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FLAT-SPECTRUM RADIO SOURCES WITH FAINT OPTICAL COUNTERPARTS[1]

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ABSTRACT

For the last 15 years, we have monitored the infrared variability of 14 flat-spectrum radio sources with very faint optical-infrared counterparts and of the steep spectrum source 3C 422. We find that variability is a salient property of most of these objects, demonstrating that the near-infrared is sampling directly the output of the active galactic nuclei (AGNs). However, the infrared-to-optical continua tend to be so steep that these sources are frequently classified as flat-spectrum radio galaxies, and many of them have narrow, moderate-ionization emission-line spectra in support of this classification. We conclude that many radio galaxy identifications of flat-spectrum radio sources would have been classified as quasars with infrared observations. The red colors that cause these AGNs to drop from sight in the visible appear in many cases to arise from reddening within the QSO host galaxy or a foreground galaxy along the line of sight. However, the faint identifications are not all of this type, but they include traditional high-redshift galaxies, sources with intrinsically red continua, and objects that have anomalously faint optical outputs for their radio flux densities. For example, the steepest intrinsic nonthermal continua appear to have spectral indices ≥ -2.5 between the infrared and optical. One object in our sample, 0742+103, and a closely related object, 1413+349, have ratios of infrared-optical to radio luminosity far below the average for these sources and may represent a rare class of truly optically quiet quasar.

Subject headings: dust, extinction — galaxies: individual (0742+103, 1413+349) — infrared: galaxies — quasars: general — radio continuum: galaxies

1. INTRODUCTION

Among identifications of strong extragalactic radio sources, a small number of objects are faint ($m > 19.5$ mag) optically but relatively bright and frequently rapidly varying in the infrared. Their rather steep optical or optical-IR spectral indices ("red quasars") separates them quite clearly from the group of "normal" quasars. The steep optical or optical-IR continuum can be explained by two fundamentally different mechanisms. On the one hand, it could be an intrinsic property of the central AGN source caused by a sharp break in the energy distribution of the emitting electrons, which leads to a cutoff in the optical synchrotron emission. For the most extreme objects, the drop in the optical continuum is as steep as theoretically possible (Rieke, Lebofsky, & Wisniewski 1982). On the other hand, the steep optical continuum could be due to extrinsic factors (Ledden & O'Dell 1983), the most promising of which is foreground absorption caused by dust and gas. Such reddening could occur either in a gas- and dust-rich host galaxy or in an intervening galaxy lying close to the line of sight.

A number of red quasars are known to have foreground galaxies along the line of sight, including the BL Lac objects 0235+164 (Abraham et al. 1993, and references therein) and 1413+135 (Stocke et al. 1992). In other cases, such galaxies can be deduced because of gravitational lensing, including the smallest Einstein ring source 0218+357 (O'Dea et al. 1992a; Patnaik et al. 1993; Browne et al. 1993; Carilli, Rupen, & Yanny 1993; Stickel & Kühr 1993a) and the reddest currently known object 0411+054 (Hewitt et al. 1992; Katz & Hewitt 1993; Schechter & Moore 1993; Angonin-Williams et al. 1994).

Of importance for understanding the red quasars is the distinction between the two possible mechanisms (intrinsic vs. absorption) and the separation of the foreground-galaxy and lensing candidates from those with a dusty host galaxy. Achieving this goal in turn requires a reasonably large number of objects, preferably drawn from a complete parent population, which can be studied in detail. We report such an investigation, carried out over the past 15 years on a homogeneous group of flat-spectrum radio sources.

2. SAMPLE SELECTION AND SUMMARY PROPERTIES

Our sample was selected from the original version of the 1 Jy catalog (Kühr et al. 1981) according to the following criteria: (1) radio flux density greater than 1 Jy at 5 GHz; (2) optically unidentified on the POSS, i.e., $m > 20$; (3) flat or inverted radio spectrum ($\alpha \geq -0.5$ between 11 and 6 cm); and (4) declination greater than $-20°$. The resulting sample of 15 sources is listed in Table 1, which gives the source name (col. [1]), the optical magnitude and type of optical identification (cols. [2]–[3]), the redshift (col. [4]), the type of the IR counterpart (col. [5]) as well as a characterization of the IR variability (col. [6]), the broadband spectral energy distribution (col. [7]), and a description of the optical spectrum (col. [8]).

"Normal" quasars have relatively small amplitude variability in the near-infrared, with amplitudes seldom exceeding a factor of 2 and timescales of years (Cutri et al. 1985; Neugebauer et al. 1989). This behavior appears to hold at J (1.25 μm) as well as at longer wavelengths, so it should be typical even at moderate redshifts. Therefore, we have designated any object with variations by more than a factor of 2 in a period of a year to be violently variable in column (6).

