THE ASTROPHYSICAL JOURNAL, 244:5–11, 1981 February 15

MULTIFREQUENCY RADIO OBSERVATIONS OF OPTICALLY SELECTED QUASARS

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Received 1980 March 24; accepted 1980 August 26

ABSTRACT

A complete sample of 12 radio sources stronger than 10 mJy at 5.0 GHz are identified with optically selected quasars (discovered with the Curtis-Schmidt telescope) on the basis of precise radio-optical position coincidence. Radio spectra determined from flux densities at 0.408, 1.465, 2.29, 5.0, and 14.5 GHz indicate synchrotron self-absorption in 11 cases. The only steep-spectrum source is resolved by the VLA at 1.465 GHz. It is shown that the spectral-index distributions of radio sources identified with optically selected quasars can vary only weakly with radio finding frequency since the radio number-flux-density relation of these identifications is so flat. The number-magnitude distributions of radio-selected and optically selected quasars are compared and interpreted in terms of a radio-optical core-flux correlation. Finally, physical differences between radio-selected and optically selected quasars are considered. We find that differing orientations of relativistically beamed radio jets cannot explain the differences between the radio luminosity functions of radio-selected and optically selected quasars.

Subject headings: quasars — radio sources: spectra

I. INTRODUCTION

A sample of 122 of the 125 optically selected quasars (hereafter OSQs) from the Curtis-Schmidt objective prism survey of the region $-42\overset{\circ}{.}5 < \delta < -37\overset{\circ}{.}5$, $19^{h}50^{m} < \alpha < 05^{h}46^{m}$ (Osmer and Smith 1980) were first observed with the Parkes 64 m telescope at 5.0 and 14.5 GHz (Smith and Wright 1980). We have reobserved the Parkes radio identifications at 2.29, 1.465, and 0.408 GHz in order to determine detailed radio spectra and structures of a complete sample of high-redshift OSQs for the first time. The 1.465 GHz observations were made with the Very Large Array (VLA) to yield the accurate radio positions needed to confirm the Parkes identifications. The VLA maps also allow us to see if the radio sources are compact or extended on the scale of several seconds of arc. These observations yield a complete sample of 12 confirmed radio identifications stronger than 10 mJy at 5.0 GHz. The observational methods and results are described in § II.

The statistical properties of quasars—both optically selected quasars (OSQs) and radio-selected quasars (RSQs)—are considered in § III. We show that the very slow increase in the number of radio identifications with increasing radio sensitivity has two effects on complete samples of radio identifications of OSQs: (i) it is very difficult to attain reliable identifications with confusion-limited pencil-beam observations, and (ii) spectral-index distributions of complete samples of radio sources identified with OSQs are nearly independent of the radio identification frequency. The final topic covered in § III is the difference between the optical magnitude distributions of complete samples of OSQs and RSQs.

The physical differences between OSQs and RSQs are discussed in § IV. Comparisons of complete samples of RSQs found at low radio frequencies with

[1]Alfred P. Sloan Foundation Fellow.
[2]NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

complete samples of OSQs indicate that the differences between the radio luminosity functions of RSQs and OSQs cannot be entirely due to differing orientations of relativistic jets in otherwise similar objects. No evidence for a strongly frequency-dependent absorption was found in the radio spectra of our OSQ radio identifications. It is not clear whether most OSQs have only very weak infrared and optical synchrotron emission, or whether the present sample, selected on the basis of optical emission lines, is different from OSQ samples which might be found via other characteristics such as optical polarization or variability.

II. OBSERVATIONS

The original radio observations and identifications were made at 5.0 and 14.5 GHz in several observing sessions during 1978 with the Parkes 64 m telescope (Smith and Wright 1980). Those radio identifications with 5.0 GHz flux densities above 10 mJy were observed with the VLA, and some of the identifications were rejected as nearby confusing sources. The confirmed identifications form a complete sample suitable for statistical studies. The Parkes 5.0 and 14.5 GHz flux densities (Smith and Wright 1980) of all sources in this sample are listed in Table 1.

