimodal distributions.

v. PG quasars have substantially higher radio-loud fraction than the LBQS for M_B brighter than -24 over the redshift range in common to the two samples. A similar discrepancy exists between the PG and other samples, which has led to the conclusion that the radio-loud fraction decreases for $z > 1$, compared to lower redshifts (e.g., Paper I; La Franca et al. 1994). La Franca et al. (1994) note that their combined sample is consistent with no evolution in the radio-loud fraction among $z > 1$ quasars if the PG is excluded. The expanded LBQS sample contains a large number of quasars with $z < 1$, and the strong evolution between low and high redshifts indicated by the PG is not seen. The reason for the enhanced radio-loud fraction in the PG, relative to other optically selected quasar samples, is unknown.

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APPENDIX A

TESTS FOR A BIMODAL DISTRIBUTION

The effectiveness of the Lee statistic in determining whether a set of observed data has a bimodal distribution depends on the ability of the statistic to distinguish between a unimodal distribution and one with similar overall shape containing a local minimum. The discrimination between unimodal and bimodal in general depends on the distribution of the observed data, the number of points in the sample, and the assumed comparison distribution. For illustration, the Lee statistic was evaluated for 1000 realizations of each of a pair of simple unimodal and bimodal $\log R_{8.4}$ distributions having the rough characteristics of and the same number of data points as the LBQS $\log R_{8.4}$ sample. Each $\log R_{8.4}$ value was paired with an absolute magnitude chosen from a model based on the observed distribution of M_B . Upper limits were treated the same as detections in evaluating the statistic. The set of values of the Lee statistic for the unimodal comparison distribution establishes the significance of the result for each test data set drawn from the bimodal population. The fraction of Lee values in the comparison set less than the value for the test is the confidence level that the test data set is not consistent with the comparison distribution. A large number of test data sets establishes a range of confidence levels, useful for evaluating the utility of the statistic in differentiating two populations. Results for three illustrative pairs of distributions are described below and plotted in Figure 8. Each distribution was normalized by requiring that the cumulative probability over all values of $\log R_{8.4}$ be unity.

i. The simplest comparison is between a uniform probability distribution over the observed $\log R_{8.4}$ range, $-0.6 < \log R_{8.4} < 3.6$ (solid line in Fig. 8a), and the same distribution with zero probability in the range of the observed gap, $0.5 < \log R_{8.4} < 1.2$ (dotted line in Fig. 8a). The chance of finding an object with any other value of $\log R_{8.4}$ is zero. The distribution with the gap shows evidence for being bimodal, since 83% of the realizations are different from the unbroken comparison distribution at or above the 95% confidence level.

ii. A hybrid model consisting of a probability function based on the observed $\log R_{8.4}$ distribution for $\log R_{8.4} < 0.5$, and a constant probability for higher values, is a closer approximation to the observed data and hence a better test of the utility of the Lee

FIG. 8.—Functions employed in tests for a bimodal distribution. Panel (a) contains a simple bimodal distribution (dotted line) and a uniform comparison distribution (solid line). The model in (b) is a hybrid of observed LBQS data joined to a uniform probability function with (dotted line) and without (solid line) a gap between the two distributions. A Gaussian-based model is shown in (c).

statistic. The value of the constant probability was chosen to match the observed fraction of objects with $\log R_{8.4} > 0.5$. This model is displayed as the solid line in Figure 8b, with the observed data represented by bins of width 0.1 in $\log R_{8.4}$. The dotted line represents the same model, except for a region of zero probability in the range $0.5 < \log R_{8.4} < 1.2$. The statistic is not as successful at distinguishing the hybrid model with and without the gap; only 34% of the test data sets have values of the Lee statistic exceeding the 95% confidence level.

iii. The hybrid model with a gap was also compared to a Gaussian with a mean of -2.2 and standard deviation of 2.3 in $\log R_{8.4}$, selected to match the range of the observed values of $\log R_{8.4}$ and the fraction of quasars in the sample with $\log R_{8.4} > 1$. A detection limit of $\log R_{8.4} = 0 \pm 0.2$ was imposed to correspond to the observed sample. The statistic exceeded the 95% confidence level in 50% of the realizations of the hybrid model. There is a discontinuity in the Gaussian-based model at $\log R_{8.4} = 0$ (Fig. 8c) resulting from the imposed detection threshold, which allows upper limits of $\log R_{8.4} > 0$ but excludes detections with $\log R_{8.4} < 0$. The shape of the function near $\log R_{8.4} = 0$ is similar to the probability distribution of the observed data (cf. Fig. 8b), although the value of the function is approximately a factor of 2 higher, a result of constraining the Gaussian to accurately reproduce the radio-loud ($\log R_{8.4} > 1$) fraction.

A similar idealized test of a large ensemble of data sets to give the full range of significance levels for each comparison function is not possible with observed $\log R_{8.4}$ data, since the true distribution is unknown, and the number of available empirical “realizations” is limited. However, the basic method of comparing the value of the Lee statistic for an observed sample to a set of values from a comparison distribution to determine a confidence level is unchanged.

The effectiveness of the Lee statistic applied to the LBQS radio sample is limited by the relatively narrow apparent gap in $\log R_{8.4}$ and by the small number of quasars expected to have $\log R_{8.4}$ values in the range of this gap under the null hypothesis of a unimodal distribution. Simulations indicate that the Lee statistic often cannot distinguish between a unimodal $\log R_{8.4}$ distribution similar to that observed (ii. above) and one with a local minimum.

APPENDIX B

HOST GALAXY SELECTION EFFECTS

Selection of LBQS candidates with redshift less than about 2 depends primarily on the color of the object as derived from its objective-prism spectrum. Since elliptical galaxies are redder than quasars, if an elliptical host galaxy were sufficiently luminous the quasar plus elliptical objective-prism spectrum could be reddened enough that it would fail the color-selection criterion.

Simulated spectra consisting of weighted sums of quasar and elliptical galaxy template spectra were constructed to examine the sensitivity of the LBQS selection criteria to a population of relatively optically faint quasars within giant elliptical host galaxies. The host galaxy template chosen for the simulations is the reddest elliptical (NGC 3379; $B - V = 0.95$) in the spectral atlas of Kennicutt (1992). Data from Burstein et al. (1988) were used to extend the spectral coverage into the ultraviolet. Using a red elliptical is conservative, in that rest frame optical colors of quasar host galaxies tend to be bluer than those of normal ellipticals (e.g., Hutchings 1987). The composite quasar spectrum of Francis et al. (1991) was used as the quasar template. Two simulated spectra were created by applying different relative scalings to the quasar and elliptical galaxy templates before co-adding; the quasar had the same absolute B magnitude as the galaxy in one and was 0.25 magnitudes brighter in the other. Only a small percentage of quasars with $M_B < -23$ have host galaxies which are more luminous than the quasar (e.g., Véron-Cetty & Woltjer 1990). The simulation did not include morphological information, because the LBQS selection criteria were applied irrespective of the morphological classification of the image on the direct plates, as long as the quasar flux equalled or exceeded that of the host galaxy.

Each quasar plus elliptical spectrum was redshifted to produce observed-frame spectra for the range $0.0 < z < 0.6$. The redshifted spectra were then transformed to simulate their appearance on a typical objective-prism plate, including the effects of atmospheric extinction, seeing, sensitivity of the IIIaJ emulsion and the nonlinear dispersion of the objective prism. The transformation was derived empirically by matching ~ 100 flux-calibrated spectra of LBQS candidates taken at the Multiple Mirror Telescope to their corresponding spectra on the objective-prism plate. The resulting transformation function produces synthetic objective-prism spectra that are indistinguishable from the actual spectra. Colors of the synthetic spectra were then calculated in exactly the same way as in the generation of the LBQS candidate list (Hewett et al. 1995).

Color tracks of the redshifted synthetic spectra are shown as solid lines in Figure 9, with the upper, redder track corresponding to the case in which the quasar and its host galaxy have equal rest-frame B magnitudes. Redshift is listed along the abscissa, the ordinate is the color estimate derived from objective-prism spectra, with lower numbers indicating bluer colors, and the dashed horizontal line represents the color boundary used to select quasar candidates for spectroscopic follow-up. The region below this line has been explored extensively, whereas few objects above the line have been selected for follow-up spectroscopy on the basis of their color. Quasars above the boundary, such as objects with $z > 2.5$, are identified by the presence of strong emission lines or continuum breaks. The upper color track crosses the selection boundary at $z = 0.24$, implying that the equal-brightness test object would be selected for redshifts $z > 0.24$. A quasar 0.25 magnitudes brighter than the host galaxy (lower track in Fig. 9) would be selected for $z > 0.18$, a redshift range which includes all of the LBQS quasars. Filled circles in Figure 9 represent LBQS quasars selected by color and/or spectral features from the plate used to determine the transformation for the simulated spectra.

The probability of selecting a quasar as a function of the ratio of quasar to host galaxy luminosity was used to estimate the expected fraction of quasars with $M_B \geq -24.0$ having $\log L_{B,4} > 23.8$ in the LBQS. All quasars with $\log L_{B,4} > 23.8$ were assumed to have elliptical host galaxies, with the remainder residing in spirals. The selection probability equals the probability that the

FIG. 9—Color derived from an objective-prism LBQS plate plotted against redshift. Larger color values represent redder objects. The horizontal line is the LBQS color-selection boundary for this plate. Confirmed quasars and active galactic nuclei are represented by filled circles. The colors of two synthetic quasar plus elliptical spectra as functions of redshift are shown as solid lines crossing the color-selection boundary at $z = 0.18$ and $z = 0.24$.

quasar is brighter than the host galaxy for $z > 0.24$ and at least 0.25 magnitudes brighter for $z < 0.24$. The distribution of quasar to host galaxy optical luminosity ratios was drawn from the literature (Romanishin & Hintzen 1989; Hutchings 1987; Smith et al. 1986; Gehren et al. 1984), subject to the following restrictions: the quasars were radio-selected to avoid a potential optical selection bias against faint quasars in bright host galaxies; the total magnitude of the host galaxy and quasar was fainter than $M_B = -24$; the magnitude of the quasar alone was brighter than an absolute blue magnitude of -22 , corresponding to the faintest total M_B in the LBQS radio sample if the quasar and host galaxy contribute equally to the total. The quasar is brighter than its host galaxy in 92% of the cases and is at least 0.25 magnitudes brighter for 77% of the objects.

The likelihood of selecting a quasar with $\log L_{8.4} > 23.8$, $P(\text{select}|\text{radio})$, is related by Bayes's theorem to the probability, $P(\text{radio}|\text{select})$, that a quasar selected by the survey meets this radio luminosity criterion:

$$P(\text{radio}|\text{select}) = \frac{P(\text{select}|\text{radio})P(\text{radio})}{P(\text{select}|\text{radio})P(\text{radio}) + P(\text{select}|\text{radio})[1 - P(\text{radio})]} \quad (\text{B1})$$

$P(\text{select}|\text{radio})$ is 0.92 for quasars with $z > 0.24$ and 0.77 for $z < 0.24$, as determined from the analysis of the LBQS selection criteria. $P(\text{radio})$ is the unconditional probability that a quasar has $\log L_{8.4} > 23.8$, and $P(\text{select}|\text{radio})$ is the probability of selecting an object with lower radio luminosity, assumed to be unity, a conservative estimate, since a lower probability would raise $P(\text{radio}|\text{select})$. The results for $P(\text{radio}|\text{select})$ are 0.146 and 0.170 for low and high redshifts, respectively, using $P(\text{radio}) = 43/236(18\%)$, the fraction of $M_B < -24$ detections with $\log L_{8.4} > 23.8$.

Of the 20 quasars in the LBQS radio subsample with $M_B \geq -24$, eight have $z < 0.24$. The expected number of quasars with $\log L_{8.4} > 23.8$ is $8 \times 0.146 + 12 \times 0.170 = 3.21$. The binomial probability of finding 0/20 quasars exceeding this radio luminosity when 3.21 are expected is 0.030, a result insensitive to the exact value of the redshift at which the selection criteria change. For example, if the redshift division had been 0.3, the final probability would change by less than 0.01.

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APPENDIX B.

RADIO PROPERTIES OF OPTICALLY AND X-RAY SELECTED QUASARS

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THE RADIO PROPERTIES OF OPTICALLY SELECTED QUASARS. III. COMPARISON BETWEEN OPTICAL AND X-RAY SELECTED SAMPLES¹

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ABSTRACT

A sample of 103 quasars from the Large Bright Quasar Survey (LBQS) has been observed with the VLA at 8.4 GHz to study the evolution of the radio luminosity distribution and its dependence on absolute magnitude. Radio data from pointed observations are now available for 359 of the 1055 LBQS quasars. The radio-loud fraction is constant at $\approx 10\%$ over the absolute magnitude range $-28 \leq M_B \leq -23$, and it rises to $\sim 20\%$ ($\log R_{8.4} > 1$) or $\sim 35\%$ ($\log L_{8.4} > 25$) at the brightest absolute magnitudes in the sample. This nearly flat distribution differs markedly from those of the optically selected Palomar-Green (PG) Bright Quasar Survey and the X-ray selected Extended Medium Sensitivity Survey (EMSS), both of which have lower radio-loud fractions for absolute magnitudes fainter than $M_B = -24$ and higher fractions at brighter magnitudes. The reason for the high radio-loud fraction at bright absolute magnitudes in the PG, compared to the LBQS and other optically selected quasar surveys, is unknown. The trend of increasing radio-loud fraction with absolute magnitude in the EMSS is due at least in part to a correlation between X-ray and radio luminosity. Combining the LBQS data with radio studies of high-redshift quasars leads to the conclusion that the radio-loud fraction in optically selected quasars does not appear to evolve significantly, aside from a modest increase at $z \sim 1$, from $z = 0.2$ to redshifts approaching 5, a result contrary to previous studies that found a decrease in radio-loud fraction with increasing redshift by comparing the low- z fraction in the PG to higher redshift samples.

