IDENTIFICATION OF INFRARED SOURCES IN "EMPTY" FIELDS

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Abstract

From infrared observation of a radio selected sample of QSOs, it is shown that optical identification programs produce samples biased against very red sources, even if identifications are made without regard to color.

I. INTRODUCTION

The optical identification of flat-spectrum radio sources has been pursued very actively because it appears possible to obtain a complete set of identifications for a statistically complete sample of radio sources (see, e.g., Condon, Jauncey, and Wright 1978). This possibility is suggested by the high positional accuracy that can be achieved for these objects in the radio, by the correlation between optical and radio brightnesses, by the exact positional coincidence between radio and optical counterparts, and by the average brightness of the optical identifications which is well above the Palomar sky survey limit. Nonetheless, 10 to 15 per cent of these sources cannot be identified to the limit of the Palomar survey (Condon, Hicks, and Jauncey 1977); it is frequently assumed that the unidentified objects have optical counterparts similar to the identified ones except for being relatively faint, at least at the time of the Palomar survey.

The following is an interim report on a study of the infrared properties of these sources. We have found that at least half of the unidentified sources have optical-infrared spectra distinctly different from the optically identified portion of the sample. Any identification program which works only to the limit of the Palomar survey will produce a biased sample, even if it ignores color in making identifications. By combining optical and infrared observations, it appears possible to identify at least 95% of the brighter flat-spectrum radio sources.

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It is likely that the identifications of steeper-spectrum radio sources suffer from similar biases, although it will be difficult to prove this hypothesis because the radio and optical counterparts do not always coincide.

II. OBSERVATIONS

Measurements were obtained with a high-performance near infrared photometer on the University of Arizona 1.54 m (61 inch) and 2.25 m (90 inch) telescopes. The infrared beam, of diameter 8", was centered on the radio sources by offset guiding from nearby field stars. The positions of these stars had been measured to an accuracy of $\sim$ 0".7; an additional $\sim$ 1" of error was introduced by uncertainties in the offset guiding. The radio sources themselves had positional errors of $\sim$ 1" or less. Measurements were begun at K(2.2μm) and extended to H(1.6μm) and J(1.25μm) if a detection was achieved.

Initially, we concentrated on empty fields (to the limit of the Palomar survey). When it was clear that a substantial number of these objects could be detected and had spectra much steeper and redder than other types of extragalactic source (Rieke, Lebofsky, and Kinman 1979), the survey was extended to include infrared measurements of a complete radio sample. This sample is the sources listed by Condon, Hicks, and Jauncey (1977) brighter than 0.6 Jy at 8 GHz and lying in the declination range $4° < \delta < 25°$. To be included in the sample, the sources must have spectral indices $\alpha < 0.5$ between 2.7 and 5 GHz (where the spectrum is represented by $S = \nu^{-\alpha}$). Of a total of 69 sources in the sample, 23 have been observed in the infrared, or 1/3. Roughly 1/3 of each class of identification (EF, BSO, NSO, RSO) has been included. The K magnitudes, spectral indices (B to K), and identification class are listed in Table 1.

III. DISCUSSION

The spectra of the sources have been characterized by their spectral indices, α_{KB}, assuming they are power laws between K and B(0.44μm). The B magnitudes given by Condon, Hicks, and Jauncey (1977) were assumed, although for about half of the identifications it was verified with a TV acquisition system that the objects had not varied significantly (more than $\sim$ 0.5 mag.). For the empty fields, the B magnitudes were estimated from Rieke, Lebofsky, and Kinman (1979) or by extrapolating from the J-K color.

The distribution of α_{KB} for this sample is compared with that for other QSOs in figure 1. The optically brighter objects, including those that are part of the radio sample, have α near 1, whereas the fainter objects have α ranging fairly uniformly from 0 to 3, with a greatly increased number of objects with large α and possibly an increased number with very small α.

Table 1. New Measurements of Flat Spectrum Radio Sources

Name	ID	K	α_{KB}
0722+145	BSO	15.08±0.15	1.1
0745+241	NSO*	14.08±0.06	1.7
0748+126	BSO	13.85±0.09	1.2
0754+100	NSO	11.86	1.5
0759+183	BSO	>16.7	<0.5
0829+046	BSO	12.27	1.6
0952+179	BSO	15.05±0.13	0.2
1014+208	BSO	>16.1	<0.8
1155+169	BSO	13.91±0.07	1.2
1257+145	BSO	>15.8	<0.1
1402+044	R(G)†	>16.3	<0.1
1427+109	BSO	16.7±0.4	∿-0.1
1434+235	BSO	16.4±0.4	∿0.1
1614+051	BSO	16.3±0.4	∿0.7
1656+053	BSO	14.04±0.08	1.1
1756+237	BSO	14.90±0.08	0.6
2149+056	EF	15.51±0.16	>2.0

* Listed by Condon, Hicks, and Jauncey (1977) as BSO; remeasurement of Palomar plate indicates NSO

† Z = 3.2

The increase of α with increasing m_B is not a selection effect. We have observed six more objects with $m_B \geq 20$ that meet all the criteria for inclusion in the radio sample except that they fall outside the 4-25° declination range. From the total of 11 sources with appropriate radio properties, 5 have been detected and shown to have large values of α. It is therefore clear that a large percentage of the optically very faint objects have steep, red spectra.

Two lines of evidence indicate a general similarity between the very red sources and the rest of the sample. First, in common with many of the optically brighter sources, at least two of the red sources are variable on timescales of a month or less (Rieke, Lebofsky, and Kinman 1979). Second, the ratio of 2-μm flux to radio flux is similar for these objects to the average ratio for the whole sample, corresponding to a spectral index of $\alpha = 0.64$. In comparison, the average radio-optical spectral index is $\alpha = 0.71$ (Condon, Jauncey, and Wright 1978). The red sources do not appear to have any distinguishing properties in the radio.