The observations at 2.29 GHz were made on 1978 March 19 and 20 with the Tidbinbilla Interferometer (Batty *et al.* 1980). Briefly, this instrument has as elements the 26 and 64 m antennas of the Deep Space Network near Canberra, Australia, with a baseline of 200 m on a north-south line. The system temperature is 25 K, and the bandwidth is 12 MHz. All observations were made with right-circular polarization. Each source was observed for 5 minutes at one hour angle only. The observed system noise is only 1 mJy after 5 minutes of integration; but the instrument is confusion limited, with a measured confusion error of 5 mJy. The phase and flux-density calibrations are based on observations of a number of sources from the Parkes $-4° < \delta < +4°$ (Wall, Shimmins, and Merkelijn 1971) and $-35° < \delta < -30°$ (Shimmins and Bolton 1974) 2.7 GHz survey catalogs. The overall intensity-proportional flux-density error is 2% rms.

The 2.29 GHz flux densities and their errors are listed in Table 1. The identifications of these radio sources with the associated OSQs are all supported by the measured interferometer phases. Only the source near Q2355−389 showed a significant departure from the expected phase, in agreement with the VLA observations which show a nearby confusing source.

Those 19 OSQs with 5.0 GHz flux densities of 10 mJy or greater (Smith and Wright 1980) were observed at 1.465 GHz with the VLA during 1978 June 16–18. These observations yielded (i) accurate radio positions which could be used to confirm or reject the Parkes radio identifications, (ii) 1.465 GHz flux densities to help determine the detailed radio spectra of the identified OSQs, and (iii) radio structures as determined with the 18″ by 3″ beam of the VLA. In addition the OSQ Q0000−398, whose 5.0 GHz flux density is only 9 mJy, was observed because of its reported large angular size. For a discussion of the results on this object, see Condon, Buckman, and Smith (1979).

There were six antennas operating at 1.465 GHz on the southwest arm of the VLA at the time of these observations, with baselines between 3500 and 52000 wavelengths long. From six to nine scans were made of each source. The scans were spread uniformly over the hour-angle range for which the source elevation exceeded 10°, typically $\pm 2^h$ from transit. The integration time per scan varied from 3 to 8 minutes, depending on the source's 5.0 GHz flux density, so the total integration time per source was between 20 and 60 minutes.

TABLE 1

FLUX DENSITIES OF SOURCES STRONGER THAN 10 mJy AT 5.0 GHz IDENTIFIED WITH THE OPTICALLY SELECTED QUASARS

	FLUX DENSITIES (mJy) AT				
SOURCE	0.408 (GHz)	1.465 (GHz)	2.29 (GHz)	5.0 (GHz)	14.5 (GHz)
Q0205−379...	28±15	24± 6	31± 5	28± 4	14± 7
Q0329−385...	0±16	30± 3	50± 5	76± 4	53± 5
Q0353−383...	110±20	91± 7	98± 5	98± 4	36± 4
Q0420−388...	190±15	204±13	140± 6	107±11	57± 6
Q0448−392...	116±25	630±43	727±20	768±77	351±35
Q2204−408...	−4±20	25± 3	23± 5	31± 4	23± 4
Q2217−406...	135±27	113± 8	111± 5	105±11	78± 8
Q2219−394...	600±17	200±19	155± 6	136±14	52± 5
Q2227−399...	740±16	660±45	567±15	631±63	720±72
Q2321−375...	550±20	345±23	388±10	436±44	540±54
Q2329−376...	...	60± 6	66± 5	51± 5	29± 6
Q2355−389...	30±17	15± 4	...	18± 4	13± 6

Low-declination phase-calibration sources (0104−408, 0402−362, 2149−306, and 2227−399) were observed every 15–20 minutes. Flux-density calibrations were made by referencing the observed amplitudes of these sources to that of DA 267, whose 1.465 GHz flux density was taken to be 2.75 Jy. Calibration uncertainties in the positions are about 0″.5 in right ascension and 1″ in declination. The flux-density calibration error is approximately 5 %.