Subject headings: quasars: general — radio continuum: galaxies — surveys — X-rays: galaxies

1. INTRODUCTION

Optical and near-UV light from quasars is comprised primarily of thermal components and emission lines, with some contribution from synchrotron radiation. The source of the optical continuum and broad lines in the standard black hole model for quasars (e.g., Rees 1984) is an accretion disk and centrally concentrated hot gas clouds, respectively. In this model, optical luminosity is closely tied to the accretion rate and the mass of the central engine.

Radiation at radio frequencies is predominantly due to synchrotron processes, which depend on the energy distribution of relativistic particles and magnetic field strength. The ultimate power source for particle acceleration and magnetic field production is presumably the same gravitational engine producing the optical flux, but the relationship is not straightforward. Radio and optical data for an ensemble of quasars should place constraints on the connections between the fueling of the black hole, the gas and dust in the vicinity of the central engine, and the particle acceleration mechanism.

The relationship between quasar radio and optical emission was studied initially using radio-selected objects, which

generally had high radio luminosities due to the relatively low sensitivity limits of the surveys. Sandage (1965) determined that not all quasars are powerful radio sources and hence detectable in radio surveys. Since then, in addition to radio surveys, radio follow-up observations have been made of surveys conducted in the optical (e.g., Sramek & Weedman 1980; Condon et al. 1981; Marshall 1987; Miller, Peacock, & Mead 1990; Schmidt et al. 1995) and other wave bands. Targeted radio observations of quasars selected by other means typically go deeper than the radio surveys. As a result the median radio luminosity of these samples is lower, but they usually contain few of the very powerful objects common in radio surveys. Taken together, the two survey methods have detected quasars with a range of more than 6 orders of magnitude in radio luminosity. This wide span of radio power has commonly been divided into two regimes, radio-loud and radio-quiet.

Two definitions of radio-loud are generally employed, one based on radio luminosity, and the other on the ratio, R_{ν} , of radio luminosity at frequency ν to optical or near-ultraviolet luminosity. These different definitions produce the same classification for most quasars, except at low and high optical luminosities. The empirical basis for this was discussed extensively in Stocke et al. (1992) and in Hooper et al. (1995, hereafter Paper II). Peacock, Miller, & Longair (1986) explored the implications of using radio luminosity or a radio-to-optical luminosity ratio as the parameter of

¹ Some of the observations reported here were obtained with the Multiple Mirror Telescope, a facility operated jointly by the University of Arizona and the Smithsonian Institution.

radio strength in a joint radio-optical luminosity function. The analysis in the present work is conducted using both definitions.

Many studies have concluded that the fraction of radio-loud quasars decreases with increasing redshifts by comparing the radio observations of the predominantly low-redshift Palomar-Green optical quasar survey (Kellermann et al. 1989, hereafter PG), which has a high radio-loud fraction, to higher redshift optically selected samples with relatively fewer radio-loud quasars (Peacock et al. 1986; Miller et al. 1990; Schneider et al. 1992; Visnovsky et al. 1992). However, there is no strong evidence for evolution for $z > 1$ if the PG is excluded from the ensemble of optically selected samples (La Franca et al. 1994). A sample of quasars from the Large Bright Quasar Survey (Hewett, Foltz, & Chaffee 1995, hereafter LBQS) in the redshift range $0.2 < z < 3.4$ did not show the strong evolution in radio-loud fraction inferred from comparisons of the PG with other surveys (Paper II). These results indicate that the PG has an anomalously high radio-loud fraction (at bright absolute magnitudes) compared to other optically selected quasar samples. This difference remains unexplained.

Peacock et al. (1986) noted that strong radio emitters were found to be relatively rare at absolute blue magnitudes (M_B) fainter than -24 . These authors proposed a simple and plausible selection effect, arising from the classification of active galactic nuclei (AGNs) as either quasars or radio galaxies, to explain this observation. If radio-loud AGNs reside in large bright elliptical galaxies, and radio-quiet AGNs have less luminous spiral host galaxies (see, e.g., Smith et al. 1986; Véron-Cetty & Woltjer 1990; Hutchings et al. 1994; however, there are indications that some radio-quiet quasars reside in elliptical host galaxies: e.g., Disney et al. 1995; Bahcall, Kirhakos, & Schneider 1996), powerful radio sources with optically weak nuclei would be classified as radio galaxies in radio surveys. They would not be selected by optical surveys because of the low contrast between the quasar light and the relatively bright, red, and extended stellar component. In fact, just such a decrease in the fraction of radio-loud quasars with $M_B > -24$ has been seen directly in follow-up radio data to optical and X-ray surveys. The effect is highly significant in the PG survey (see also Padovani 1993; La Franca et al. 1994), and a sharp decrease in radio-loud fraction at the same optical luminosity is present among the quasars selected at X-ray wavelengths by the Extended Medium Sensitivity Survey (Della Ceca et al. 1994, hereafter EMSS). In apparent support of this conclusion, no radio-loud quasars fainter than $M_B = -24$ were found in a sample from the LBQS discussed in Paper II. The probability of selecting a quasar using the LBQS criteria is quantifiable in terms of quasar spectral energy distribution, absolute magnitude, redshift, and brightness relative to the host galaxy, an advantage over many existing surveys. This probability distribution was used to test the selection effect hypothesis of Peacock et al. (1986), which was found to not explain the trend seen in the sample drawn from the LBQS.

Further analysis of the radio properties of optically selected quasars with absolute magnitudes near $M_B = -24$ was the primary motivation for obtaining the data presented in the current work, which is the third paper in a series examining the radio properties of the LBQS. Paper I in the series (Visnovsky et al. 1992) presented radio data for 124

high-redshift ($1.0 < z < 3.0$) LBQS quasars, selected as a comparison sample for the predominantly low-redshift PG survey. The parameter $R_{8.4}$ was found to be independent of both redshift and absolute magnitude in this subsample, and the distribution of $\log R_{8.4}$ appeared to be bimodal. The radio-loud fraction was lower than in the PG sample, from which it was inferred that the fraction evolves. One of the principal motivations at that point for expanding the LBQS radio sample was to cover the full redshift range of the LBQS ($0.2 < z < 3.4$), in order to independently investigate the evolution of the radio-loud fraction using a single well-defined survey. An additional 132 LBQS quasars were added to the radio sample in Paper II to accomplish this. The optically brightest quasars at each redshift were selected for Papers I and II in order to study the radio properties at the lowest values of $R_{8.4}$ possible for a given radio flux limit. A more detailed discussion of sample selection is given in § 2.1. The radio-loud fraction in the Paper II sample was nearly constant at $\sim 10\%$ from redshift 0.2 to 3.4, and, with the addition of high- z samples from the literature, showed no evolution to a redshift of almost 5. The fraction was also independent of absolute blue magnitude in the range $-27.5 < M_B < -24$. A higher radio-loud fraction was found at the brightest absolute magnitudes. As discussed above, there were no radio-loud quasars with $M_B > -24$.

The change in radio-loud fraction of LBQS quasars at faint absolute magnitudes reported in Paper II, while significant at the 97% confidence level, was based on only 20 quasars with M_B fainter than -24 . Absolute magnitude errors were 0.3–0.4 for $M_B \sim -24$. Given the survey's relative insensitivity to selection bias against optically weak, radio-loud quasars (see Paper II and Hewett et al. 1995 for details), it is important to expand the radio database of LBQS quasars and to reduce the magnitude uncertainties of radio-loud objects with absolute magnitudes near $M_B = -24$. New observations with the Very Large Array² (VLA) of an additional 103 LBQS quasars with absolute magnitudes in the range $-25 < M_B < -23$ and redshifts $0.2 < z < 1.1$ are presented in this paper, along with improved magnitude determinations for objects at faint optical M_B (§ 2). The latest data are combined with those from Paper I and Paper II to form one of the largest samples of sensitive radio observations of quasars selected at other wavelengths in a single survey. The distribution of radio luminosity as a function of M_B is analyzed and compared to the PG and EMSS samples (§ 3), and the evolution of the radio properties of these three samples is explored in § 4. Models proposed to explain the radio luminosity distribution as a function of absolute magnitude are discussed in § 5. Section 6 contains a summary of the major results.

2. OBSERVATIONS AND DATA REDUCTION

Radio observations of an additional sample of LBQS quasars and improved optical data for a subset of the radio-loud quasars are presented and discussed below. Rest-frame 8.4 GHz luminosities ($L_{8.4}$) and absolute blue magnitudes (M_B) were calculated using $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and

² The Very Large Array (VLA) of the National Radio Astronomy Observatory is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.

$q_0 = 0.5$. The luminosity ratio, $R_{8.4}$, is $L_{8.4}$ divided by the average luminosity over the B passband.

The radio luminosities were derived from observed fluxes assuming a radio spectral index $\alpha = -0.5$ ($f_\nu \propto \nu^{-0.5}$). Optical k -corrections for the majority of the quasars in the sample were calculated from the composite quasar spectrum of Francis et al. (1991). Details of these calculations and attendant error analysis are given in Paper II. The absolute magnitude errors, which are conservative overestimates, are typically ± 0.4 mag for $M_B \approx -24$, rising at brighter M_B (higher redshifts) to ± 0.9 . These errors are the quadrature sum of three components: (1) uncertainty in the k -correction, the dominant source of error for most of the quasars in the sample, particularly at high redshifts; (2) optical variability of the quasars over the time interval between the optical and radio observations; and (3) a photometric imprecision of ≈ 0.15 mag in the original B , magnitudes determined from Schmidt photographic plates (Hewett et al. 1995), which is the smallest contributor to the total uncertainty, although still significant at faint absolute magnitudes. While the resulting precision is adequate for determining large-scale trends in a substantial data set, a detailed view of the change in radio-loud fraction around $M_B = -24$ is difficult with the current magnitude uncertainties, given the small number of radio-loud quasars. Each of these uncertainties was reduced for several radio-loud quasars with absolute magnitudes near $M_B = -24$ by obtaining improved optical spectra and multicolor CCD photometry at an epoch closer to that of the radio data.

2.1. Sample Selection

Each subsample of the LBQS selected for observing with the VLA was chosen to address specific scientific questions, as discussed in the introduction. Neither the individual subsamples nor the combined set of radio data are representative of the LBQS as a whole, in the sense that the

distributions of B , z , and M_B are different for the radio sample and the remaining LBQS quasars (see Fig. 1 in Paper II). The current sample is simply that from Paper II with the addition of many of the remaining LBQS quasars in the magnitude range $-25 < M_B < -23$. The radio sample now contains 146/276 (53%) of all LBQS quasars in this absolute magnitude range. The 103 new observations are nearly equally divided about $M_B = -24$. Figure 1 demonstrates the effects of the various selection criteria on the radio sample. Absolute blue magnitude is plotted against redshift, with individual radio detections and upper limits indicated by filled circles and horizontal lines, respectively, and the Y-shaped symbols represent LBQS quasars without radio data. All of the quasars without radio data are plotted for $z > 2.5$, but, due to the large numbers of such objects at lower redshifts, only $\frac{1}{3}$ of them with $z < 2.5$ are plotted.

Figure 1 shows that, for $M_B < -25$, the radio sample lies in the brighter portion of the region of absolute magnitude-redshift space occupied by the LBQS. This effect is due to the selection priorities of Papers I and II, which resulted in the exclusion of almost all LBQS quasars with $B > 18.4$ from those samples. There is a thin strip corresponding to $B > 18.4$ in which there are no radio data, and the radio properties of the LBQS are formally unconstrained for these combinations of z and M_B . However, it is unlikely that the radio properties are radically different in this unsampled region. The strip is narrow, typically half a magnitude at any redshift. The difference between the brightest members of the radio sample and the remaining LBQS quasars was measured in a series of adjoining redshift intervals of width 0.2 over the range $1.1 < z < 3.3$. The average magnitude difference is 0.55 mag, with an rms dispersion about the mean of 0.15 mag. The unsampled region spans between 125 Myr and 1 Gyr of lookback time. Therefore, any major differences between the sample and the unsampled region

FIG. 1.—Distributions of M_B against redshift for the LBQS radio detections (filled circles) and upper limits (horizontal lines). Y-shaped symbols represent LBQS quasars without radio observations. All of the latter class with $z > 2.5$ are plotted, but the large numbers at lower redshifts would overclutter the plot. Therefore, a random selection of $\frac{1}{3}$ of the quasars with $z < 2.5$ lacking radio data are plotted.

would have to occur over a luminosity interval of 0.5 mag and ≤ 1 Gyr in lookback time. These are small intervals for major changes, given that the radio properties of LBQS quasars for which data exist are nearly constant over 5 mag and 8 Gyr of lookback time (see §§ 3 and 4). Note that, for every value of redshift and absolute magnitude in the unsampled strip, there are radio data at a different z/M_B .

The unsampled region extended over all absolute magnitudes in Paper II, but it ends at $M_B = -25$ in the present work due to the addition of the new radio data in the range $-25 < M_B < -23$. The radio sample now covers the same region of absolute magnitude/redshift space as the entire LBQS in this absolute magnitude range. No radio data are available for LBQS quasars fainter than $M_B = -22.7$ (Fig. 1), but this does not affect the conclusions regarding the radio properties of the brighter quasars in the sample.