For all sources, the broadband spectral energy distribution (SED) from the radio to the optical was derived by

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TABLE 1

SOURCE PROPERTIES

Object (1)	m_R (2)	Type (optical)[a] (3)	z (4)	Type (IR)[a] (5)	IR Variability[b] (6)	Radio Spectrum[c] (7)	Optical Spectrum[c] (8)
0108+388......	22.0	G	0.670	G	V	GPS	NEL, ABS
0202+149......	21.3	Q	0.833	Q	VV	WF	NEL
0218+357......	20.0	BL	>0.686	Q	VV	WF	NEL, ABS
0332+078......	21.5	Q	...	Q	V	GPS	...
0500+019......	20.7	G	0.583	Q	V	GPS	NEL, ABS
0539−057......	19.2	Q	0.839	Q	VV	GPS	NEL, BEL
0602+673......	20.6	Q	...	Q	V (?)	GPS	...
0742+103......	~23.6	?	...	?	?	GPS	...
0945+664......	21.6	G	...	?	no	HPar	...
1504+377......	21.2	G	0.674	G	VV	WF	NEL
1638+124......	21.8	G	1.152 (?)	?	VV (?)	HPar	BEL (?)
1648+015......	20.7	Q	...	Q	V (?)	WF (?)	...
2044−027......	19.5	Q	0.942	Q	V	SS	NEL, BEL, ABS
2149+056......	20.4	G	0.740	G	V	GPS	NEL
2150+173......	18.9	BL	>0.2	Q	VV	WF	No lines

[a] G = galaxy, Q = quasar, BL = BL Lac object.
[b] V = variable, VV = violently variable.
[c] GPS = gigahertz-peaked spectrum. WF = power-law spectrum, weakly falling to high frequencies. HPar = spectrum that curves downward toward high frequencies roughly as a half-parabola. SS = steep spectrum. NEL = narrow emission lines. BEL = broad emission lines.

gathering all photometric data points accessible in the NASA Extragalactic Database (NED) and the catalogs in the *Einstein* On-Line Database, supplemented by measurements taken during this study and from the literature. Besides the already known group of gigahertz-peaked spectrum sources (and the classical steep spectrum source 2044−027), a second group of sources shows a SED resembling half a parabola (almost flat at low radio frequencies, gradually steepening toward the optical), while a third group is characterized by an almost perfect power law from the lowest radio frequencies up to (in the case of 0202+149) $\nu \sim 3 \times 10^{11}$ Hz.

As already noted in Stickel, Meisenheimer, & Kühr (1994), the two-point spectral index for 2044−027 listed in the original 1 Jy catalog (Kühr et al. 1981) is incorrect. Since this source is actually a classical steep-spectrum radio source, it was erroneously included in the present sample.

3. NEW OBSERVATIONS

Aperture photometry was obtained with the Multiple Mirror Telescope using the facility InSb photometer. With the exception of 0742+010 (where a 5″ aperture was used with an 8″ throw to avoid nearby bright stars), all objects were measured in an 8″.5 aperture with a throw of 10″ in elevation. Calibration used the suite of standard stars of Elias et al. (1982), or a preliminary version that was identical to within the accuracy of these measurements. The data are reported along with statistical errors in Table 2.

The accuracy of such measurements depends both on the statistical noise and on confusion noise. Confusing sources at the position of the radio object are unlikely because these objects are already known to have extremely faint optical counterparts. Furthermore, given their very red colors (see below), confusion would require an accurate positional coincidence of a peculiar object. However, confusion can also occur due to objects in the photometer reference beams. Measurement of faint nonvariable stars to evaluate the net errors in our photometry would have required prohibitive amounts of additional telescope time and would not have given a reliable measure of this source of confusion (unless a huge number of stars was observed). Therefore, we estimated the nonphotometric errors from a large program of measurements of faint galaxies, which used the identical instrument and techniques (Lebofsky & Eisenhardt 1986). We can place an upper limit of 20% on these errors, unless there is an obvious object in the reference beam of the photometer.

As a further guard against confusion noise, a current epoch image at K_s (2.15 μm) was obtained both for comparison with the flux levels in the aperture photometry and to examine the field for possible confusing sources. These measurements were made on the Steward 90 inch (2.29 m) Bok Telescope with a camera based on a NICMOS3 256 × 256 array, with the pixel scale set to 0″.63. The measurements consist of a set of exposures (usually 16) in a grid, moving the source on the array. In the data reduction, the suite of fields is used to generate a flat field for all the images. A sky-background image is then created by taking the median of several immediately preceding and succeeding integrations, for which sources are flagged and excluded to avoid biasing the median toward higher values. The sky images were rescaled to the median of each individual object frame and subtracted. The individual sky-subtracted object exposures were then aligned with an integer-pixel shift and averaged, during which the lowest and highest value for each pixel of the stack were rejected. Calibration was relative to the same set of standard stars used for the aperture photometry (Elias et al. 1982). The photometry of the sources is reported in Table 2, and an estimate of the infrared morphology is given in Table 1.