These observations synthesized elliptical beams with major axes from 12″ to 20″ between half-power points, minor axes 3″ to 5″ in size, and position angles 0° to 20° west of north. The rms noise per beam area was 1–2 mJy. Only one source, Q2219−394, was resolved; it is a double with component separation about 9″ in position angle 0° ± 5°. For the remaining detections we set upper limits of 6″ by 1″ to the source angular size. Smooth components much larger than 30″ in size could have been missed by the VLA.

The 1.465 GHz flux densities of the sources lying precisely on the optical positions of the OSQs observed (see discussion below) are listed in Table 1. The VLA positions of these positively identified sources are given in Table 2. Strong confusing radio sources were found near Q0132−409 (at $\alpha = 01^h32^m44^s.3$, $\delta = -40°54'33''$), Q2307 − 422 (at $\alpha = 23^h07^m10^s.3$, $\delta = -42°15'05''$), Q2323 − 389 (at $\alpha = 23^h23^m31^s.1$, $\delta = -39°00'30''$), Q2355−389 (at $\alpha = 23^h55^m00^s.7$, $\delta = -38°54'43''$), and Q2359 − 397 (at $\alpha = 23^h59^m09^s.1$, $\delta = -39°47'21''$). These confusing sources could account for some, or perhaps all, of the reported 5.0 GHz pencil-beam flux densities of the nearby OSQs. No radio sources were detected by the VLA within ± 1′ of the positions of Q0002−387, Q0132−409, Q2307−422, Q2319−383, Q2322−414, Q2323−389, and Q2359−397. We set 99% confidence upper limits of 6 mJy to the 1.465 GHz flux densities of compact radio sources in these OSQs.

The 0.408 GHz flux densities were measured with the Molonglo one-mile-cross radio telescope, which has been described by Mills *et al.* (1963).

Optical positions of all OSQs reported as stronger than 10 mJy at 5.0 GHz were measured to about 1″ accuracy from the National Geographic-Palomar Observatory Sky Survey (PSS) prints with a measuring engine of the type described by Jauncey and Durdin (1974). The optical-minus-radio position offsets of those OSQs with radio sources confirmed by the VLA are given in Table 2. Thus, the objects listed in Tables 1 and 2 comprise a complete sample of 12 radio sources stronger than 10 mJy at 5.0 GHz and in close position agreement with the OSQs of the Osmer and Smith (1980) Curtis-Schmidt objective-prism survey.

III. CHARACTERISTICS OF COMPLETE SAMPLES OF QUASARS

a) *Consequences of the Flat N*(*S*) *Relation for Radio Sources Identified with OSQs*

The most remarked-upon radio characteristic of OSQs, be they selected by emission lines, ultraviolet excess, or optical variability, is the very slow increase in the number of radio identifications that can be made with increasing radio sensitivity (Wardle and Miley 1971; Katgert *et al.* 1973; Fanti *et al.* 1977; Murdoch and Crawford 1977; Sramek and Weedman 1978; Condon *et al.* 1980; Smith and Wright 1980). Quantitatively, the observed differential number–flux-density exponent γ [defined by $dN(S) \propto S^{-\gamma} dS$] of radio sources identified with OSQs is much less than the $\gamma \sim +2.5$ characteristic of all radio sources selected at 5 GHz. For example, it is only $\gamma = +1.4 \pm 0.4$ in the present sample. The low value of γ has two immediate consequences for radio observations of OSQs. (i) High