2.2. Radio

All of the radio observations of LBQS quasars were obtained with the VLA at a frequency of 8.4 GHz. The latest group of 103 quasars, presented here, were observed on UT 1993 June 4 and 25 in the B/C and C array configurations, respectively. Exposure times were about 2 minutes for all objects. Standard AIPS software was employed to produce dirty total intensity (Stokes I) maps for all fields. Those containing a strong source were subsequently CLEANed.

A detailed description of the noise analysis and source detection procedure used for these maps was presented in Paper II, but the principal steps are summarized here. Radio flux at any point on a map was determined by fitting the core of the corresponding beam to the region around the desired map location. Noise levels were determined by performing the fitting procedure on a random sample of points across each map. Subsequently, a circle of radius $2''$ at the center of the map was searched for radio flux exceeding a detection threshold of three times the rms noise value.

A small number of spurious detections are expected near the 3σ detection limit. The probability of obtaining a 3σ or greater positive fluctuation at a given position on an apparently empty map in the latest set of observations is 1.9×10^{-3} , 1.4 times greater than predicted by a Gaussian noise model using the measured rms. The excess of positive fluctuations may be due to weak sources in the maps, or it may be due to part of the sidelobe patterns from unknown off-map sources. The chance of a spurious detection in a map is this probability multiplied by the number of independent sampling points within the $2''$ search radius. The average number of independent sample points per search disk for the current data set is 3.4, giving an expected total of $(1.9 \times 10^{-3})(3.4)103 \approx 0.7$ spurious detections among the 103 maps. The expected number of spurious detections in the previous radio data sets is 2.4 (Paper II), for a total of 3.1 among 61 recorded detections from 359 observed fields.

The search radius was chosen to match the astrometric accuracy of the LBQS, estimated to be $\leq 2''$ for the original quasar positions. The results were checked by reanalyzing the data with a $4.5''$ search radius to look for larger positional offsets. Every strong source (flux $> 7\sigma$, where σ is the rms noise) found using the larger search radius is within $2''$ of the map center, and the greatest distance from the center of any detected source is 2.74 (1322–0204, a 3.8σ detection). One quasar not detected using a $2''$ radius had a positive fluctuation greater than 3σ within a $4.5''$ radius. The

expected number of additional spurious detections using the larger radius in 103 maps is ~ 2.7 . These tests indicate that a $2''$ search radius is adequate, and this value was used to determine the LBQS radio fluxes.

Radio and optical data for each quasar in the current data set, as well as quasars listed in Paper II with new optical data, are listed in Table 1 in the following format:

Column (1).—Object name, listed in order of increasing right ascension.

Column (2).—Apparent B magnitude derived from observed B_f (Hewett et al. 1995) as described in Paper II, or, for five quasars flagged in the table, measured directly (§ 2.3).

Column (3).—Redshift from Hewett et al. (1995).

Column (4).—Absolute B magnitude.

Column (5).—Flux density (mJy) at 8.4 GHz and 1σ error, or 3σ upper limit.

Column (6).—Logarithm of the ratio of 8.4 GHz luminosity (W Hz^{-1}) to optical luminosity (W Hz^{-1}) averaged over the B passband; $R_{8.4} = L_{8.4}/L_B$.

Column (7).—Logarithm of 8.4 GHz luminosity (W Hz^{-1}), $\log L_{8.4}$.

2.3. Optical

Many existing spectra of LBQS quasars suffer from systematic light loss in the blue due to several instrumental effects and from poor signal-to-noise ratio. Higher quality long-slit CCD spectra were obtained with the Multiple Mirror Telescope (MMT) for 10 radio-loud LBQS quasars on the night of UT 1995 February 5. The new data, which cover a wavelength range 3400–6900 Å, were reduced using standard procedures. The normalization of the flux scale is unreliable, due to a narrow slit and thin cirrus during the observations, but the relative flux calibration is unaffected, since the long axis of the slit was maintained parallel to the direction of atmospheric dispersion.

Improved spectra were not obtained for three radio-loud quasars with M_B near -24 (1430–0046, 2348+0210, and 2351–0036), so archival spectra were analyzed. The spectrum for the latter object does not appear to suffer from the instrumental blue light loss mentioned previously. The other two archival spectra show downturns blueward of 4000 Å. This wavelength region was excluded from spectral index determinations.

A spectral slope was determined for each of the 13 quasars using the ratios of fluxes measured in pairs of fixed rest frame continuum windows chosen to avoid prominent emission lines (Francis 1993). Only one pair of windows was observable in each spectrum, either 2150–2230 to 3020–3100 Å or 3020–3100 to 4150–4250 Å rest frame, depending on the redshift of the quasar. Uncertainties in the spectral slopes were calculated from the error in the mean flux of each window (standard deviation across the window divided by the square root of the number of spectral resolution elements) and a wavelength uncertainty equal to half of the width of the window. Equivalent widths were measured for Mg II and, for higher redshift objects, C III, the only prominent emission lines in the spectra of these quasars.

Broadband optical magnitudes were obtained with the Steward Observatory 2.3 m (nights of UT 1995 February 7 and 8, April 8) and 1.5 m (nights of UT 1995 February 19, March 14) telescopes. Exposure times were 5 minutes or less per frame. In almost all cases, each quasar was observed

TABLE I
RADIO AND OPTICAL OBSERVATIONS OF LBQS QUASARS

Source (1)	B (2)	z (3)	M_B (4)	$S_{8.4}$ (mJy) (5)	$\log R_{8.4}$ (6)	$\log L_{8.4}$ (W Hz ⁻¹) (7)
0002-0243.....	18.30	0.432	-23.57 ± 0.40	<0.41	<0.38	<23.52
0004+0036.....	17.80	0.317	-23.44 ± 0.38	0.84 ± 0.13	0.47 ± 0.17	23.56 ± 0.08
0004+0224.....	17.34	0.300	-23.80 ± 0.37	1.31 ± 0.13	0.48 ± 0.16	23.70 ± 0.06
0006+0015.....	17.42	0.263	-23.45 ± 0.37	<0.42	<0.00	<23.09
0010+0035.....	17.85	0.363	-23.67 ± 0.39	<0.78	<0.47	<23.65
0010+0131.....	18.73	0.433	-23.15 ± 0.41	2.32 ± 0.16	1.30 ± 0.18	24.27 ± 0.07
0017+0209.....	17.54	0.401	-24.17 ± 0.38	<0.38	<0.04	<23.41
0020+0018.....	18.62	0.423	-23.20 ± 0.41	<0.41	<0.51	<23.50
0021+0241.....	17.94	0.495	-24.21 ± 0.40	<0.42	<0.25	<23.64
0021-0301.....	18.79	0.422	-23.02 ± 0.41	<0.41	<0.58	<23.50
0022+0015.....	16.92	0.404	-24.81 ± 0.37	<0.41	<-0.18	<23.45
0028-0101.....	18.45	0.543	-23.88 ± 0.42	<0.48	<0.52	<23.78
0042-2550.....	18.32	0.454	-23.65 ± 0.40	<0.42	<0.40	<23.57
0047-2647.....	18.62	0.495	-23.53 ± 0.41	<0.44	<0.54	<23.66
0049-2840.....	18.74	0.640	-23.94 ± 0.44	<0.51	<0.67	<23.95
0050-2742.....	17.89	0.479	-24.19 ± 0.39	<0.43	<0.24	<23.62
0052-0203.....	18.48	0.577	-23.98 ± 0.43	<0.40	<0.46	<23.75
0053+0124.....	17.82	0.440	-24.09 ± 0.39	4.78 ± 0.16	1.25 ± 0.17	24.60 ± 0.06
0055-0206.....	17.50	0.239	-23.17 ± 0.38	<0.44	<0.05	<23.03
0057-0135.....	17.94	0.325	-23.35 ± 0.39	<0.43	<0.24	<23.29
0058+0205.....	18.54	0.600	-24.00 ± 0.44	<0.39	<0.46	<23.77
0059-2525.....	17.61	0.454	-24.36 ± 0.38	<0.47	<0.16	<23.61
0100+0205.....	17.53	0.393	-24.14 ± 0.38	<0.43	<0.08	<23.45
0101+0009.....	17.42	0.394	-24.26 ± 0.38	<0.40	<0.01	<23.42
0110-0047.....	18.70	0.412	-23.07 ± 0.41	<0.43	<0.56	<23.49
0251-0054.....	17.77	0.433	-24.11 ± 0.39	<0.45	<0.21	<23.56
1137+0110 ^a	18.24	1.138	-25.76 ± 0.21	70.19 ± 2.37	2.57 ± 0.15	26.57 ± 0.13
1138-0003 ^a	18.35 ^a	0.500	-23.37 ± 0.25	37.73 ± 0.81	2.55 ± 0.12	25.60 ± 0.07
1148-0033 ^a	17.73	0.800	-24.90 ± 0.25	4.14 ± 0.12	1.38 ± 0.14	25.04 ± 0.10
1209+1259.....	18.57	0.418	-23.23 ± 0.42	<0.44	<0.52	<23.52
1210+1434.....	18.62	0.870	-24.75 ± 0.50	<0.38	<0.48	<24.09
1211+0848 ^a	17.84	0.810	-25.30 ± 0.19	7.06 ± 0.15	1.46 ± 0.13	25.29 ± 0.10
1212+0945.....	18.24	0.373	-23.33 ± 0.41	<0.43	<0.36	<23.40
1212+1217.....	18.72	0.872	-24.65 ± 0.51	<0.40	<0.54	<24.11
1218+1734.....	18.36 ^b	0.444	-23.35 ± 0.23	25.36 ± 1.11	2.28 ± 0.12	25.33 ± 0.07
1222+1010.....	18.35	0.398	-23.35 ± 0.41	<0.42	<0.41	<23.46
1222+1235 ^a	17.93 ^b	0.412	-23.67 ± 0.26	21.80 ± 0.43	2.02 ± 0.12	25.19 ± 0.06
1223+1226.....	18.70	0.874	-24.68 ± 0.51	<0.42	<0.55	<24.13
1224+1604.....	18.81	0.533	-23.48 ± 0.44	<0.49	<0.68	<23.78
1228+1001.....	18.07	0.637	-24.60 ± 0.44	2.81 ± 0.22	1.14 ± 0.20	24.68 ± 0.09
1228+1411.....	18.70	0.512	-23.51 ± 0.44	<0.53	<0.66	<23.77
1229+0834.....	18.65	0.761	-24.42 ± 0.48	1.06 ± 0.26	0.94 ± 0.24	24.41 ± 0.15
1229-0207 ^a	17.69	1.045	-26.42 ± 0.18	283.9 ± 23.9	2.84 ± 0.14	27.11 ± 0.12
1230+1427.....	18.75	0.422	-23.06 ± 0.43	<0.42	<0.57	<23.51
1230-0015 ^a	17.04	0.470	-23.77 ± 0.28	63.33 ± 1.91	2.56 ± 0.13	25.77 ± 0.06
1230+1627A.....	18.74	0.918	-24.74 ± 0.52	<0.49	<0.63	<24.24
1231+1627.....	18.85	0.999	-24.79 ± 0.54	<0.47	<0.67	<24.29
1231+1728.....	18.38	0.623	-24.24 ± 0.45	<0.41	<0.42	<23.83
1232+1433.....	18.88	0.920	-24.61 ± 0.52	<0.37	<0.57	<24.12
1234+1217.....	18.48	0.662	-24.28 ± 0.46	<0.44	<0.49	<23.91
1236+1802.....	18.70	0.517	-23.53 ± 0.44	1.12 ± 0.12	0.99 ± 0.19	24.11 ± 0.09
1237+0824.....	18.65	0.412	-23.12 ± 0.42	<0.53	<0.63	<23.58
1237+1100.....	18.69	0.881	-24.71 ± 0.51	0.70 ± 0.13	0.77 ± 0.24	24.36 ± 0.14
1238+1401.....	18.41	0.641	-24.27 ± 0.45	<0.45	<0.47	<23.89
1240+1551.....	18.86	0.573	-23.58 ± 0.45	<0.36	<0.56	<23.70
1240+1746.....	18.05	0.549	-24.31 ± 0.43	<0.42	<0.30	<23.73
1241+0107.....	18.49	0.786	-24.66 ± 0.48	<0.45	<0.50	<24.07
1241+0844.....	18.37	0.378	-23.22 ± 0.41	0.54 ± 0.14	0.52 ± 0.21	23.52 ± 0.12
1242+1719.....	18.64	0.540	-23.68 ± 0.44	<0.44	<0.56	<23.74
1244+1358.....	18.84	0.601	-23.70 ± 0.45	<0.39	<0.59	<23.78
1244+1529.....	18.90	0.781	-24.23 ± 0.49	<0.42	<0.64	<24.04
1250+0109.....	18.45	0.792	-24.71 ± 0.48	<0.39	<0.43	<24.02
1308+0047.....	18.63	0.428	-23.21 ± 0.40	<0.69	<0.74	<23.73
1308-0111.....	18.51	1.004	-24.65 ± 0.18	4.58 ± 0.21	1.72 ± 0.14	25.28 ± 0.12
1311+0131.....	18.50	0.781	-24.63 ± 0.47	<0.42	<0.47	<24.03
1313+0020.....	18.32	0.735	-24.67 ± 0.45	<0.41	<0.39	<23.97
1313-0228.....	18.67	0.704	-24.22 ± 0.45	<0.30	<0.41	<23.80
1315+0150.....	18.60	0.539	-23.72 ± 0.41	<0.37	<0.47	<23.66
1316+0103.....	18.53	0.394	-23.15 ± 0.39	<0.41	<0.47	<23.44
1321-0213.....	18.83	0.991	-24.80 ± 0.52	<0.36	<0.54	<24.17