Spectra of 0202+149 and 0500+019 were obtained on 1994 September 10 (UT) with the Red Channel spectrograph at the Multiple Mirror Telescope. A 270 lines mm^{-1} grating together with a Loral 1200 × 800 pixel CCD covered the wavelength range between 4200 and 8200 Å with a reciprocal dispersion of 3.6 Å per pixel. The slit was 2″ wide, and the resolution, judged from the FWHM of night-sky lines, was 18 Å. Data reduction followed standard procedures of de-biasing, flat-fielding, and extraction according to the optimal procedure outlined by Horne

TABLE 2

INFRARED PHOTOMETRY

Source	Date (UT)	J	H	K
0108+38	1981 Nov 17	95 ± 11	...	145 ± 22
	1981 Dec 6	...	...	200 ± 22
	1982 Sep 4	...	...	92 ± 26
	1982 Dec 27	...	...	93 ± 13
	1983 Sep 15	...	...	78 ± 36
	1994 Oct 20	...	...	118 ± 12
0202+14	1981 Oct 17	80 ± 30	150 ± 40	340 ± 120
	1981 Oct 31	...	...	550 ± 60
	1981 Nov 2	...	...	830 ± 90
	1981 Nov 16	620	1450	2600
	1982 Dec 27	...	...	310 ± 23
	1994 Sep 14	...	...	1033
0218+35	1982 Sep 1	80 ± 11	237 ± 22	538 ± 60
	1982 Dec 27	242 ± 18	479 ± 16	861 ± 11
	1983 Jan 24	...	...	779 ± 34
	1983 Sep 15	324 ± 21	500 ± 21	1261 ± 46
	1994 Oct 20	...	...	730
0332+07	1980 Oct 27	...	...	27 ± 7
	1982 Dec 27	...	...	22 ± 10
	1984 Feb 12	...	...	54 ± 12
	1994 Oct 20	...	...	73 ± 6
0500+01	1981 Nov 16	135	240	300
	1981 Dec 6	...	...	380
	1982 Sep 2	...	113 ± 12	...
	1982 Dec 27	...	...	234 ± 8
	1983 Sep 15	...	175 ± 17	...
	1984 Feb 10	...	...	196 ± 26
	1994 Sep 15	...	...	291
	1994 Oct 20	...	...	285
0539−057	1978 Oct 23	...	...	68 ± 70
	1979 Nov 30	42 ± 81	...	212 ± 41
	1981 Dec 6	...	...	152 ± 31
	1982 Dec 27	35 ± 9	...	202 ± 16
	1983 Nov 20	...	...	309 ± 17
	1984 Feb 10	...	...	118 ± 21
	1994 Sep 16	...	...	357
0602+67	1978 Dec 10	...	130 ± 30	200 ± 30
	1982 Dec 27	...	...	40 ± 12
	1994 Oct 20	...	...	400
0742+10	1981 Nov 17	...	...	5.2 ± 8.4
	1982 Dec 27	...	...	5.1 ± 4.2
	1983 Nov 20	...	...	13.2 ± 14.1
	1984 Feb 10	...	...	15.7 ± 5.7
	1987 Mar 14	...	...	23.5 ± 8.3
	1994 Feb 27	...	...	7.8 ± 2.1
0945+66	1981 Dec 6	...	...	65 ± 21
	1983 Jan 22	25 ± 3	50 ± 10	79 ± 9
	1994 Jun 24	...	...	51 ± 15
1504+37	1982 Mar 7	...	...	97 ± 14
	1983 May 3	55 ± 8	124 ± 11	245 ± 19
	1983 Jun 26	...	31 ± 8	...
	1994 Jun 25	...	...	239
1638+12	1982 Sep 2	...	20 ± 7	...
	1983 May 30	...	26 ± 8	...
	1983 Jun 25	...	37 ± 6	...
	1994 Jun 25	...	...	42 ± 10
1648+01	1983 Apr 24	74 ± 9	173 ± 24	273 ± 32
	1983 May 30	...	92 ± 8	...
	1983 Jun 25	...	137 ± 13	...
	1984 Feb 26	...	180 ± 20	...
	1984 Apr 10	...	179 ± 14	...
	1984 May 21	...	172 ± 16	...
	1994 Jun 25	...	...	278
2044−02	1982 Sep 2	206	264	466
	1983 May 30	...	173 ± 10	...
	1983 Jun 25	...	391 ± 11	...
	1983 Sep 27–30[a]	90 ± 30	130 ± 30	150 ± 30
	1984 May 21	...	269 ± 10	...
	1984 Jun 24	...	...	507
2149+05	1979 Jul 3	90 ± 56	220 ± 43	425 ± 68
	1983 May 30	52 ± 4	116 ± 12	274 ± 53
	1983 Jun 25	...	148 ± 7	223 ± 18
	1984 May 21	...	131 ± 17	...
	1994 Jun 25	...	...	229

TABLE 2—*Continued*

Source	Date (UT)	J	H	K
2150+17......	1982 Sep 2	84 ± 9	165 ± 15	316 ± 31
	1983 May 31	...	264 ± 18	...
	1983 Jun 25	...	904	1287
	1983 Jun 26	...	699	1055
	1983 Jun 28	...	1026	1354
	1994 Jun 25	...	...	1259

[a] Stein & Sitko 1984.

(1986), and flux calibration used standard stars from the list of Oke (1990). A spectrum of 1638+124 at a resolution of ~10 Å was also obtained with the facility spectrometer and Cryo-Camera on the KPNO 4 m telescope on 1983 August 12.

R-band images of 0202+149, 0500+019, 0539−057, 0742+103, and 0945+664 were obtained on the 90 inch telescope in 1994 September and 1995 February. A 2k × 2k pixel Loral CCD with 15 μm pixels gave an image scale of 0″29 pixel^{-1} after binning by 2 pixels. The images were de-biased and flat-fielded with dome flats, and then co-added and sky subtracted. Observations of standard star fields from Odewahn, Bryja, & Humphreys (1992) were taken for calibration, but conditions were nonphotometric during the February run.