TABLE 2

Radio Positions and Optical Offsets of the Optically Selected Quasars

Source	R.A. (1950.0)	decl. (1950.0)	ΔR.A. (sec)	Δdecl. (″)
Q0205−379...	$02^h05^m20^s.61 \pm 0^s.05$	$-37°56'12''.4 \pm 1''.6$	−0.02	+2.3
Q0329−385...	03 29 14.82±0.05	−38 34 16.2±1.2	−0.10	+1.2
Q0353−383...	03 53 01.02±0.05	−38 18 39.7±1.1	−0.01	−0.6
Q0420−388...	04 20 29.87±0.05	−38 51 49.3±1.0	+0.02	−0.4
Q0448−392...	04 48 00.42±0.05	−39 16 13.7±1.1	−0.05	−1.9
Q2204−408...	22 04 33.19±0.05	−40 51 36.9±1.2	−0.04	−1.4
Q2217−406...	22 17 14.53±0.05	−40 39 03.2±1.1	−0.09	−0.5
Q2219−394...	22 19 54.68±0.05	−39 28 44.0±2.1	−0.03	+1.4
Q2227−399...	22 27 45.03±0.04	−39 58 17.4±1.0	−0.08	−1.1
Q2321−375...	23 21 25.05±0.05	−37 30 48.8±1.1	−0.05	−2.7
Q2329−376...	23 29 27.81±0.05	−37 38 52.7±1.1	+0.05	−2.7
Q2355−389...	23 55 11.04±0.09	−38 58 09.0±2.5	+0.04	−3.7

reliability (reliability is defined as the fraction of claimed radio-source identifications which are correct) is very difficult to attain with confusion-limited pencil-beam observations. (ii) The radio spectral-index distributions of radio-detected OSQs are nearly independent of the radio detection frequency.

The reliability of confusion-limited radio source identifications is low because the *a priori* probability of finding a radio identification in a narrow logarithmic range of flux density (between 5 and 10 times the rms confusion flux-density, e.g.) is low when γ is low. This probability is in practice comparable with the probability that a confusing source with flux density between 5 and 10 times the rms confusion is close to the optical position of any particular OSQ. Consequently, the reliability of radio identifications whose flux densities are only 5–10 times the rms confusion is only about 0.5. Reliabilities of this order were in fact observed in the present sample with $S > 10$ mJy at 5.0 GHz and VLA observations of radio identifications of OSQs made at 2.4 GHz at Arecibo (Sramek and Weedman 1978, 1980). We conclude that reliable radio identifications of OSQs cannot be made at levels below about 10 times the rms confusion.

All but one of the radio sources originally detected at 5.0 GHz and confirmed as identifications are unresolved by the VLA. Figure 1 shows that the unresolved sources have the flat or peaked spectra suggesting synchrotron self-absorption and angular structure on the 0″001 scale. In terms of radio spectra and structures, they are therefore similar to RSQs found in strong-source surveys at the same frequency (e.g., Pauliny-Toth 1977). Yet RSQs selected in strong-source surveys below 1 GHz are quite different, the majority having steep radio spectra and angular sizes easily resolved by the VLA. At first glance, it might seem that a comparably radical difference in structures and spectra would be found if the radio sources associated with OSQs were originally detected at a low frequency. However, the low value of γ for these sources ensures that this does not happen.

Qualitatively, the reason that two comparably sensitive (i.e., capable of detecting equal *numbers* of OSQs) radio surveys of OSQs, conducted at widely different frequencies, will detect nearly the *same* source population is that most of the detections are well above the sensitivity limits of both surveys. Quantitatively, it is possible to calculate the change in the distribution of spectral indices $\alpha(\nu_1, \nu_2)$ of radio sources selected at the two frequencies ν_1 and ν_2 if the number counts are power-law (Kellermann 1964). Comparison of the radio spectra of the present sample of OSQs (Fig. 2) with those of RSQs selected at 5.0 GHz (e.g., Pauliny-Toth 1977) makes it reasonable to suppose that the radio spectral-index distributions of both OSQs and RSQs are the same at $\nu_1 = 5.0$ GHz. An estimate of γ_r for RSQs selected at 5.0 GHz was calculated from the