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TABLE 1—Continued

Source (1)	<i>B</i> (2)	<i>z</i> (3)	<i>M_B</i> (4)	<i>S_{8.4}</i> (mJy) (5)	log <i>R_{8.4}</i> (6)	log <i>L_{8.4}</i> (W Hz ⁻¹) (7)
1322-0204	18.54	0.573	-23.90 ± 0.42	0.53 ± 0.14	0.60 ± 0.22	23.87 ± 0.14
1323+0205	18.55	0.641	-24.13 ± 0.43	<0.51	<0.59	<23.95
1324+0125	18.73	0.970	-24.86 ± 0.52	<0.48	<0.63	<24.28
1326-0257	18.19	0.743	-24.83 ± 0.45	<0.41	<0.34	<23.98
1328+0205	18.16	0.692	-24.69 ± 0.44	<0.41	<0.33	<23.92
1330-0156	18.87	0.889	-24.55 ± 0.50	<0.48	<0.67	<24.20
1334+0053	18.29	0.647	-24.41 ± 0.44	<1.76	<1.02	<24.49
1335-0241	18.09	0.608	-24.48 ± 0.43	<0.38	<0.27	<23.77
1340-0020	18.15	0.786	-25.00 ± 0.47	<0.40	<0.31	<24.02
1344-0227	18.29	0.511	-23.92 ± 0.41	<0.43	<0.40	<23.68
1345-0000	17.99	0.552	-24.38 ± 0.41	<0.45	<0.31	<23.77
1350+0052	18.43	0.485	-23.68 ± 0.41	<0.45	<0.47	<23.65
1429-0039	18.21	0.362	-23.30 ± 0.40	<0.40	<0.33	<23.35
1429-0246	18.63	0.853	-24.69 ± 0.50	<0.40	<0.50	<24.09
1430-0046*	17.57	1.023	-26.17 ± 0.17	14.97 ± 0.31	1.64 ± 0.14	25.81 ± 0.12
1433+0011	18.57	0.583	-23.91 ± 0.44	<0.39	<0.48	<23.75
1433-0016	17.80	0.325	-23.49 ± 0.39	<0.47	<0.22	<23.32
1435+0130	18.33	0.633	-24.32 ± 0.45	<0.41	<0.41	<23.84
1437-0143	18.15	0.718	-24.79 ± 0.46	<0.49	<0.40	<24.03
1438+0210	19.34	0.797	-23.78 ± 0.20	236.6 ± 11.0	3.58 ± 0.13	26.80 ± 0.10
1440-0303	18.63	0.754	-24.42 ± 0.48	<0.45	<0.56	<24.03
1441+0134	18.45	0.753	-24.60 ± 0.47	<0.40	<0.44	<23.99
1443-0207	18.49	0.397	-23.20 ± 0.41	0.58 ± 0.16	0.60 ± 0.21	23.59 ± 0.14
1444-0019	18.20	0.697	-24.67 ± 0.46	<0.49	<0.43	<24.00
1444-0300	18.46	0.549	-23.90 ± 0.43	<0.43	<0.48	<23.74
1445+0222	18.54	0.775	-24.57 ± 0.48	<0.35	<0.41	<23.95
1446+0027	18.61	0.832	-24.66 ± 0.49	<0.74	<0.76	<24.33
1446+0218	17.89	0.672	-24.90 ± 0.44	<0.37	<0.19	<23.85
2158-1657	18.47	0.475	-23.60 ± 0.43	<0.42	<0.46	<23.61
2159-1906	18.22	0.364	-23.30 ± 0.42	<0.47	<0.40	<23.43
2207-1703	18.43	0.371	-23.13 ± 0.42	<0.42	<0.43	<23.39
2212-1634	17.80	0.296	-23.31 ± 0.41	<0.42	<0.17	<23.20
2214-1903	18.18	0.396	-23.51 ± 0.42	<0.45	<0.37	<23.48
2235+0054	18.57	0.529	-23.71 ± 0.42	2.67 ± 0.43	1.31 ± 0.20	24.50 ± 0.10
2235-0112	18.21	0.361	-23.29 ± 0.39	<0.45	<0.37	<23.40
2348+0210	17.67*	0.504	-24.73 ± 0.18	33.77 ± 0.45	1.96 ± 0.10	25.56 ± 0.07
2350-0045B	18.43	0.764	-24.65 ± 0.47	<0.43	<0.46	<24.02
2351-0036	18.71*	0.460	-23.61 ± 0.22	279.0 ± 3.4	3.25 ± 0.11	26.40 ± 0.07
2352+0025	17.81	0.271	-23.12 ± 0.38	<0.43	<0.17	<23.13
2353+0032	18.59	0.558	-23.80 ± 0.43	<0.46	<0.56	<23.79
2357-0014	17.86	0.479	-24.22 ± 0.40	<0.41	<0.21	<23.60

* Previously reported in Paper II. The derived quantities *M_B* and log *R_{8.4}*, including errors, have been updated using the numbers in Table 2. Redshift and 8.4 GHz flux and luminosity, and in most cases apparent *B* magnitude, are retained from Paper II. A new *B* magnitude, if available, is listed in Col. (2) and flagged (see below).

* The apparent *B* magnitude was determined from the new photometry in Table 2. Entries without this flag have *B*-values calculated from original *B_j* magnitudes, as described in Paper II.

more than once per passband. Standard reduction techniques of bias subtraction and flat-fielding were applied to all frames, followed by the determination of instrumental magnitudes for standard stars and program quasars using Stetson's (1987, 1990) DAOPHOT and DAOGROW packages. Additional data, flagged in Table 2, were drawn from a large multiband photometric study of the LBQS, currently in preparation.

The *R* passband is roughly coincident with rest frame *B* at redshifts *z* ~ 0.5, making it more accurate to calculate *M_B* from the *R* magnitude, rather than observed *B*. This conversion can be expressed as

$$M_B - R = -2.5 \left\{ \log \left[\frac{(d_L/10 \text{ pc})^2}{(1+z)^2} \right] + \log \left(\frac{F_B}{F_R} \right) + \log \left[\frac{f_{\nu}(R=0)}{f_{\nu}(B=0)} \right] \right\} \quad (1)$$

where *F_B* and *F_R* are the flux densities of a power-law spectrum with index *α* averaged over the rest frame *B* and *R* passbands, respectively. *d_L* is the luminosity distance, and *f_ν*(*B* or *R* = 0) is the flux density for magnitude zero. The error in the conversion from *R* to *M_B*, given an uncertainty in spectral index *σ_α*, is

$$\sigma_{(M_B - R)} = \frac{2.5\sigma_\alpha}{\ln 10} \left[\ln(1+z) - \frac{\int \nu^2 \ln \nu B(\nu) d\nu}{\int \nu^2 B(\nu) d\nu} + \frac{\int \nu^2 \ln \nu R(\nu) d\nu}{\int \nu^2 R(\nu) d\nu} \right] \quad (2)$$

where *B*(*ν*) and *R*(*ν*) are the filter transmission functions. The factor ln *ν* arises from the derivative of *ν*² with respect to *α*. Spectral indices determined for each quasar were used in these calculations. Absolute magnitude was derived from observed *V* in an analogous manner for the two quasars in Table 2 without *R* magnitudes. Uncertainties in the conver-

TABLE 2
OPTICAL DATA FOR SELECTED RADIO-LOUD LBQS QUASARS

Name (1)	V (2)	B-V (3)	V-R (4)	α (5)	Mg II (6)	C III (7)
1137+0110 ^a	17.71 $\pm$ 0.09	...	0.30 $\pm$ 0.17	-0.25 $\pm$ 0.13	97 $\pm$ 10	61 $\pm$ 4
1138+0003	18.30 $\pm$ 0.02	0.05 $\pm$ 0.02	0.16 $\pm$ 0.02	1.09 $\pm$ 0.19	79 $\pm$ 3	...
1148-0033 ^a	17.96 $\pm$ 0.11	...	0.37 $\pm$ 0.20	-0.37 $\pm$ 0.11	53 $\pm$ 4	...
1211+0848 ^a	17.46 $\pm$ 0.06	...	0.20 $\pm$ 0.10	-0.56 $\pm$ 0.10	59 $\pm$ 5	...
1218+1734	18.30 $\pm$ 0.03	0.06 $\pm$ 0.04	0.36 $\pm$ 0.04	0.35 $\pm$ 0.14	14 $\pm$ 1	...
1222+1235	17.86 $\pm$ 0.04	0.07 $\pm$ 0.04	0.34 $\pm$ 0.04	1.00 $\pm$ 0.18	78 $\pm$ 3	...
1229-0207 ^a	16.76 $\pm$ 0.07	...	0.18 $\pm$ 0.13	-0.23 $\pm$ 0.12	95 $\pm$ 8	31 $\pm$ 4
1230-0015 ^a	17.63 $\pm$ 0.12	...	0.00 $\pm$ 0.22	0.66 $\pm$ 0.16	15 $\pm$ 1	...
1308-0111	18.34 $\pm$ 0.02	...	0.13 $\pm$ 0.02	-0.04 $\pm$ 0.14	71 $\pm$ 6	46 $\pm$ 6
1430-0046 ^{a,b}	17.31 $\pm$ 0.05	...	0.45 $\pm$ 0.09	-0.47 $\pm$ 0.15	59 $\pm$ 10	35 $\pm$ 5
1438+0210	19.01 $\pm$ 0.03	...	0.25 $\pm$ 0.03	-0.68 $\pm$ 0.11	30 $\pm$ 6	...
2348+0210 ^b	17.33 $\pm$ 0.04	0.34 $\pm$ 0.04	...	-0.29 $\pm$ 0.18	36 $\pm$ 4	...
2351-0036 ^b	18.30 $\pm$ 0.05	0.41 $\pm$ 0.06	...	-0.50 $\pm$ 0.24	41 $\pm$ 7	...

^a V and V-R are from a large multiband study of the LBQS currently in progress.

^b No recent long-slit CCD spectra are available for these quasars. Archival spectra were used to calculate spectral indices, k -corrections, and equivalent widths.

sion from V or R to M_B were typically 0.03 mag and did not exceed 0.05 mag for any object, leaving variability as the largest error component for the 13 quasars with new photometry. The final errors in M_B , listed for each object in Table 1, are a factor of 2 lower for the quasars with improved optical data, compared to other LBQS quasars at the same redshifts. Absolute magnitudes for LBQS quasars other than those listed in Table 2 were calculated using the method described in Paper II.

The newly obtained optical data, including 1 σ errors, for selected radio-loud quasars are presented in Table 2 as follows:

Column (1).—Object name.

Columns (2)–(4).—V magnitude, B-V and V-R colors, where available.

Column (5).—Spectral index, α ($f_\nu \propto \nu^\alpha$).

Columns (6) and (7).—Observed-frame equivalent widths for Mg II $\lambda 2798$ and C III $\lambda 1909$.

3. DISTRIBUTION OF RADIO LUMINOSITY AND $\log R_{8.4}$ AS FUNCTIONS OF M_B

Figure 2 shows the distributions of $\log L_{8.4}$ and $\log R_{8.4}$ versus M_B for the data from Table 1 plus those from Table 2 in Paper II. Detections with $\log L_{8.4} \geq 25$ or alternatively $\log R_{8.4} \geq 1$ are considered to be radio loud, the same definitions employed in Paper II. Quasars in the new radio sample form a cluster of upper limits and detections with elevated radio luminosities in the magnitude range $-25 < M_B < -23$, due to shorter integration times than the observations described in Paper II.

Radio-loud LBQS quasars are distributed fairly uniformly throughout a range of over two decades in $R_{8.4}$ and $L_{8.4}$ and across all absolute magnitudes sampled by the survey. No correlation between either $\log R_{8.4}$ or $\log L_{8.4}$ and M_B is observed among the radio-loud quasars, consistent with previous studies by Miller et al. (1990) and Stocke et al. (1992). The apparent correlation between radio luminosity and absolute magnitude at low values of $\log L_{8.4}$ is the result of the LBQS flux limit.

Comparisons between the LBQS and other optically selected surveys, such as the PG, demonstrate the effects of different optical selection criteria on the inferred radio properties. Contrasting the LBQS with surveys selected at other wave bands, such as the X-ray selected EMSS, pro-

vides further insights into the relevant physical mechanisms and helps identify radio properties of quasars that are universal, regardless of selection frequency. The overall radio-loud ($\log L_{8.4} > 25$) fraction for the LBQS, 32/359 (9%), is nearly identical to that in the EMSS, 39/411 (9%), but is less than half of the value for the PG, 24/114 (21%). Overall fractions with $\log R_{8.4} > 1$ are similar, with the LBQS at 31/359 (9%), the EMSS at 46/411 (11%), and the PG at 22/114 (19%). Radio data for all of the PG quasars (Table 1 in Kellermann et al. 1989) and the EMSS detections classified as "AGNs" and having radio fluxes (Table 4 in Stocke et al. 1991) are used in the comparisons throughout this paper. Radio fluxes and luminosities at other frequencies taken from the literature were extrapolated to 8.4 GHz using a spectral index of -0.5 , the same value employed for the LBQS data. The radio luminosity and $\log R_{8.4}$ distributions versus absolute magnitude for the LBQS differ from the PG and the EMSS, as shown in Figure 3. These plots were constructed by calculating the radio-loud fraction of objects within a 1 mag range centered on the M_B -value of each quasar in the sample, producing essentially a boxcar smoothing of the data. The error bars ($\pm 1 \sigma$) shown at selected values of M_B are the standard deviations of a fraction calculated from a binomial random variable: $\sigma = [f(1-f)/N]^{1/2}$, where f is the radio-loud fraction in a 1.0 mag bin centered on M_B containing N points. The radio-loud fraction in the LBQS is constant at $\approx 10\%$ for all but the most optically luminous quasars, rising to $\sim 35\%$ ($\sim 20\%$ for $\log R_{8.4} = 1$) for $M_B \leq -28$. The latter fraction is rather uncertain due to the small number of objects in this range.