4. DISCUSSION

Notes on the individual sources are collected in an appendix. Our new spectra and images are also discussed there, as appropriate for the sources under discussion. When integrated with previous results on other well-studied similar sources, such as AO 0235+163, 3C 68.1, and PKS 1413+135, there is now a substantial body of information regarding the optically faint flat-spectrum radio source identifications. As a result, it is appropriate to summarize their general attributes.

The properties of the sources in our study are summarized in Table 1. A salient characteristic is the high degree of source variability. Of 14 objects, we find at least five that are violently variable, with one more possible violent variable (1638). Five more show substantial variability, with two additional probable variables (0602 and 1648). Only two sources show no evidence for variations, and they are the faintest and fourth faintest objects, so variations might have escaped detection. Strong variability is a common attribute of the other optically faint flat-spectrum radio sources (e.g., Rieke et al. 1976; Bregman et al. 1981; Rieke et al. 1982), so we can conclude it is a general characteristic of this type of object.

Of the 14 flat-spectrum radio sources in this sample, six are classified as galaxies based on their optical morphology. However, we find that at least four of these six galaxies harbor variable nuclei; these variable sources are seen clearly at wavelengths longer than 1 μm in the galaxy rest frame, and in some cases they dominate the output of the system in the near-infrared. These nuclear sources must have SEDs falling extremely steeply toward the optical, to avoid being seen as point nuclear sources in the blue where the stellar outputs of the host galaxies are low. Optically based identification campaigns find that a moderate portion of flat-spectrum sources lie in galaxies; for example, Stickel & Kühr (1994a) classify 18% (26 sources) as galaxies in the

S4 catalog, and Stickel et al. (1994) identify 11% (32 in number) of the flat-spectrum members of the 1 Jy catalog as galaxies. From our work, many of these apparent radio galaxies would be found to have AGNs if studied in the near-infrared, despite their extended morphology and radio galaxy–like spectral characteristics in the optical.

At least four of the six sources with galaxy morphology in our sample show narrow emission lines typical of low- to moderate-ionization narrow-line radio galaxies (see, e.g., Cohen & Osterbrock 1981). That is, these spectra have strong [O III], moderate [O II] and [Ne III], and weak hydrogen and [Ne V]. The spectrum of 0202+149 shows a similar narrow emission-line spectrum. The emission-line system in AO 0235+164 is also similar, although with somewhat higher ionization (Cohen et al. 1987). It appears that a spectrum similar to that of narrow-line radio galaxies, perhaps with a weak broad-line component, is the most common characteristic of the optically faint flat-spectrum radio sources. The portion of these sources with traditional quasar emission lines, of high ionization and with strong and broad hydrogen recombination lines, is very low, far lower than generally in flat spectrum source samples, which tend to be dominated by this type of source (e.g., 74% of the 1 Jy sample [Stickel et al. 1994] and 69% of the S4 sample [Stickel & Kühr 1994a]).

True BL Lac sources, with no or virtually no emission lines, constitute two of the nine flat-spectrum sources in our sample with measured spectra. This portion is not significantly different from the number of BL Lac sources found generally in the flat-spectrum portion of the 1 Jy catalog, namely, 13% (Stickel et al. 1994), nor the portion in the S4 survey, namely, 10% (Stickel & Kühr 1994a). However, the other well-studied related sources include at least two BL Lac objects: AO 0235+164 and PKS 1413+135. We would conclude that the portion of BL Lac sources is perhaps higher than average among the optically faint identifications, but not by a large margin.

A correlation exists between the radio and optical brightness of flat-spectrum radio sources. For example, Condon et al. (1983) find that α_{RO}, defined as the power-law slope between 1.4 MHz and blue, lies at 0.6 ± 0.2 for their entire sample of optically identified flat-spectrum sources. The discovery that most very faint optical identifications (even traditional empty fields) are relatively bright in the near-infrared (e.g., Rieke, Lebofsky, & Kinman 1979; Rieke et al. 1982) established that this behavior is nearly universal, and that at least the majority of the faint optical identifications are only faint because their SEDs drop precipitously between the near-infrared and optical. Our conclusion that many traditional flat-spectrum radio galaxies harbor nuclei that are prominent in the near-infrared adds further evidence for the near-universality of the correlation between radio and optical-infrared flux densities of flat-spectrum AGNs. If an index, α_{RIR}, is computed between 1.4 GHz and 2 μm, nearly all the faint optical identifications contain AGNs that fall within the general range, i.e., $\alpha_{RIR} \geq -0.8$. As a result, it seems very likely that the underlying physical processes in all these sources are related in a way that produces similar spectra over a wide range of frequencies.

However, within our new sample, at least one source, 0742+103, seems to fall far outside this range, with $\alpha_{RO} \sim \alpha_{RIR} \sim -1.1$. Two more, 0945+664 and 1638+124, have $\alpha_{RO} \sim \alpha_{RIR} \sim -0.9$, but with the optical and infrared flux densities apparently measured to the stellar continuum of the host galaxy; hence, for the active nucleus in these two sources, $\alpha_{RIR} \sim \alpha_{RO} < -0.9$. The latter two objects may be far outliers to the general distribution, but the former source stands out as being significantly different and probably represents some unique type of process that produces a true optically quiet flat-spectrum radio source.