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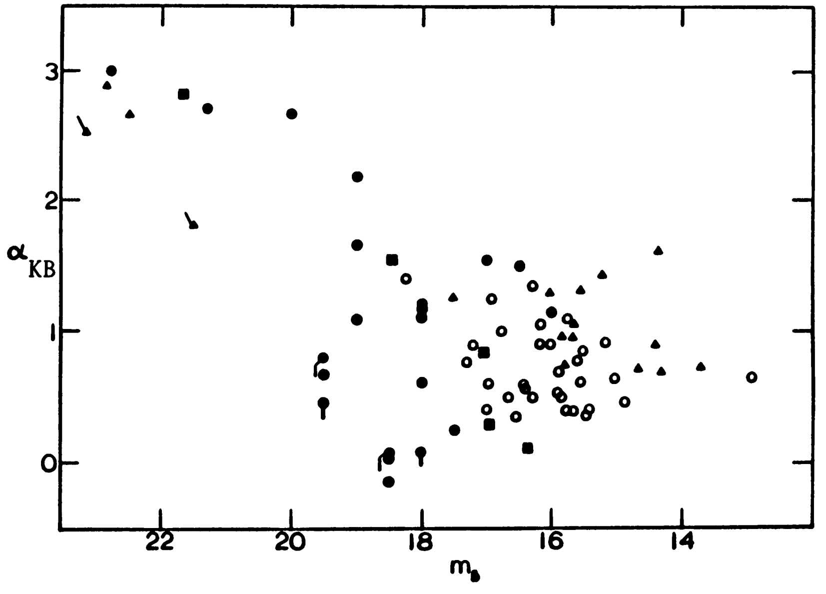

Figure 1. α_{KB} (2µm-to-blue power law slope) vs. m_B. Filled dots represent radio-selected QSOs from this study. Open dots are optically selected QSOs from Neugebauer et al. (1979); squares are from the same reference, but with Z > 1.0. Triangles are from other work (see references summarized by Rieke and Lebofsky 1979).

The explanation for the trend of α_{KB} with m_B is probably that the observed correlation between radio and optical fluxes (Condon, Jauncey, and Wright 1978) is a manifestation of a proportionality of the luminosities in the radio and the ultraviolet-optical-infrared spectral regions. For sources with UV-O-IR spectral slopes near 1, m_B is a reliable indicator of the luminosity. Sources with slopes near B substantially different from one will have larger UV-O-IR luminosities than indicated by m_B alone and therefore will be discriminated against in optically selected samples. The possible increase in the percentage of sources with very small α_{KB} near m_B = 18 is also consistent with this hypothesis. Some of these sources have extremely blue colors, with B-R ∿ -0.4 to -0.8 estimated from the Palomar plates.

Of the radio sources listed by Condon, Hicks, and Jauncey (1977) and Condon, Jauncey, and Wright (1978) that meet all the criteria for inclusion in our sample except for declination range, 89% have optical identifications. With allowance for sources missed because of variability and sensitivity limitations in the infrared, our success rate in detecting the empty fields indicates that optical-infrared counterparts can be found for 95% or more of these objects. The goal of a virtually complete set of identifications can therefore be met, but until it is, it must be recognized that the optical identifications represent a biased sample.

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DISCUSSION

Schild: At Mt. Hopkins we have been observing the Einstein Observatory deep fields with our CCD camera. In two fields which were blank on the Palomar Sky Survey and on a deep IIIa-J plate taken with the Palomar 48-inch Schmidt by Sargent, we found faint stellar sources with very red (R-I) color indices. If these are M stars they would have an unexpectedly high ratio of X-ray to optical luminosity. We think it is more likely that they are the same kind of very red quasar that Dr. Rieke has found. This suggests that X-ray as well as radar surveys turn up more red quasars than do the optical searches.

Smith: Perhaps you need not be so pessimistic about spectroscopy: Spinrad and I have been observing QSO identifications at the faint end. About 10% of 3C QSOs are quire red ($1.5 \lesssim \alpha_{opt} \lesssim 4.5$). Although the ionizing continuum at CIV may be down by a factor of 10 (or more) with respect to hydrogen, the line strengths of these objects are relatively normal.

Epstein: You said that the 2-micron magnitudes vary by a factor of as large as 2 or 3 on a time scale of about one month. Do any other objects have 2-micron variability this large?

Rieke: BL Lac-type sources have been observed to vary in the infrared by large amounts in a few days.

Murdoch: We can add one more steep optical spectrum QSO (with a flat spectrum) to the Smith and Spinrad sample. The optical spectral index is 3.5, and with a redshift of 1.71, Lyα is in the observation window, but was only marginally detected due to dispersion of the UV image. The continuum slope of 3.5 corrected for dispersion extends to Lyα.

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Rieke: That is undoubtedly an interesting QSO. However, before classifying it with the ones found in the infrared, we need to measure it there. All of the QSOs discovered so far in the optical that have red optical continua have a change in spectral slope near one micron, and a much flatter continuum in the infrared. These sources were discovered only because their continua allow their energy to emerge predominantly near the optical despite their red colors, so that the selection effects I have discussed are reduced.

Wolfe: Are these objects too faint to measure infrared polarization? If not, the detection of significant polarization would put them in the BL Lac class, and thus help you to classify these objects.

Rieke: The sources are a little too faint for easy infrared polarimetry, although if we find one just slightly brighter we certainly plan to try.