A series of statistical tests were performed on the M_B distributions of the radio-loud and radio-quiet quasars in the LBQS to quantify the significance of the observed trends. A Wilcoxon two-sample rank sum test indicated that the radio-loud and radio-quiet quasars do not have significantly different absolute magnitude distributions (the statistic differed by only 0.03 σ from the value expected under the null hypothesis of equivalent M_B distributions) using the $\log R_{8.4} > 1$ definition of radio-loud. There is some indication of a difference using the $\log L_{8.4} > 25$ criterion (97% confidence). However, when the 11 quasars with $M_B < -28$ —the approximate region where the fraction of detections with $\log L_{8.4} > 25$ is observed to rise—

FIG. 2.—Distribution of (a) $\log R_{8.4}$ and (b) $\log L_{8.4}$ against M_B for the LBQS. The data shown consist of the new observations from Table 1 and those from Table 2 in Paper II. Filled circles represent detections, and horizontal lines are upper limits. Error bars ($\pm 1\sigma$), calculated as described in § 2, are shown for a representative point at bright ($M_B = -27.8$; $\log R_{8.4} = 3.5$, $\log L_{8.4} = 28.3$) and one at faint ($M_B = -23.2$; $\log R_{8.4} = 1.3$, $\log L_{8.4} = 24.3$) absolute magnitudes and individually for those quasars that were reobserved in the optical. Error bars in $\log L_{8.4}$ are not plotted in (b) for the quasars with new photometry to avoid unnecessary crowding and because the radio luminosity uncertainties are not affected by the new data.

were excluded, no significant difference (82% confidence level) was found between the radio-loud and radio-quiet distributions. The Wilcoxon test was also applied to the absolute magnitude distributions in a series of redshift bins in order to remove some of the degeneracy between z and M_B inherent in any flux-limited sample. Data for the 40 high-redshift quasars in Schmidt et al. (1995), discussed in more detail in § 4, were added to the LBQS radio sample to extend the redshift range. Two binning schemes were employed, one using the redshift ranges of Schmidt et al. (1995), and in the other case the combined sample was divided into five bins of nearly equal numbers. The only moderately significant (96.8% confidence) difference between the radio-loud, using either definition, and remaining distributions occurred for $\log L_{8.4} > 25$ in the equal-number bin covering the redshift range $2.34 < z < 4.90$. Again, this was due to the enhanced radio-loud fraction at bright absolute magnitudes. Ties in the rankings for the Wilcoxon tests were handled in the standard way by averaging the ranks of a group of quasars with the same M_B , and the probabilities quoted are for a two-sided test

FIG. 3.—Smoothed radio-loud fraction as a function of M_B (smoothed over an interval of 1.0 mag) for the LBQS (a), the PG survey (b), and the EMSS (c). Solid lines represent the fraction with $\log L_{8.4} > 25$, and dotted lines are for $\log R_{8.4} > 1$. Error bars, calculated as described in the text, are shown at selected values of M_B .

using the asymptotic normal distribution of the rank sum statistic.

The LBQS radio data, sorted by M_B , were divided into 10 bins each containing ≈ 36 objects to perform some of the χ^2 and binomial tests described in § 3.2.2 of Paper II. The results are very close to those in Paper II and are consistent with the results of the Wilcoxon tests above. The number of detections with $\log R_{8.4} > 1$ in each bin is consistent with a constant radio-loud fraction equal to the average fraction for the whole LBQS radio sample (the probability that the sample is not consistent with the flat distribution is 81%). This is not the case, however, using the radio luminosity criterion for radio-loud, which produces a distribution that is not flat at the 99.7% confidence level. The discrepancy lies in the brightest absolute magnitude bin, $-28.7 < M_B < -27.5$, and if this bin is excluded the confidence level drops to an insignificant 76%. The likelihood from a binomial distribution of selecting at least the observed number, 10/36 (28%), of radio-loud quasars in the brightest bin, given the average radio-loud fraction for the full sample, is 0.00092. Since this bin was selected a posteriori because of its high incidence of radio-loud quasars, the true significance of the enhanced radio-loud fraction is the binomial probability multiplied by the number of bins (10), for a final confidence level of 99.1%.

All of the statistical tests performed on the distribution of radio-loud objects with M_B in the LBQS sample are consis-

tent with the representation shown in Figure 3a: the radio-loud fraction is essentially constant except at the brightest absolute magnitudes, and even then it is only significantly higher using the $\log L_{8.4} > 25$ criterion. Some possible interpretations of this distribution are discussed in § 5.

Both the PG and EMSS have substantially higher radio-loud fractions than the LBQS for M_B brighter than -24 (see Figs. 3b and 3c). Note that the PG has an anomalously high radio-loud fraction in this absolute magnitude range compared to other optically selected quasar samples (La Franca et al. 1994; Della Ceca et al. 1994). The reason for this discrepancy remains unexplained. A strong trend in radio-loud fraction as a function of both absolute magnitude and redshift is expected in the EMSS, due to the well-known correlations between radio, X-ray, and optical luminosity (see, e.g., Worrall et al. 1987) and the X-ray flux limit. Figure 4 shows absolute magnitude plotted against redshift for the LBQS and EMSS, with the radio-loud ($\log L_{8.4} > 25$) quasars indicated by filled triangles. It is apparent that the observed trends with redshift and absolute magnitude are mostly degenerate. In particular, all but one of the radio-loud EMSS quasars brighter than $M_B = -24$ have $z > 0.5$, whereas the bulk of the radio-quiet quasars fainter than this absolute magnitude are at redshifts $z < 0.5$. However, some discrimination as a function of M_B is possible in the redshift interval $0.4 < z < 0.7$. In this redshift range the radio-loud fraction is 7/20 (35%) for $M_B < -24$ and 3/45 (7%) among the fainter quasars, suggesting that at

$z \sim 0.5$ the radio-loud fraction of X-ray selected quasars is dependent upon absolute magnitude, decreasing for M_B fainter than -24 . The selection effect proposed by Peacock et al. (1986) does not explain the decline in radio-loud fraction for $M_B > -24$ in the EMSS, since the ratio of quasar to host galaxy optical luminosity is not expected to affect X-ray selection.

The Peacock et al. (1986) selection effect is still a viable explanation for the decrease in radio-loud fraction in the PG, since a quantitative test of the applicability of this hypothesis to the PG cannot be performed, as was done for the LBQS in Paper II. Alternatively, the PG may have a nearly normal radio-loud fraction for $M_B > -24$, perhaps only slightly depressed by the selection effect, which only appears abnormally low because the fraction at brighter absolute magnitudes is atypically high. If the radio-loud fraction among the optically faint PG quasars is compared to the fraction at absolute magnitudes brighter than -24 in the LBQS, rather than in the PG, the significance of the change becomes equivocal. The fraction of quasars with $\log R_{8.4} > 1$ in the faint PG sample (2/45, 4%) is not significantly different (71% confidence level) from the LBQS value of 23/286 (8%) for $M_B < -24$. However, the difference is significant at the 98.6% confidence level using the $\log L_{8.4}$ definition of radio-loud, for which the fractions are 0/45 and 26/286 (9%) in the PG and LBQS subsamples, respectively. If PG quasars with M_B fainter than -22.7 —the faint absolute magnitude limit of the LBQS—are excluded from the comparison, the fractions for both definitions become 0/24, for which the confidence levels are 87% ($\log R_{8.4} > 1$) and 90% ($\log L_{8.4} > 25$).

No pronounced decline in radio-loud fraction at absolute magnitudes fainter than -24 is seen in the LBQS, contrary to the other two samples (Fig. 3). As noted in the introduction, a decrease was seen in this range in Paper II, but the number of objects with $M_B > -24$ was small (20), and the absolute magnitude uncertainties were ± 0.4 mag. The new LBQS data increase the sample size at faint optical luminosities by more than a factor of 3 and decrease the magnitude uncertainties for radio-loud objects near $M_B = -24$ by a factor of 2. Improved absolute magnitude determinations for two radio-loud quasars listed as slightly brighter than $M_B = -24$ in Paper II (see Fig. 4 of that work) now place them fainter than this division, along with four new radio-loud quasars. The radio-loud ($\log L_{8.4} > 25$) fraction in the combined LBQS sample is 6/73 (8%) at absolute magnitudes fainter than $M_B = -24$, nearly identical to the fraction (26/286, 9%) at brighter absolute magnitudes. Much of the discussion to date on the radio luminosity distribution of quasars at low optical luminosities has been based at least in part on the PG (Peacock et al. 1986; Miller et al. 1990; Padovani 1993; Falcke, Gopal-Krishna, & Biermann 1995). The LBQS results show that the radio-loud fraction does not decline for $M_B > -24$ in all optically selected quasar samples. In cases where it does, the cause may be a selection effect at faint absolute magnitudes or an increased prevalence of radio-loud quasars at bright absolute magnitudes.

4. THE EVOLUTION OF RADIO AND OPTICAL LUMINOSITY

Radio-loud fraction is nearly constant in the LBQS over most of the redshift range of the survey, as shown in Figure 5. The smoothed fraction as a function of z was calculated with a redshift smoothing interval of 0.5 in a manner analo-

FIG. 4.—Absolute magnitude vs. redshift for the LBQS (a) and the EMSS (b). This is similar to Fig. 1, but in this case the filled triangles are radio-loud ($\log L_{8.4} > 25$) detections, crosses represent radio-quiet detections, and horizontal lines indicate upper limits, assumed to be radio-quiet.

FIG. 5.—Smoothed radio-loud fraction as a function of redshift in the LBQS sample using the (a) $\log L_{8.4} > 25$ and (b) $\log R_{8.4} > 1$ criteria. Solid lines indicate the observed data, while dotted and dashed lines represent the flat and steep spectrum model predictions, respectively. Values for the data as well as the models were calculated with a redshift smoothing interval of 0.5. Error bars, calculated in an analogous manner to those in Fig. 3, are shown at representative data values.

gous to its determination as a function of M_B , above. Some of the same statistical tests used in § 3 were applied to the distributions of $\log L_{8.4}$ and $\log R_{8.4}$, with a similar result that the quantitative measures confirm the trends displayed graphically in Figure 5. The Wilcoxon rank sum statistic for detections with $\log R_{8.4} > 1$ differs by only 0.2σ from the value expected if these have the same redshift distribution as the remaining quasars in the LBQS radio sample. The radio-loud quasars have a moderately significantly (confidence level 95%) different redshift distribution using $\log L_{8.4} > 25$, but the significance disappears (revised confidence level 77%) when the region with the observed spike in radio-loud fraction, $z > 3$, is excluded. The results of a χ^2 goodness of fit test of a model in which the radio-loud fraction is unevolving and equal to the sample average are not as clear cut as those from the Wilcoxon test, because of a greater sensitivity to the rise in radio-loud fraction around $z \approx 1$. While the increase in radio-loud fraction for $z \approx 1$ is not nearly as great as the apparent climb at $z \geq 3$, this enhancement contributes significantly to the χ^2 statistic. For example, the $\log R_{8.4}$ distribution, which has very close to the expected number of radio-loud quasars in the highest redshift bin, is inconsistent with a flat distribution at the 94% confidence level based on the χ^2 test.

A model for the evolution of the radio-loud fraction was constructed from the radio luminosity functions of Dunlop

& Peacock (1990). They derived separate luminosity functions for flat and steep spectrum objects, divided at a spectral index $\alpha = -0.5$, from a radio-selected sample of quasars and radio galaxies. Distinct versions of the model were formed from the steep and flat spectrum RLF1 MEAN- z luminosity functions, since radio spectral information is not available for most quasars in the LBQS. The luminosity functions were truncated at a radio luminosity equivalent to $\log L_{8.4} = 28.85$, two decades below the limit employed by Dunlop & Peacock (1990). The steep spectrum RLF1 function has an unphysical sharp upturn in number density at luminosities greater than this value. Function RLF2 remedies this with an imposed exponential cutoff at high luminosities, but the model based on this luminosity function does not match the observed data as well as the truncated RLF1. The true number of objects excluded by truncating the luminosity functions nearly 4 orders of magnitude above the radio-loud threshold of $\log L_{8.4} = 25$ is expected to be relatively small and have negligible impact on the predicted space density of radio-loud quasars. The $\log R_{8.4}$ radio-loud criterion was also employed, although indirectly, as the luminosity functions do not provide a one-to-one correspondence between radio luminosity and absolute magnitude. A radio luminosity threshold that depends on redshift, $\log L_{8.4} = 24.6 + 0.36z$, was used to approximate the $\log R_{8.4} = 1$ boundary (see Fig. 7 in Paper II). The normalization of the predicted fraction is set by the overall radio-loud fraction of the LBQS, as described, along with other details of the model, in Paper II. The predicted evolution of radio-loud fraction for various model parameters is shown with the observed smoothed fraction in Figure 5. The flat spectrum versions match the data well, including the modest rise around $z = 1$, at all except the highest redshifts, where the model does not reproduce the substantial rise in the fraction with $\log L_{8.4} > 25$. A similar local maximum occurs in the steep spectrum version, but at higher redshifts than observed.