Another source that may be closely related to 0742+103 is 1413+349. This object has a radio spectral index of -0.56, only marginally disqualifying it as a "flat spectrum" source, defined by a radio spectral index ≥ -0.50. The counterpart is not detected in the optical, with $m > 24$ mag (Stanghellini et al. 1993), and it is marginally detected in the near-infrared (O'Dea et al. 1992b, our unpublished observations), with $m_K \sim$ 19–19.5. These measurements indicate that α_{RIR} is similar to that of 0742+103, and α_{RO} may be even larger.

When it was first discovered that "empty field" flat-spectrum radio sources were very red in color and could be detected in the infrared, a number of considerations led to the conclusion that many of these objects had intrinsically rapidly falling spectra due to a sharp cutoff in the energy spectrum of the synchrotron-emitting electrons (Rieke et al. 1976, 1979; Bregman et al. 1981; Beichman et al. 1981; Rieke et al. 1982; McHardy et al. 1991). With the sample of faint optical identifications now available, it is possible to reassess this conclusion. The fact that seven of the nine flat-spectrum sources in our sample for which spectra are available show emission lines indicative of moderate excitation (i.e., including [O III] and [Ne III]) indicates that the intrinsic spectrum of these seven sources is very unlikely to drop as rapidly as previously suspected from the near-infrared toward the ultraviolet. The behavior of these seven sources is more consistent with a spectrum that has a break somewhere near 1 μm, and for which the extremely steep fall of the SED into the visible is a result of both this intrinsic spectral break and interstellar reddening. A model of this type has already been suggested for the related object PKS 1413+135 by Stocke et al. (1992).

The two BL Lac–type sources in our sample, 0218+35 and 2150+17, can be combined with the similar objects AO 0235+164 and PKS 1413+135 to examine the behavior of sources without emission lines. For all except 2150+17, there is evidence that reddening plays a significant role in producing the steep optical SED: 0218 is gravitationally lensed by a foreground galaxy, 0235 lies behind a galaxy, and 1413 lies either within a dusty spiral or behind it (Stocke et al. 1992; McHardy et al. 1994). In all three cases, the detection of interstellar absorptions in the radio, optical, and X-ray spectra of the active sources proves that the foreground (or host) galaxies have interstellar media that would result in reddening sufficient to influence the SEDs substantially (see, e.g., Stocke et al. 1992). The detection of faint [Ne V] in the spectrum of 0235 (Cohen et al. 1987) appears to confirm the hypothesis that this source has a relatively "normal" power-law intrinsic spectrum.

Two sources, 0202+149 and 2150+17, are of interest because they may define the extreme red end of the intrinsic optical spectra for this type of object. In both cases, the optical and infrared colors are consistent with a power law of index $\alpha \sim -2.4$, without the dramatic steepening in the optical that should characterize a reddened source. Three other objects, 1504+377, 1648+015, and 2149+056, have nonthermal infrared spectra of similar steepness, supporting the supposition that $\alpha \sim -2.5$ is a limiting case.

Recently, Webster et al. (1995) have reported optical and infrared photometry of a Parkes sample of flat-spectrum radio sources. Although they seem unaware of the 1 Jy sample, it is virtually identical to theirs (complete to 0.5 Jy at 2.7 GHz, equivalent to 0.35 Jy at 5 GHz for the Parkes sample, vs. complete to 1 Jy at 5 GHz for the 1 Jy sample). The 1 Jy flat-spectrum sample has been studied very extensively (e.g., spectra are available for 92% of the 251 objects classified morphologically as quasars or BL Lac objects; see Stickel et al. 1994). Webster et al. (1995) assume that the large number of sources in the Parkes sample with extremely faint optical counterparts and very red B_J-K colors are all quasars, and on this basis they conclude that as many as 80% of the quasars are missed in optical searches because of obscuration by dust. It is interesting to compare this claim with the results from the 1 Jy sample. Although we have also concluded that many of the extremely red identifications are reddened, we find a number of other causes for faint identifications. For example, Webster et al. find 16 red sources (K detections, upper limits at B_J) in a subset of the Parkes survey; they assume that all these sources are obscured quasars. We find 17 faint objects ($m > 21$, usually m_R) in the 1 Jy sample (Stickel et al. 1994), perhaps a similar portion (although it is difficult to be sure from the information given by Webster et al. 1995). However, five of the 1 Jy objects are classified as galaxies by Stickel et al. (1994); of these five, we have infrared imaging for three and agree with the classification. At least three of the 1 Jy QSO identifications have SEDs that are not suggestive of strong reddening (0202+149, 0742+103, and 1648+015). Only one source shows strong evidence for reddening based on currently available data (0500+019; see Stickel et al. 1995); however, from the behavior of slightly brighter members of the sample, it is likely that reddened objects are underrepresented by this single case. Five more QSO identifications are southerly, and we have little information on their behavior. Even if all these sources are highly reddened QSOs, only half the faint identifications could fall into this category. Consequently, we believe that Webster et al. (1995) significantly overestimate the portion of quasars missed because of reddening.