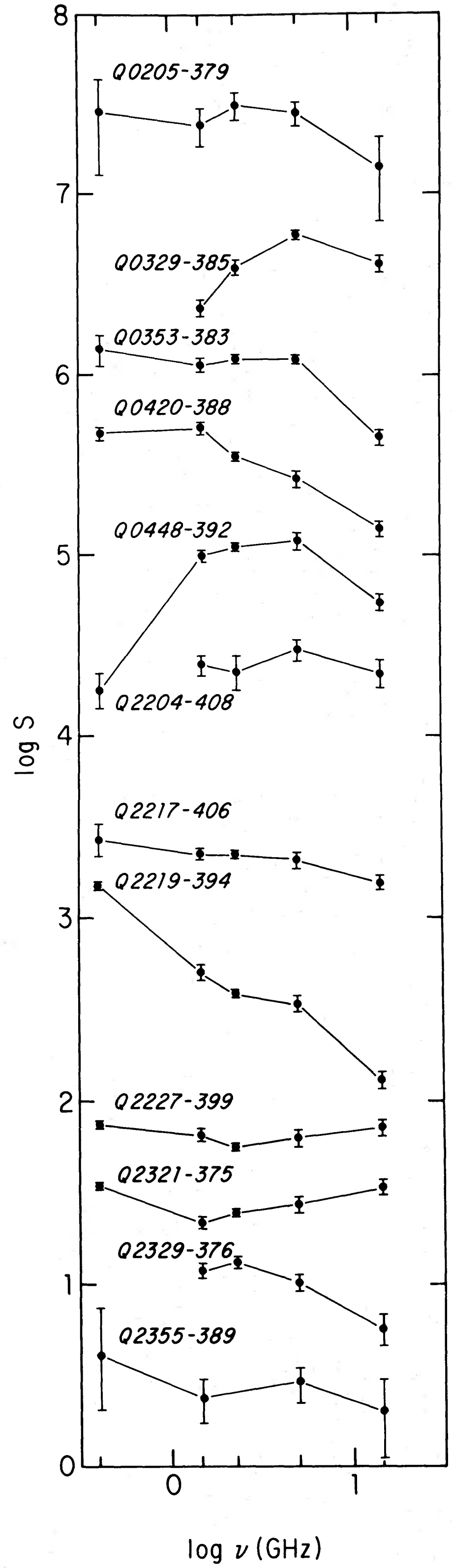

FIG. 1.—Radio spectra of the detected OSQs. *Abscissa*, log frequency (GHz); *ordinate*, log flux density (arbitrary scale).

RSQ identifications in the S4 survey (Pauliny-Toth *et al.* 1978) by the ungrouped maximum-likelihood method (Crawford, Jauncey, and Murdoch 1970); it is $\gamma_r = +2.6 \pm 0.2$. We use $\gamma_o = +1.4$ from our sample for radio sources associated with OSQs. If it is found that the spectral-index distribution of these RSQs does not change significantly until the radio survey frequency is lowered to the frequency ν_{2r} (1.465 GHz, for example), then the corresponding frequency ν_{2o} at which the spectral-index distribution of radio sources associated with OSQs has changed by the same amount will be

$$\nu_{2o} = \nu_1 \left(\frac{\nu_{2r}}{\nu_1} \right)^{(\gamma_r - 1)/(\gamma_o - 1)}$$

For the numerical values given above, ν_{2o} is only 0.04 GHz. Even if $\gamma_r = 2.4$ and $\gamma_o = 1.8$ were used, ν_{2o} is just 0.58 GHz. Thus, the spectral characteristics of the radio-source sample found by observing OSQs at 5.0 GHz are representative of those which would be seen in samples selected over the whole range of radio frequencies at which sensitive observations can currently be made.