Many of the quasars at high redshift, where the radio-loud fraction rises, have absolute magnitudes ~ -28 (Fig. 3a). It is not possible to disentangle redshift from M_B as the causal variable for the enhanced radio-loud fraction using only the LBQS data. However, the radio-loud fraction in the restricted redshift ($1.8 < z < 2.5$) sample of Miller et al. (1990) rises steeply for M_B brighter than -27 , indicating that elevated radio-loud fraction at bright absolute magnitudes is a common feature of optically selected quasars over a wide range in redshift. A similar ambiguity between M_B and z involving the rise at $z = 1$ was discussed in Paper II, where it was concluded that the effect is probably evolutionary. The new data support this, as there is no peak in radio-loud fraction at $M_B \sim -25.5$, the typical absolute magnitude for LBQS quasars with $z \approx 1$ (Fig. 3).

Optically selected quasars with $z > 3.0$ have a radio-loud fraction similar to that of the LBQS. McMahon, Irwin, & Hazard (1992) collected radio data for 29 quasars in the redshift range $3.5 < z < 4.7$, 4 of which have $\log L_{8.4} > 25$, and 3 have $\log R_{8.4} > 1$. Individual absolute magnitudes and redshifts for these quasars were not published. Schneider et al. (1992) observed 22 quasars at 5 GHz, which were reobserved at 1.5 GHz along with an additional 18 quasars by Schmidt et al. (1995). One target was detected in the original study, and it was also above the detection threshold at 1.5 GHz, along with two others that were not included in the first sample. The common detection has log

$L_{8.4} > 25$ and $\log R_{8.4} > 1$ for both observations. The remaining two low-frequency detections have $\log L_{8.4} > 25$, but only one is radio-loud by the $R_{8.4}$ criterion. The 40 quasars in the combined sample lie in a redshift interval $3.1 < z < 4.9$ and have absolute magnitudes ranging from -24.1 to -27.8 , with an average of -26.3 (values taken directly from Schmidt et al. 1995). Merging the high- z data sets gives a high-redshift radio-loud fraction of 7/69 (10%) for $\log L_{8.4} > 25$ and 5/69 (7%) using the luminosity ratio criterion, values consistent with the LBQS in the redshift range $1.5 < z < 2.5$. A Wilcoxon test on the combined LBQS and Schmidt et al. (1995) samples found no statistically significant (88% confidence level) difference in the redshift distributions of the detections with $\log L_{8.4} > 25$ and the remaining quasars, even without removing the high- z LBQS objects. Similar results were obtained when this combined sample was divided into five equal-number absolute magnitude bins. No significant differences in the redshift distributions were found among the bright bins, which contain the high- z quasars. Ten of the quasars in the Schmidt et al. (1995) sample lie in a redshift range that overlaps the LBQS ($3.1 < z < 3.4$), and none are radio loud. All of these have M_B fainter than -27.3 , lending further support to the conclusion that the apparent rise in radio-loud fraction at high z in the LBQS is a manifestation of a trend with absolute magnitude. Therefore, despite the appearance of Figure 5 at high redshift, there is substantial evidence that the radio-loud fraction of optically selected quasars does not evolve, aside from a modest peak around $z \approx 1$, over 65% of cosmic time, from $z = 0.2$ to redshifts approaching 5: (1) the radio-loud fraction at high z is consistent with that of the LBQS at moderate redshift; (2) a model that matches the LBQS data well at most redshifts does not reproduce the large fraction at high z ; and (3) M_B is the causal variable for the apparent rise in radio-loud fraction for $z \geq 3$ in the LBQS, indicated by higher redshift samples. The overall radio-loud fraction in the high- z sample and the LBQS data with $z < 3.1$, together covering the redshift range $0.2 < z < 4.9$, is 37/426 (9%) for $\log L_{8.4} > 25$ and 34/426 (8%) for $\log R_{8.4} > 1$.

A nearly unevolving radio-loud fraction is inconsistent with many previous studies, which compared the predominantly low- z PG with higher redshift optically selected samples and found a pronounced decrease in radio-loud fraction with increasing redshift (Peacock et al. 1986; Miller et al. 1990; Paper I; Schneider et al. 1992). La Franca et al. (1994) noted the same trend but found that evolution of the fraction was no longer indicated conclusively if the PG were excluded from the analysis. Recently, Schmidt et al. (1995) compared cumulative distributions of $\log R$ in four non-overlapping redshift ranges using data from a different survey for each distribution. The cumulative functions for the three highest redshift bins ($z > 1$) do not indicate substantial evolution over this range, but the low-redshift distribution ($z < 0.6$), containing only PG quasars, has a significantly larger fraction of quasars with high values of $\log R$, especially for $M_B < -24.5$ (see their Figs. 2 and 3). They concluded that the radio properties of quasars have evolved such that either the values of R have decreased by 2 orders of magnitude from $z = 0.3$ to 1.3 while maintaining the same distribution or that a population of quasars with very weak radio emission was more prevalent at $z > 1$.

The redshift coverage of the LBQS is extensive enough to generate cumulative distributions in three of the four red-

shift bins from Schmidt et al. (1995), listed in Figure 6, from a single well-defined survey, with the following constraints. The LBQS has little overlap with their highest redshift bin ($3.1 < z < 4.9$), in which they used their own observations. Many of the PG quasars in the low- z bin ($z < 0.6$) have $z < 0.2$, the lower redshift limit of the LBQS. The absolute magnitude discrimination used for most of the analysis by Schmidt et al. (1995), $M_B < -24.5$, excludes almost 90% of these low- z PG quasars but also restricts the LBQS to $z > 0.35$. Redshift-segregated cumulative distributions of LBQS quasars are shown in Figure 6, along with the high- z data of McMahon et al. (1992) and Schmidt et al. (1995) plotted as a single distribution. Kolmogorov-Smirnov tests were performed on these distributions in two ways. In one case, the true $\log R_{8.4}$ -values of the upper limits were assumed to all lie below the smallest value for a detection, as displayed in Figure 6. Only the portions of the distributions consisting of detections were compared to derive the test statistic. In the other case, the cumulative distributions were formed only from the detections, ignoring the upper limits completely. A significant difference was not found in any of these tests, the highest confidence level being 92%.

FIG. 6.—Cumulative distributions $G(>\log R_{8.4})$ of LBQS quasars in three redshift ranges: squares represent $z < 0.6$; filled circles represent $1.0 < z < 1.8$; and plus signs represent $1.8 < z < 2.5$. The high-redshift range $3.1 < z < 4.9$, represented by stars, contains the samples of McMahon et al. (1992) and Schmidt et al. (1995). Panel (a) includes all quasars with $M_B < -23$, and the absolute magnitude restriction is $M_B < -24.5$ in panel (b). The redshift bins, symbols, and absolute magnitude ranges match those used in Schmidt et al. (1995). Only the detections are plotted for clarity. All of the quasars in each redshift range were used to calculate the cumulative probabilities, assuming that all of the upper limits have $\log R_{8.4}$ -values less than the lowest detection.

The cumulative distributions in the four redshift ranges are similar, indicating no evolution. In particular, the $z < 0.6$ distribution, which had a cumulative fraction substantially higher than the other redshift ranges in the Schmidt et al. (1995) analysis, is slightly below that for $1.0 < z < 1.8$ for most values of $\log R_{8.4}$.

While the radio-loud fraction in the LBQS shows little dependence on redshift, the EMSS exhibits a rapid rise with redshift until reaching a plateau at $\approx 40\%$ for $z > 1$, as shown by the solid line in Figure 7. The fractions with $\log L_{8.4} > 25$ and $\log R_{8.4} > 1$ are nearly identical; the latter is slightly higher at low redshifts. Note that the behavior of the radio-loud fraction at the high-redshift end of this plot is particularly uncertain, as there are only four quasars in the EMSS sample with $z > 2$. This trend of radio-loud fraction with redshift is expected in X-ray selected samples as a result of the correlation between X-ray and radio luminosities, which is thought to arise from a synchrotron self-Compton component of the X-ray emission. At higher redshifts the flux limits of an X-ray survey correspond to higher luminosities, which, because of the correlation, tend to have higher radio luminosities.

A model for the relationship between radio-loud fraction and redshift in the EMSS was constructed using the expression for the dependence of X-ray luminosity on radio

luminosity given by Brinkmann et al. (1995). They parameterized the correlation as $\log(l_x) = A_{rq} + \beta_{rq} \times \log(l_r)$, where l_x and l_r are X-ray and radio monochromatic luminosities at 2 keV and 5 GHz, respectively. The constants were determined from ROSAT All-Sky Survey (Voges 1992) data on quasars in the 87 Green Bank radio survey (Condon et al. 1989) to be $A_{rq} = 8.44 \pm 0.40$, and $\beta_{rq} = 0.56 \pm 0.03$, where the uncertainties quoted here have been converted to 1σ errors assuming Gaussian probability. Rest frame 2 keV luminosities were determined from the survey flux limit at each redshift using a spectral index $\alpha = -1.13$ (Brinkmann et al. 1995). The corresponding value of l_r was used as the lower luminosity limit in the integrals of the Dunlop & Peacock (1990) steep and flat spectrum MEAN-RLF1 luminosity functions. The upper limit was the same as for the LBQS comparison model. These functions were also integrated over a redshift interval of 0.5 to find the total expected number of quasars. The number of radio-loud quasars was determined by integrating the same function using as the lower limit the larger of the radio-loud luminosity threshold, converted to the units employed in the luminosity function, or the luminosity determined from the correlation. This threshold was either $\log L_{8.4} = 25$ or the redshift-dependent value equivalent to $\log R_{8.4} = 1$ discussed earlier. The radio-loud boundary was not permitted to be lower than the luminosity corresponding to the 0.9 mJy flux limit of the radio observations of the EMSS (Stocke et al. 1991). The EMSS did not have a uniform X-ray flux limit. A weighted average for each integral was calculated from six values of limiting X-ray flux determined from Gioia et al. (1990), with the weights proportional to the number of EMSS objects found at each limiting flux.

The predicted overall EMSS radio-loud fractions range mostly between 10% and 20% [cf. the observed fractions of 9% ($\log L_{8.4}$) and 11% ($\log R_{8.4}$); see § 3] as the values of A_{rq} and β_{rq} were varied within their 1σ uncertainties. Values for these parameters were chosen so that the predicted average radio-loud fraction for the EMSS sample matched that observed. Each combination of radio-loud definition and luminosity function in the model was normalized separately. The predicted radio-loud fractions are plotted in Figure 7, along with the observed fractions. Most of the EMSS quasars are at low redshift (median z is 0.268), where the radio-loud fraction is small, resulting in the modest overall radio-loud fraction. While there is little difference between the steep and flat spectrum models, the form of the predicted redshift dependence varies widely within the 1σ uncertainties of the correlation parameters, and none of the model distributions match the observed one for $z > 1$. The excess of predicted radio-loud quasars at high redshifts and the relative depletion at lower z are directly connected, due to the normalization of the model by the observed average fraction. Radio luminosity has a spread of almost 2 dex for all l_x in the Brinkmann et al. (1995) sample, which would lower the predicted radio-loud fraction, especially at high redshift. In particular, the model fraction would not reach 100% until a redshift at which the radio luminosity predicted from the X-ray limiting flux attained a value ~ 1 dex above the radio-loud boundary, since the intrinsic scatter in l_r would provide some radio-quiet quasars up to this point. While these simple models do not conform to the observed data over all redshifts, they indicate that the rise in radio-loud fraction for $z < 1$ is an expected feature of the X-ray-radio luminosity correlation.

FIG. 7.—Smoothed radio-loud fraction as a function of redshift in the EMSS sample using the (a) $\log L_{8.4} > 25$ and (b) $\log R_{8.4} > 1$ criteria. Solid lines indicate the observed data, while dotted and dashed lines represent the flat and steep spectrum model predictions, respectively. Values for the data as well as the models were calculated with a redshift smoothing interval of 0.5. The error bars are analogous to those in the other plots of smoothed radio-loud fraction.

5. DISCUSSION

Understanding the connection between the radio emission and the properties of the central engines of quasars continues to be an elusive problem. The constancy of the radio luminosity distribution over more than 2 orders of magnitude in optical luminosity and other similarities between radio-loud and radio-quiet quasars are somewhat surprising in the context of the standard black hole model of AGNs. The radio emission mechanism appears to be only weakly tied to the mass accretion rate that presumably drives the optical and near-UV emission. Some models decouple the radio and optical emission, an important feature in attempting to explain the results from the LBQS and other studies that show little connection between these emission mechanisms. Coleman & Dopita (1992) hypothesized that quasar radio luminosity may depend on the angle of the accretion disk with respect to the rotation axis of the central supermassive black hole. More recently however, Wilson & Colbert (1995) proposed that the hole masses and accretion rates are similar in radio-loud and quiet quasars, which would account for the similarities in emission features at other wave bands. The total radio luminosity is presumed to derive from the spin energy of the hole via the Blandford-Znajek process (Blandford & Znajek 1977). Powerful radio emission arises only from massive rapidly rotating holes, which in the view of Wilson & Colbert are produced exclusively by mergers of two holes with similar large masses. They assume that accretion of material from the host galaxy is insufficient to spin up the hole to the necessary level because of either loss of angular momentum to gas around the hole or variable orientation of the accretion disk with respect to the spin axis of the hole. Therefore, two quasars with identical black hole masses and accretion rates can have vastly different radio luminosities depending on whether the hole was (1) built up by accretion and/or the merger of a large and small hole or (2) produced by the coalescence of two massive holes. The infrequency of mergers of galaxies containing massive black holes accounts for the rarity of powerful radio sources. The Wilson & Colbert scenario is qualitatively consistent with the LBQS results that radio luminosity is not correlated with M_B and that the radio-loud fraction is constant over most values of M_B .