5. CONCLUSIONS

We report results of a comprehensive optical-infrared evaluation of the very faint identifications of flat-spectrum radio sources. We find the following:

1. Variability is a salient property of these objects;
2. Many objects classified as flat-spectrum radio galaxies have active nuclei that are visible in the near-infrared;
3. The well-known correlation between radio and optical brightnesses for these objects is strengthened by including the infrared properties of the sources;
4. However, at least one source, 0742+103, is much too faint to follow this correlation and may represent some type of object distinct in its nuclear properties from virtually all other flat-spectrum radio sources. The source 1413+349, although not in our sample and marginally not a flat-spectrum radio source, appears to be a similar object;
5. For many of these sources, the very red optical colors appear to arise at least in part from reddening within the host galaxy or by a foreground galaxy along the line of sight;
6. However, a significant portion of faint identifications are also galaxies or non-reddened AGNs with red continua—studies assuming all these sources are reddened quasars are likely to be in error; and
7. The steepest infrared-to-optical spectra that appear to be intrinsic to the active nuclei have power-law spectral indices of $\alpha \geq -2.5$.

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APPENDIX

NOTES ON INDIVIDUAL SOURCES

0108+388.—The source has been imaged in the optical by Stanghellini et al. (1993), who find it to be a galaxy toward the faint end of the normal distribution of radio galaxies (compare Laing, Riley, & Longair 1983), possibly containing a QSO nucleus. The optical spectrum shows only narrow emission lines as well as stellar absorption features at a redshift of $z = 0.670$ (C. Lawrence, private communication). Our data suggest variability; if the two measurements for 1981 are averaged and compared with the average of the two for 1982, the source is twice as bright in the earlier year. The infrared image does not reveal any potential confusing sources that could cause photometric errors on this scale. The fainter level corresponds to $r-K = 4.8$, which is toward the red limit in color for a galaxy at the redshift of 0108+38 (e.g., Eisenhardt & Lebofsky 1987); the brighter level of $r-K = 5.5$ is redder than expected for a nonevolving galaxy and presumably indicates a brightening of the nucleus. The slight extent we detect in the infrared image is consistent with this interpretation because the flux level is near minimum, when the galaxy would account for much of the signal.

0202+149.—The source has been imaged by Peacock et al. (1981), who find it to be faint and pointlike, and by Fugmann & Meisenheimer (1988), who find it to be pointlike with a possible faint envelope. This result is in agreement with the morphology seen in our R-band image. Our infrared measurements show variations by a factor of ~ 8 in 1 month; there are no plausible candidates in the infrared image of the field to account for this change through photometric errors. Therefore, the object is violently variable. The photometric colors in the visible indicate a power law with index $\alpha = -2.3$ (Fugmann & Meisenheimer 1988); the infrared colors indicate a power law with $\alpha = -2.5$ both when the source is faint and when it is bright. The two slopes agree within the errors; although we do not have simultaneous data to allow constructing a single-epoch spectral energy distribution, the constancy of the slope indicates that the SED is a single steep power law. Such a SED is not compatible with a flatter spectrum that is reddened. Extrapolated into the ultraviolet, the SED would not be capable of photoionizing emission lines of large equivalent width. The spectrum of the source (Fig. 1) shows narrow emission lines at $z = 0.833$ and of moderate excitation, consistent with this conclusion.

0218+357.—We find this source to be violently variable, by a factor of more than 2 over 1 year. The infrared image shows an edge-on galaxy just outside the region in which our reference beam would be placed, but it would appear there is no serious interference with the measurements. The source is a gravitational lens showing a characteristic Einstein ring radio image (O'Dea et al. 1992a; Patnaik et al. 1993). The optical spectrum shows intervening absorption and weak emission lines at $z = 0.687$ (Browne et al. 1993; Stickel & Kühr 1993a), interpreted as being due to the lensing foreground galaxy, but no emission lines from the imaged source itself. The red colors of this source are likely due to obscuration in the foreground galaxy.

0332 + 078.—An optical image of the field of this source has been published by Chu, Zhu, & Butcher (1985); there is a nearby source that might cause larger than normal errors in our photometry, but it is faint in our infrared image, and the photometry should be accurate. The source shows evidence for variability in the infrared.

0500+019.—The source appears to be moderately variable; the infrared image indicates no significant interference with the aperture photometry from nearby sources. Fugmann, Meisenheimer, & Roeser (1988) described the optical counterpart as an unresolved QSO lying only 2″ north of a galaxy. The imaging data shown in Stickel et al. (1995) and in a deeper *R*-band image from 1995 February, however, show only an asymmetric extended galaxy without a noticeable point source, while a strong point source has been detected in the infrared image. The differences in optical morphology could be due to variability. The optical spectrum shows narrow, moderate-excitation emission lines and Ca II absorption at $z = 0.583$ as well as an additional unidentified emission line of unknown redshift (Stickel et al. 1995). The infrared spectrum is relatively flat (spectral index $\alpha = -1.4$), but Fugmann & Meisenheimer (1988) find that the optical SED is extremely steep, consistent either with an exponential cutoff or with very strong reddening. From the optical and infrared morphology in conjunction with the optical spectrum, it seems likely that the very steep SED is caused by reddening in the galaxy, and it is possible that the QSO lies behind it rather than within it.