The low observed value of γ does not indicate anything about the evolution of OSQs because their radio luminosity function is probably power-law over a wide range, while the redshift range in which most OSQs are seen is limited to the narrow band in which Lα is visible. So long as the sensitivity limits of radio observations of OSQs are such that the strongest radio sources can be detected at the highest redshifts present in the OSQ sample and the least powerful radio sources cannot be detected at the lowest redshift commonly seen in the sample, the slope of the radio $dN(S)$ relation observed will be equal to the slope of the radio luminosity function, with little dependence on other factors (cf. von Hoerner 1973). In any case, as discussed by Smith and Wright (1980), the low observed value of γ_0, may be in part caused by incompleteness in the Curtis-Schmidt survey at faint optical magnitudes.

b) *Magnitude Distributions of Quasars*

RSQs and OSQs also differ in their differential number-magnitude distributions $n(m)$. RSQs identified with strong radio sources have a peaked magnitude distribution (e.g., Bolton 1969), while the integrated magnitude distribution of OSQs increases monotonically up to at least $m = 19.5$ (Hoag and Smith 1977). The difference between the $n(m)$ distributions of RSQs and OSQs does not necessarily indicate that RSQs and OSQs evolve differently; rather, it is largely a consequence of the correlation between the radio-core and optical luminosities of the RSQs (Condon, Jauncey, and Wright 1978). The $n(m)$ distribution of OSQs *is* a measure of their distribution in space, but that of RSQs depends on their radio-core flux densities as well. If RSQs are selected which have only very weak radio *cores*, then their $n(m)$ distribution should approach that of the OSQs.

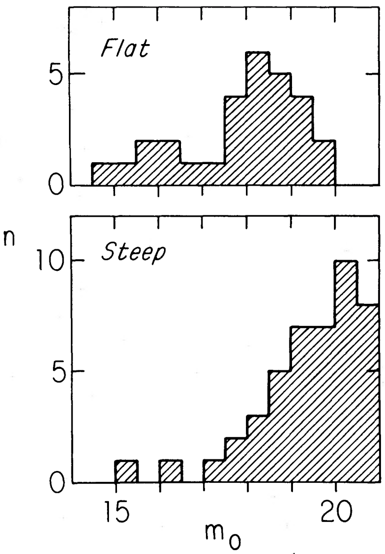

FIG. 2.—Magnitude distributions of the B2 RSQs, separated into groups with flat-spectrum and steep-spectrum *cores*. *Abscissa*, apparent blue magnitude estimated from the PSS O-prints by Fanti *et al.* (1979); *ordinate*, number of RSQs.

This effect can be seen in a complete sample of Bologna B2-survey RSQs (Fanti *et al.* 1975), which are stronger than 0.25 Jy at 0.408 GHz and for which 1.4 GHz and 5.0 GHz Westerbork interferometer maps are available (Fanti *et al.* 1979). RSQs in the 0.408 GHz B2 catalog appear primarily because of flux contributions from steep-spectrum extended radio components, but most of them also contain compact flat-spectrum nuclear components. Since these B2 RSQs are such faint radio sources, their steep-spectrum components usually do not completely dominate their nuclear components at higher frequencies (in contrast to the situation with stronger RSQs found at the same frequency); and most of these radio sources have concave-upward high-frequency spectra (Fanti *et al.* 1979). It is therefore relatively easy to isolate those with flat-spectrum *nuclear* components at high frequencies. If the B2 sample of RSQs is divided into those with flat [$\alpha(1.4, 5) \leq +0.55$] or steep [$\alpha(1.4, 5) > +0.55$] high-frequency spectra, the two $n(m)$ distributions of Figure 2 result. The RSQs with compact flat-spectrum radio nuclei show the typical peaked $n(m)$ distribution, while those RSQs which are without a detectable flat-spectrum nucleus have an $n(m)$ distribution which increases rapidly to the PSS magnitude limit.

IV. DISCUSSION

Although radio observations of representative OSQ samples have led to some understanding of the statistical properties of OSQ radio emission, they have not been so successful in explaining the physical causes for the enormously broad radio luminosity function of OSQs. OSQs and RSQs might be intrinsically different; or they may only differ in some extrinsic way, such as the orientation of relativistic beams with respect to the observer (Scheuer and Readhead 1979). If they are intrinsically different, most OSQs might be radio-quiet owing to frequency-selective absorption (either synchrotron self-absorption or free-free absorption in the broad-emission-line region surrounding the nonthermal core); or it may be that most OSQs simply are not strong synchrotron sources in *any* of the radio, infrared, or optical portions of the spectrum.