A different radio emission mechanism that is correlated with optical luminosity may be responsible for the rise in radio-loud fraction at bright absolute magnitudes ($M_B \leq -28$), seen also by Miller et al. (1990) and La Franca et al. (1994). Stocke et al. (1992) noted that radio and optical luminosity are correlated among the radio-quiet PG quasars. The detection frequency among the radio-quiet objects in the LBQS is too low to directly test for such a correlation, but there is indirect evidence that such a correlation is present: the fraction of radio detections among the radio-quiet LBQS quasars does not show a trend with absolute magnitude. If there were a null or negative correlation between the luminosities, the detection fraction among these objects would decline at higher redshifts, corresponding to brighter M_B , since the radio luminosity of the 3σ detection limit increases with z . Stocke et al. (1992) hypothesized that the correlation arises from a component of radio emission powered by the kinetic energy of outflowing material driven by optical/UV radiation pressure. Radiation pressure and consequently outflow velocity are

not large enough to produce $\log L_{R,4} > 25$ by this mechanism alone for $M_B \geq -28$, but this emission component could exceed the radio-loud threshold ($\log L_{R,4} > 25$) at the brightest absolute magnitudes in the LBQS. In this scenario the enhanced radio-loud fraction at $M_B \leq -28$ arises from the combination of the black hole spin-driven component, which is independent of M_B , and the onset of powerful radio emission driven by outflows. The presence of two radio emission mechanisms, one correlated with optical luminosity, the other independent, accounts for the observed features of the radio luminosity distribution as a function of M_B in the LBQS.

Neither radio emission mechanism explains the low radio-loud fraction observed at $M_B > -24$ in the EMSS and the PG surveys. Falcke et al. (1995) proposed that the decrease in radio-loud fraction at faint optical luminosities can be explained by a consolidation of two standard quasar unification schemes incorporating obscuring tori (e.g., Barthel 1989; Urry, Padovani, & Stickel 1991; Antonucci 1993). Radio-loud AGNs with weaker (presumably fainter M_B) engines are observed as either BL Lac objects or FR I radio galaxies, not as quasars, as the opening angle of the torus is not wide enough in these objects for a direct view of the nuclear region free from contamination by the jet emission. This explanation is not directly tenable for the LBQS, since the incidence of radio-loud quasars is not observed to change at faint M_B . It is possible that, due to some poorly understood difference between the PG and the LBQS, orientation effects are present in the LBQS at a weaker level than originally proposed by Falcke et al. (1995) to explain the PG results. If the lines of sight to the radio-loud quasars with $M_B > -24$ lie close to relativistic jets (to avoid obscuration by the tori), the emission lines are expected to have low equivalent widths due to their dilution by Doppler-boosted optical synchrotron emission: i.e., these AGNs would be BL Lacertae-like, but not so much that they would be classified as BL Lac objects. However, the radio-loud LBQS quasars with faint absolute magnitudes are not close to being classified as BL Lac objects, as four out of six have prominent emission lines, and the lines in the remaining two, while weaker, still have Mg II equivalent widths of approximately 15 Å (Table 2). AGNs are classified as BL Lac objects typically when they have emission line equivalent widths less than 5 Å (e.g., Stocke et al. 1991). The model does not appear to be applicable to optically selected quasar samples, as the proposed orientation effect is not present in the LBQS at a detectable level, and a reasonable alternative explanation exists for the PG, although the model may partially account for the decrease observed in the EMSS.

6. SUMMARY

1. The distribution of radio luminosity does not depend on absolute magnitude over most of the range of M_B in the LBQS. The radio-loud fraction remains constant at $\approx 10\%$ for $-28 \leq M_B \leq -23$ but rises at brighter absolute magnitudes to $(20 \pm 10)\%$ for $\log R_{8,4} > 1$ and $(35 \pm 15)\%$ for $\log L_{8,4} > 25$.

2. Radio-loud fraction is nearly unevolving at a value of $\approx 10\%$ in the LBQS and three high- z optically selected samples, which together span a redshift range from $z = 0.2$ to redshifts approaching 5.

3. The PG survey differs significantly from several optically selected samples. The sudden decrease in radio-loud

fraction for M_B fainter than -24 observed in the PG is not present in the expanded LBQS sample. The fraction of quasars with $\log R_{9,4} > 1$ in the PG for $M_B > -24$ is not significantly different from the LBQS fraction, but the PG has a much greater percentage of radio-loud quasars at brighter absolute magnitudes. High radio-loud fraction in the PG relative to other optically selected samples has led several investigators to conclude that the fraction evolves to lower values at higher z . This trend is not seen in the LBQS, which provides a single well-defined sample with wide redshift coverage ($0.2 < z < 3.4$). The anomalously high radio-loud fraction in the PG sample remains unexplained.

4. The radio properties of the X-ray selected EMSS also differ from those of the LBQS. The rapid rise in radio-loud fraction observed for $M_B \approx -24$ arises primarily from a well-established correlation between X-ray and radio luminosity. However, there is still a dependence of radio-loud fraction on M_B in the redshift range $0.4 < z < 0.7$, an inter-

val containing substantial numbers of quasars both brighter and fainter than $M_B = -24$.

5. The behavior of the radio properties of the LBQS quasars as a function of M_B is consistent with the existence of two radio emission mechanisms, one correlated with optical luminosity, the other independent.

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APPENDIX C.

HOST GALAXIES OF QUASARS

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HUBBLE SPACE TELESCOPE IMAGING OF $z \geq 0.4$ QUASAR HOST GALAXIES SELECTED BY QUASAR RADIO AND OPTICAL PROPERTIES¹

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ABSTRACT

A sample of 16 quasars selected from the Large Bright Quasar Survey in the redshift range $0.4 < z < 0.5$ has been imaged in the *R* band with the Planetary Camera on the WFPC2 instrument of the *Hubble Space Telescope*. The host galaxy magnitudes are mostly similar to or brighter than L^* , and the host luminosity is positively correlated with the luminosity of the quasar nuclear component. There is no distinction in host galaxy magnitude between radio-loud and radio-quiet quasars, assuming they are all of the same galaxy type. Many of the host galaxies in the sample have small axial ratios, which may indicate that they are inclined disk systems. Alternatively, this elongated appearance may be due to bars or other distinctive morphological features which are visible while the bulk of the underlying lower surface brightness components of the host galaxy are not.

Subject heading: galaxies: active — quasars: general

1. INTRODUCTION

The refurbished *Hubble Space Telescope* (*HST*) has provided a substantial boost to the study of quasar host galaxies because of its ability to resolve the inner structures of the hosts close to the quasar nucleus. Most quasars imaged to date with *HST* lie at redshifts $z < 0.3$ and have low to moderate nuclear source luminosities (Bahcall, Kirhakos, & Schneider 1994, 1995a, 1996; Hutchings et al. 1994; Boyce et al. 1997), although Bahcall, Kirhakos, & Schneider (1995b) and Disney et al. (1995) include objects with $M_V \approx -27$ in the cosmology adopted for this paper ($H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = 0.5$). The detected host galaxies are typically at least as bright as the Schechter function's characteristic luminosity L^* , but several undetected hosts have estimated upper limits of $\leq L^*$ (Bahcall et al. 1995b). The most recent determination of L^* in the *R* passband is $M_R^* = -21.8$ (Lin et al. 1996). While classifying the host galaxies as either disk or elliptical systems is often difficult because of contamination by the quasar and the frequent occurrence of disturbed morphologies, most hosts detected to date in the *HST* observations appear to have luminosity distributions consistent with early-type galaxies (Disney et al. 1995; Bahcall et al. 1997; summarized in McLeod & Rieke 1995b). Radio-quiet quasars, which were once thought to reside in spiral host galaxies (e.g., Smith et al. 1986), appear to exist in both elliptical (e.g., Hutchings & Morris 1995) and disk (e.g., Hutchings et al. 1994) systems. Several of the hosts appear to be involved in interactions or mergers (e.g., Bahcall et al. 1995a), especially the hosts of infrared luminous quasars (Hutchings & Morris 1995; Boyce et al. 1997).

2. THE SAMPLE

Candidates for this study were selected from the Large Bright Quasar Survey (LBQS; Hewett, Foltz, & Chaffee 1995 and references therein), the largest homogeneous optical quasar survey to date, containing over 1000 quasars in the redshift range $0.2 < z < 3.4$. The LBQS was compiled from digitized UK Schmidt objective-prism plates, with candidates selected based on one or more well-defined selection criteria: (1) blue color; (2) strong emission or absorption features; or (3) strong continuum breaks. Advantages of the survey include (1) a greater than 99% success rate in classifying candidates; (2) sensitivity to almost all known types of quasars, with the exceptions of the rare classes of objects with red featureless continua or large-amplitude photometric variations; (3) detection efficiency that varies smoothly and monotonically with redshift; (4) quantifiable selection criteria, enabling the calculation of the selection probability as a function of quasar luminosity, redshift, and spectral energy distribution; and (5) the inclusion of candidates whose images on the discovery plates are resolved due to an underlying host galaxy.

This last point is particularly important for studies such as this one. Several previous optically selected quasar surveys required that a candidate appear pointlike, a seeing-dependent and often subjective criterion which could potentially exclude quasars with bright host galaxies. Quasars with typical colors and emission-line strengths at the redshifts of the sample selected for WFPC2 imaging satisfy the LBQS magnitude limit and selection criteria as long as the total luminosity of the host galaxy is approximately equal to or less than that of the quasar (Hooper et al. 1995; Hewett et al. 1995). Since the absolute magnitudes of the quasars in the *HST* sample fall in the range $-25 < M_B < -23$, very few known galaxies would be excluded a priori.

The radio properties of the LBQS have been studied using pointed Very Large Array 8.4 GHz snapshots of one-third of the sample (359 targets), reaching a median detection threshold of about 0.3 mJy (Hooper et al. 1996). The fraction of radio-loud quasars (8.4 GHz luminosity $> 10^{25} \text{ W Hz}^{-1}$) is constant at $\approx 10\%$ within the errors over almost the full redshift range of the survey and across nearly the entire

¹ Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

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TABLE 1
RESULTS OF WFPC2 ANALYSIS

Name (1)	z (2)	$\log L_{4.8}$ (W Hz ⁻¹) (3)	R (quasar) (4)	M_R (quasar) (5)	R ($r^{1/4}$) (6)	M_R ($r^{1/4}$) (7)	R (disk) (8)	M_R (disk) (9)	Axial Ratio (10)
0020+0018.....	0.423	<23.50	19.52	-22.39	19.33	-23.42	20.17	-22.19	0.7
0021-0301.....	0.422	<23.50	19.15	-22.75	19.87	-22.87	20.67	-21.68	0.6
0100+0205.....	0.393	<23.45	17.81	-23.93	19.97	-22.54	20.70	-21.47	0.3
1138+0003.....	0.500	25.60	17.94	-24.35	19.33	-23.97	20.26	-22.54	0.9
1149+0043.....	0.466	<23.66	17.37	-24.76	19.17	-23.91	19.77	-22.84	0.6
1209+1259.....	0.418	<23.52	19.56	-22.32	20.20	-22.51	20.85	-21.48	0.6
1218+1734.....	0.445	25.33	18.36	-23.66	19.63	-23.28	20.33	-22.15	0.6
1222+1010.....	0.398	<23.46	18.46	-23.30	19.36	-23.18	20.59	-21.60	0.3
1222+1235.....	0.412	25.19	17.86	-23.98	18.85	-23.81	19.55	-22.74	0.6
1230-0015.....	0.470	25.77	17.51	-24.64	18.96	-24.14	19.65	-22.98	0.4
1240+1754.....	0.459	<23.47	18.13	-23.96	19.50	-23.50	20.40	-22.16	0.3
1242-0123.....	0.491	<23.47	18.26	-23.99	19.51	-23.73	19.91	-22.84	0.4
1243+1701.....	0.459	<23.41	18.71	-23.38	20.84	-22.34	20.92	-21.64	0.1
2214-1903.....	0.397	<23.48	18.98	-22.77	19.18	-23.35	19.75	-22.43	0.5
2348+0210.....	0.504	25.56	17.18	-25.13	19.57	-23.75	20.25	-22.57	0.4
2351-0036.....	0.460	26.40	17.92	-24.18	20.07	-23.02	20.87	-21.70	0.4

absolute magnitude range ($-28 < M_B < -23$). The only changes occur at the brightest absolute magnitudes, $M_B < -28$, where the radio-loud fraction rises to $\approx 30\%$, and there is also a slight rise around $z \approx 1$.