0539−057.—A spectrum of this source shows it to be a QSO at $z = 0.84$ (Stickel & Kühr 1993b). The source is in a region of high obscuration despite its fairly high Galactic latitude, and its spectrum falls only moderately rapidly from the infrared to the visible if the visible measurement by Fugmann & Meisenheimer (1988) is typical of the levels at the time of our measurements. The source appears to be 4.6% intrinsically polarized (although the relatively strong Galactic polarization results in uncertainties; Fugmann & Meisenheimer 1988), and our data indicate large-amplitude variability that, from the infrared image, is unlikely to be due to interference by nearby stars. The object, therefore, is likely to be a violently variable QSO with some Galactic interstellar reddening.

0602+673.—From the infrared image, there are two sources that potentially interfere with our aperture photometry, one of which is brighter than the radio source. From an assessment of the position angles at which this object was measured, these sources contribute to the observed variations but probably do not account for the full amplitude. We conclude that the source is likely to be variable, but confirmation with imaging data is required. The object is pointlike in images, and its $r-K$ color from the images is too red to be a galaxy at a redshift that would be consistent with its brightness.

0742+103.—The previous optical studies of this source provided only marginal detections or upper limits (Peacock et al. 1981; Fugmann et al. 1988), indicating $m_R > 23$. Our new image (Fig. 2*a*) shows the optical counterpart with $m_R \sim 23.6$, but it is still not deep enough to say anything conclusive about its morphology. The same object is seen in the infrared image (Fig. 2*b*). Combining all the infrared data, we detect the source consistently at a level of ~ 9 μJy, or $m_K = 19.7$. Therefore, the source need not be particularly red in color, but it is of significant interest because it has an exceptionally low ratio of optical/infrared to radio emission. It is the best existing candidate to be an "optically quiet" quasar.

0945+664.—Peacock et al. (1981) classify the optical counterpart as a galaxy, which is confirmed by our new image. The infrared and optical data are consistent with the expected colors of a high-redshift galaxy and show no variations.

1504+377.—Our photometry indicates that this source is violently variable; from the infrared image, there are no interfering stars that could account for the variations. An optical image has been published by Fugmann et al. (1988); they

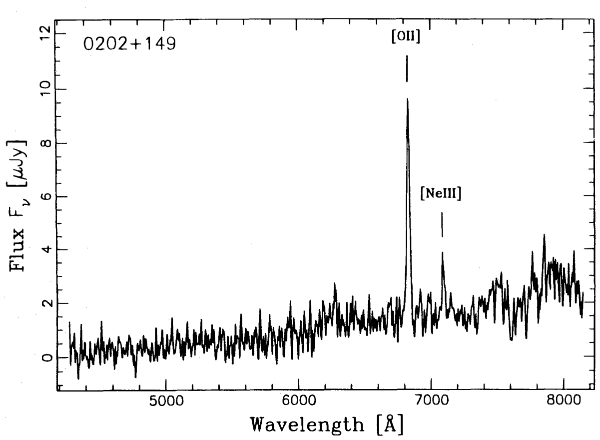

FIG. 1.—Spectrum of 0202+149

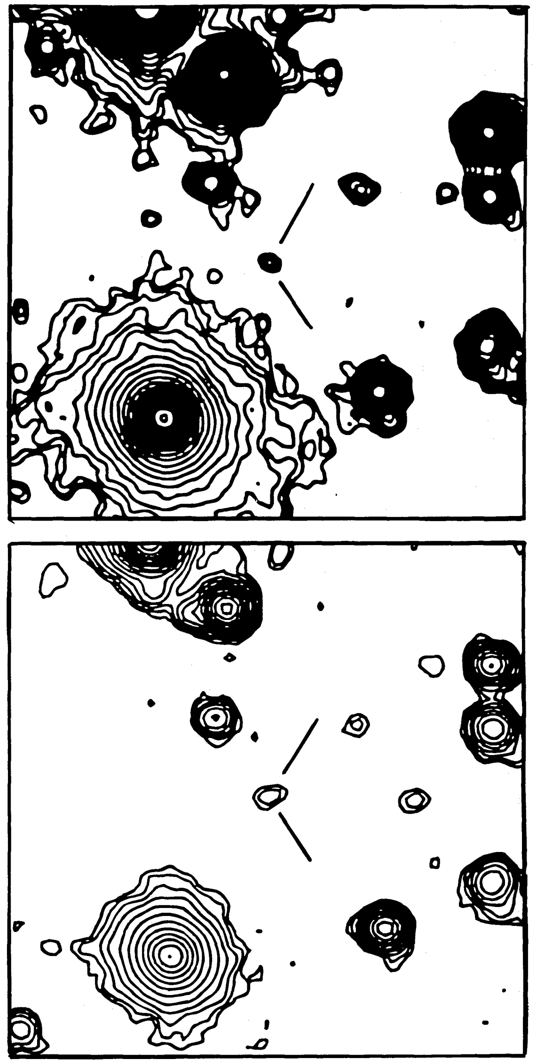

FIG. 2.—Images of 0742+103. The panels are 50″ on a side, with north to the top and east to the left. The upper panel is at R, and the lower one is at K_s.

identify the source with a pointlike object at $r = 21.2$. However, the deeper image of Stickel & Kühr (1994b) definitely shows the optical counterpart to be a galaxy without a noticeable central point source. Variability could account for the differing morphology. The optical spectrum shows moderate-excitation narrow emission lines at $z = 0.674$ (Stickel & Kühr 1994b). When the source was faint, $r - K \sim 4$, which is consistent with the colors of a galaxy; when the source was bright, $r - K = 5.1$, which is redder than expected for a nonevolving galaxy. When the source was bright, the infrared SED was very steep, with $\alpha \sim -2.6$; the continuum slope becomes even steeper if the J measurement is corrected for a possible contribution of the host galaxy. Hence, this object is probably a galaxy with a red nucleus that can flare and dominate the integrated infrared output of the system.