a) *Relativistic Beaming*

Comparisons of the radio intensities and optical spectra of OSQs and RSOs lead us to conclude that flux enhancements by relativistic beaming of intrinsically indistinguishable objects cannot be the principal cause of the observed radio power differences between OSQs and RSQs. Relativistic effects might increase the radio core and optical continuum flux densities of RSQs, but not the optical emission-line strengths. Nor can the flux densities of extended radio components be affected significantly, since measurements of both their flux-density ratios (Mackay 1973) and separation ratios (Longair and Riley 1979) indicate ejection velocities $\lesssim 0.2c$. Thus, the relativistic jets which might be associated with OSQs discovered by slitless spectroscopy should be randomly oriented. Similarly, radio sources discovered in low-frequency (<1 GHz) surveys should have random orientations, since most of their radio emission comes from extended steep-spectrum components. However, those extended radio sources which happen to be optically identified as RSQs could be preferentially beamed toward us if the probability of making an identification is significantly increased by relativistic enhancement of the optical continuum flux of the RSQs. We make use of the B2 RSQs (Fanti *et al.* 1975) found to have flat-spectrum cores at high frequency (Fig. 2) for the following argument. If relativistic beaming is responsible for making these RSQs brighter than the $m_o \approx +21$ PSS limit, their continua must have been enhanced by a factor of 5 or more in most cases. The emission-line equivalent widths of RSQs are not that much smaller than those of OSQs (Smith and Wright 1980), so optical selection in the B2 RSQ identifications should not cause these RSQs to have nonrandom orientations.

Since the B2 RSQs were discovered at 0.408 GHz primarily on the basis of their *extended* radio emission, *the fraction with flat-spectrum cores stronger than 10* mJy *at 5.0* GHz *should be the same as the fraction of OSQs with comparably strong radio cores*, or about 9%, if the OSQs and RSQs are *intrinsically* similar. Yet, flat-spectrum components stronger than 10 mJy at 5.0 GHz were seen in 39% of the B2 RSQs, a significantly higher percentage. (We note that the absolute optical luminosities of the B2 RSQs are actually somewhat fainter than those of most of the Osmer and Smith [1980] OSQs, so luminosity selection effects have not produced this result.) Although we have used only one sample of RSQs for comparison with OSQs, others would do as well—e.g., the 3CR QSSs frequently contain flat-spectrum radio cores (Riley and Jenkins 1977).

b) *Frequency-dependent Absorption*

Our radio observations of OSQs still do not distinguish between the two models for intrinsically different OSQs and RSQs described above. The lack of spectral evidence in our data for free-free absorption is not particularly significant, since the hypothetical absorbing plasma may be in the form of clouds or filaments which are individually opaque at frequencies higher than 14.5 GHz. The total emission-measure expected in the broad-line region of a quasar is about 10^{10} pc cm^{-6} (Chan and Burbidge 1975). For $T_e = 10^4$ K, radio observations of OSQs must be made at $\lambda \lesssim 1$ mm to ensure transparency.

c) *Selection of OSQs*

It is also possible that the radio characteristics of OSQs depend on the optical techniques used to discover OSQs. So far, most OSQs have been found by slitless spectroscopy, a technique which is sensitive primarily to the broad-emission-line regions which surround the central energy sources of quasars. Radio observations of OSQs indicate that these thermal plasmas may be only poor predictors of the presence of a strong nonthermal core. Optical characteristics of quasars which are more direct indicators of a nonthermal source are polarization, power-law continuum, and rapid variability. An optical survey based on one or more of these characteristics might yield a much higher fraction of radio-detectable OSQs. Initial attempts at polarization (Craine, Duerr, and Tapia 1978) and variability (Usher 1978; Usher and Mitchell 1978) surveys have been made, and they may well lead to the discovery and recognition of new classes of OSQs having different radio properties (cf. Condon *et al.* 1980).

J.J.C. was supported in part by National Science Foundation grant AST77-08013.

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