Selection of targets for WFPC2 imaging was dictated by several desiderata: (1) a radio luminosity span typical of optically selected quasars; (2) nearly identical redshifts to avoid problems of interpretation due to evolution and to provide a uniform rest-frame spatial resolution scale; and (3) quasar absolute magnitudes bright enough to exclude Seyfert galaxies, yet not so bright that the nucleus completely obscures the host galaxy. LBQS quasars in the redshift range $0.4 < z < 0.5$ satisfy these criteria. All six known LBQS radio-loud quasars within this redshift interval were selected. These objects have radio luminosities ranging up to 3×10^{25} W Hz⁻¹. Ten quasars with 8.4 GHz luminosities $\leq 10^{25.5}$ W Hz⁻¹, well below the radio-loud threshold, were selected to complete the sample. The radio-quiet quasars were chosen semiuniformly from the absolute magnitude range $-25 < M_B < -23$, an interval containing nearly all of the LBQS quasars with redshifts $0.4 < z < 0.5$.

3. DATA REDUCTION AND ANALYSIS

The quasars were centered on the Planetary Camera (PC) ($0''.046$ pixel⁻¹) of WFPC2 and imaged through the F675W filter, which approximates Johnson R . Total integration times of 20–30 minutes were divided into three or four separate exposures to avoid saturation of the quasar core and to facilitate cosmic-ray removal. The gain was set to 14 electrons per data number in all exposures. Read noise, 7 electrons on the PC, and digitization effects dominated photon noise from the background in all of the images. The pipeline data reduction products were used, which are corrected for bias, dark current, and flat-fielding.

The reduced data were analyzed by cross-correlating two-dimensional galaxy and point-spread function (psf) models with the data to determine the optimal values of host galaxy flux, exponential scale length or effective radius, axial ratio, and position angle, as well as the quasar centroid and flux. A description of the general two-dimensional cross-correlation method was presented by Philipps & Davies (1991); Boyce,

Philipps, & Davies (1993) discussed its application specifically to quasar host galaxy analysis. Advantages of this method include higher accuracy and sensitivity than one-dimensional profile fitting, accurate determination of the flux of the quasar nucleus even in low signal-to-noise data where the nature of the host galaxy is rather uncertain, and relative insensitivity to missing data or the presence of other nearby galaxies. Two-dimensional models consisting of a psf, generated with Version 4.1 of the "Tiny Tim" software (Krist 1995, 1997), and either a disk or elliptical galaxy component were repeatedly cross-correlated with the region around the quasar in the WFPC2 images while varying the psf and model galaxy parameters. The set of parameters that maximized the cross-correlation function was adopted. The two-dimensional technique was checked by analyzing one-dimensional profiles derived from elliptical isophote fits to the more prominent host galaxies, cases in which this older method is still expected to be fairly robust. The magnitudes from the one-dimensional technique were typically ≈ 0.3 mag brighter than those from the cross-correlation.

Fluxes were converted to Johnson R using equation (8) of Holtzman et al. (1995). This conversion has a color term of less than 0.15 mag for typical disk and elliptical galaxy and quasar colors at $z \approx 0.5$. Colors for galaxies and quasars, as well as k -corrections for conversion to rest-frame absolute magnitudes, were obtained from Coleman, Wu, & Weedman (1980) and Cristiani & Vio (1990), respectively. Minor (≤ 0.1 mag) corrections were applied to the derived magnitudes to account for charge transfer efficiency effects and for differences in the flux measurement methods between the calibration of the WFPC2 photometric system and the LBQS data, as described in Holtzman et al. (1995).

4. RESULTS

Numerical results of the analysis are presented in Table 1, which lists, for each target, (1) the source name; (2) the redshift from Hewett et al. (1995); (3) the 8.4 GHz luminosity (W Hz⁻¹) from Hooper et al. (1995, 1996); (4) apparent and (5) absolute R magnitudes for the quasar nuclear component; (6) apparent and (7) absolute R magnitudes for the host galaxy using an exponential disk template; (8) apparent and (9)

absolute R magnitudes for an $r^{1/4}$ model template; and (10) the axial ratio of the host galaxy. The quasar magnitudes are relatively insensitive to the galaxy template used in the analysis, differing by typically 2% or less between the two models; the average of the derived quasar magnitudes is listed in columns (4) and (5). The integrated host galaxy fluxes, however, are typically 0.5–1 mag fainter for the disk model, and both are listed in the table. Axial ratios derived from the two models are identical in most cases, and the average is listed in the few that are not.

Scaled two-dimensional psfs, normalized to the flux derived for the nuclear point source, were subtracted from the images in order to see the host galaxies better. The region around each quasar is shown in Figure 1 (Plates L12–L16) before (left column) and after (right column) psf subtraction. The stretch was adjusted to show the faint outer isophotes in most cases, although the hard-copy reproduction quality of these faint features is poor. Each pixel corresponds to a projected distance of 310 pc at $z = 0.45$, the midpoint of the redshift range of the sample, $0.4 < z < 0.5$. The psf-subtracted images contain a discontinuity at the center where the quasar component has been subtracted. This is an artifact of the subtraction and is found after a scaled psf is subtracted from a stellar image. The discontinuity often appears as a small negative feature in the images unless the central surface brightness of the host galaxy is relatively high. Apparent companion objects lying very close to the quasar were included in the displayed field. Many of the fields contain extended objects on the PC images which are not shown here. The two pointlike features close to the quasar 0100+0205 are likely to be artifacts associated with the diffraction spikes.

Rigorous analysis of the uncertainties in the derived parameters and determination of the limiting magnitude of a detectable host galaxy are challenging problems, which will be addressed in a subsequent paper. However, some information on the reliability of the analysis technique and detection sensitivity was obtained by applying the two-dimensional cross-correlation method to stars found in the Planetary Camera quasar fields. Comparison with the quasar results is complicated by the fact that the stars are typically substantially fainter than the quasars. The brightest star analyzed, in the field of 1218+1734, had $R = 20.02$, 0.5 mag fainter than the faintest quasars in the sample (0020+0018 and 1209+1259). The “host galaxy” magnitudes produced for this star were $R = 21.71$ and $R = 22.23$ for the elliptical and disk templates, respectively, in each case at least 1.4 mag fainter than the results for the quasars. One quasar, 1243+1701, had a very low axial ratio of 0.1 and an unphysically small effective radius and exponential scale length of ≤ 300 pc. Either there is little or no detectable flux from the host galaxy, or the host has an unusual morphology and low surface brightness, for which the standard templates are inadequate. Some extended residual emission is seen in the psf-subtracted image of this field (Fig. 1). The small companion very close to the quasar did not affect the analysis, since similar results were obtained after it had been removed from the image. Until additional analysis is performed, it is not certain whether a host has been detected for this quasar or others which have faint extended emission only in the near vicinity of the quasar nucleus. Consequently, the discussion that follows will consider both the entire sample and a subset consisting of the most clearly visible host galaxies.

FIG. 2.—Host galaxy absolute magnitude derived from (a) elliptical and (b) disk templates plotted against absolute magnitude of the quasar nuclear component. Filled circles are radio-loud quasars, and asterisks represent radio-quiet sources.

5. DISCUSSION

Absolute R magnitude (M_R) of the quasar nuclear component is plotted against host galaxy M_R derived from $r^{1/4}$ and disk templates in Figure 2, with radio-loud and radio-quiet quasars denoted by filled circles and asterisks, respectively. The detected host galaxies are luminous; magnitudes derived from $r^{1/4}$ fits and from many of the disk fits are brighter than $M_R = -21.8$ (Lin et al. 1996). Published values of L^* differ by up to 1 mag, but this does not alter the basic result that the elliptical fits are mostly brighter than the characteristic luminosity, while the magnitude distribution derived from disk templates straddles L^* . Note in particular that there is not a dominant population of low-luminosity host galaxies in the LBQS sample. Host galaxy luminosity is positively correlated with quasar nuclear luminosity at the 99% confidence level for the $r^{1/4}$ and disk template magnitudes, as indicated by a Kendall's τ test. This correlation is consistent with the existence of a minimum host galaxy luminosity which increases with quasar luminosity, a trend noted by McLeod & Rieke (1995a, 1995b) using H -band host galaxy magnitudes in lower redshift samples. The lower bound to the host galaxy luminosities, converted to the R band, is about 0.5 (disk template) or 1.5 (elliptical template) mag fainter than the lower luminosity envelope of the LBQS host galaxies. The host galaxy magnitudes deviate from this trend, becoming roughly constant with quasar magnitude, for quasars fainter than $M_R \approx -24$. A

similar break occurs at roughly the same magnitude, after adjusting for differences in passband and cosmology, in the McLeod & Rieke (1995a, 1995b) data. The radio-loud quasars all lie in the brighter half of the range of quasar nuclear M_B . This was not an effect of the selection of the radio-loud quasars, as the majority were in the fainter half of the range of M_B . There is no apparent distinction between the host galaxy magnitudes of radio-loud and radio-quiet quasars with similar nuclear component luminosities for a single type of galaxy template. However, if the host galaxy morphologies differ between radio luminosity classes, such that radio-loud quasars are in ellipticals and radio-quiet nuclei reside in spirals, then the hosts of luminous radio sources would be consistently brighter by about 1 mag.

The axial ratios derived for the host galaxies have a median of 0.5, with only two objects having ratios greater than 0.6. These values are significantly lower than is typical for elliptical galaxies, which generally appear less elongated. A Kolmogorov-Smirnov (KS) test indicates that the distribution of axial ratios in a sample of 171 elliptical galaxies from Ryden (1992) differs from the LBQS results at a confidence level greater than 99.99%. Fewer than 5% of the ellipticals have axial ratios less than 0.6, where the bulk of the LBQS objects lie. This result may indicate that the LBQS sample consists primarily of inclined disk systems, which differs from the conclusion of several other *HST* imaging studies that early-type host galaxies are prevalent, even among radio-quiet objects. McLeod & Rieke (1994a, 1994b) did not find any host galaxies with measurable axial ratios less than 0.5 in a sample drawn from the Palomar-Green (PG) quasar survey (Schmidt & Green 1983), even among galaxies which appeared to be spirals. They attributed the lack of inclined disk systems to the additional reddening of the active nucleus caused by this viewing geometry, which would cause the quasar to fail the UV-excess selection criterion of the PG. Increased extinction would also remove potential candidates by making them fainter than the PG magnitude limit. However, very few quasars that are intrinsically too bright to be included in the PG would cross the magnitude selection boundary of the survey due to extinction from an inclined host, because the bright flux limit of the PG exceeds the apparent fluxes of virtually all known quasars. The LBQS selection is based on spectral features in addition to color, and its bright magnitude limit is roughly coincident with the faint limit of the PG, so it is reasonable to expect that spiral host galaxies with higher inclinations could be included

in the LBQS. Another possibility is that the detected portions of some of the host galaxies are bars, particularly in the cases of very low axial ratios. These systems could have nearly face-on disks that are too faint to detect, leaving only the bar components visible.

Half of the sample, the eight targets with the most obvious host galaxies in Figure 1, was examined separately to ensure that the major results are not skewed by the lower surface brightness host galaxies, for which only marginal emission is seen and which may not have been detected in some cases. This subsample contains three radio-loud quasars (1222+1235, 1230-0015, and 2348+0210) and five radio-quiet quasars (0020+0018, 0021-0301, 1149+0043, 1222+1010, 2214-1903). The absolute magnitudes of the quasar nuclear components in these objects span the range of the full sample. A correlation with host galaxy luminosity is still suggested visually, particularly among the more luminous quasars, but the trend is too weak given the reduced sample size to produce a significant result from the Kendall's τ test (86% confidence). Radio-loud and radio-quiet quasars with similar central component magnitudes in the subsample have similar host galaxy luminosities when derived from the same class of galaxy template. Only one host galaxy in the restricted sample has an axial ratio greater than 0.6, and the flattened morphologies of the remaining objects can be easily seen in most cases in Figure 1. The KS test using Ryden's (1992) sample of elliptical galaxies was repeated, with the conservative assumption that the host galaxies not included in the subsample had relatively round morphologies closely matching the axial ratio distribution of the ellipticals. The two distributions were different at greater than the 99% confidence level, indicating that there is a significant component of clearly flattened systems in the LBQS sample.

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FIG. 1.—Each pair of linearly stretched gray-scale images across the page shows the field around one of the quasars in the sample. The quasar and its host galaxy are shown in the left-hand panel, and the same field after the nuclear component has been subtracted is displayed in the right-hand panel. A direction indicator (the arrow points north and the other line east) and size scale are printed between each pair of panels. The LBQS designation of the quasar is listed above each image pair. These are only the centers of the WFPC2 PC frames, sized to include all detectable emission from the host galaxies and any particularly close apparent companions.

HOOPER, IMPEY, & FOLTZ (see 480, L97)

PLATE L12

LBQS 1138+0003

LBQS 1149+0043

LBQS 1209+1259

LBQS 1218+1734

FIG. 1—Continued

HOOPER, IMPEY, & FOLTZ (see 480, L97)

PLATE L13

LBQS 1222+1010

LBQS 1222+1235

LBQS 1230-0015

FIG. 1—*Continued*

HOOPER, IMPEY, & FOLTZ (see 480, L97)

LBQS 1240+1754

LBQS 1242-0123

LBQS 1243+1701

FIG. 1—Continued

HOOPER, IMPEY, & FOLTZ (see 480, L97)

PLATE L15

LBQS 2214-1903

LBQS 2348+0210

LBQS 2351-0036

FIG. 1—Continued

HOOPER, IMPEY, & FOLTZ (see 480, L97)

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