1638+124.—Variability is not detected in the infrared photometry of this source, although because it is faint the ratio of signal-to-noise is modest. The infrared data are compatible with identification as either a distant galaxy or as a QSO. The image in Stickel & Kühr (1995) shows the optical counterpart to be an extended galaxy, and the r, H, and K colors are consistent with this classification. A deep K-band image obtained on 1995 March 21 shows the source to be a galaxy with no indication of a pointlike nucleus. However, for the spectrum illustrated in Figure 3, the source was far brighter than indicated by the imaging and photometry; unless there has been a misidentification, the galaxy must harbor a violently variable nucleus that had flared when the spectrum was obtained. A confirming spectrum would be desirable, since we expect it to show emission lines even if the nuclear source is faint.

1648+015.—The source appears to be variable, although without the single measurement on 1983 May 30 one would be unsure. The infrared image shows no interference with the photometry by nearby stars. The infrared spectrum falls rather steeply (spectral index $\alpha \sim -2.3$) toward high frequencies. The optical counterpart is an unresolved QSO (Stickel & Kühr 1995), at a flux level that, relative to the median of our observations, would imply $\alpha \sim -3$ between H and r.

2044−027 = 3C 422.—This object appears to be moderately variable in our photometry; the infrared image shows that there is no interference by nearby stars. The source is pointlike in the optical, and its spectrum has narrow lines and weak broad ones at $z = 0.942$ (Smith & Spinrad 1980). The spectral energy distribution falls with an index $\alpha \sim -1.3$ from K (2.2 μm) to r (0.65 μm); however, the optical spectral index is $\alpha \sim -2.5$ (Smith & Spinrad 1980). Mg II absorption has been detected by Aldcroft, Bechtold, & Elvis (1994). Both characteristics suggest that the source is strongly reddened. Subsequent

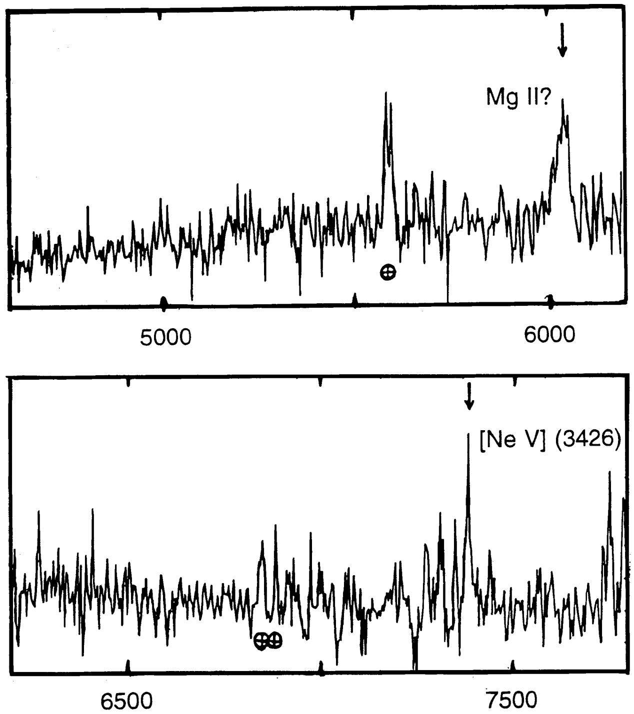

FIG. 3.—Spectrum of 1638+124

to the selection of our sample, it has been shown that this object is a steep-spectrum radio source; we include it here because of the extensive data we have obtained, but we exclude it from the accounting of the properties of the flat-spectrum sources.

2149+056.—This object appears to be moderately variable in our data. From the infrared image, there is no serious interference with our photometry. The spectrum of Stickel & Kühr (1993a) shows strong emission lines at $z = 0.74$. An image of the field shows the object to lie within a bright galaxy ($m_r = 20.4$; Stickel & Kühr 1993a). This magnitude implies the host galaxy is exceptionally luminous (compare Laing et al. 1983), unless the apparent host is a foreground object along the line of sight. The infrared spectral energy distribution is very steep, with spectral index $\alpha \sim -2.7$. Therefore, this object appears to be a violently variable QSO within a luminous galaxy and with an abnormally strong and steep nonthermal infrared emission component.

2150+173.—We find this source to be violently variable, and a similar behavior is reported in the optical by Kühr & Schmidt (1990). They also found the object to be 26% polarized. The spectra of Stickel, Kühr, & Fried (1993) and Veron-Cetty & Veron (1993) show no emission lines. These characteristics indicate a BL Lac source. The SED falls steeply, with spectral index $\alpha \sim -2.3$.

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