1979ApJ...232L.151R

THE ASTROPHYSICAL JOURNAL, 232:L151–L154, 1979 September 15
© 1979. The American Astronomical Society. All rights reserved. Printed in U.S.A.

A POSSIBLY NEW TYPE OF QSO IDENTIFIED THROUGH INFRARED MEASUREMENTS

G. H. RIEKE,[1] M. J. LEBOFSKY,[2] AND T. D. KINMAN[3]

Received 1979 April 25; accepted 1979 June 6

ABSTRACT

Six objects have been detected at 2.2 μm at the positions of flat-spectrum radio sources that had no optical identifications or were identified with very faint red sources. Three of the objects were subsequently located on deep plates. The infrared-to-optical spectra of these sources can be characterized by power laws of index $\alpha \approx -3$, and are therefore much steeper than the spectra of previously known QSOs. Two of the sources have varied at 2.2 μm on a time scale of 1 month. Sources of this sort will be discriminated against in optical searches, even if these searches disregard color in making identifications.

Subject headings: quasars — radio sources: identifications

I. INTRODUCTION

Flat-spectrum radio sources include a large proportion of BL Lacertae–type objects as well as many of the very high-redshift QSOs found to date (see, e.g., Condon, Hicks, and Jauncey 1977). In addition, a large percentage of these sources can be identified optically to allow radio-optical study of nearly complete samples (Condon, Jauncey, and Wright 1978). The identification process is aided by the high radio positional accuracy that can be obtained for these objects, by the facts that the radio sources are extremely compact and the associated optical object always seems to coincide exactly with the radio position, and by the observed correlation between optical and radio brightness (Condon, Jauncey, and Wright 1978).

Nonetheless, a significant number of these sources remain unidentified. It has generally been assumed that the unidentified sources were galaxies and QSOs similar in properties to the identifications of other flat-spectrum radio sources but slightly fainter, at least at the time of the Palomar Sky Survey. To test this assumption, we have searched for unidentified sources in the infrared. Our high success rate and the spectra of the sources we have found show that many of the unidentified sources are different from the previously identified ones in that they are exceedingly red in color.

II. OBSERVATIONS

Candidates for observation in the infrared were selected from lists of flat-spectrum radio sources (Condon, Hicks, and Jauncey 1977; Pauliny-Toth *et al.* 1978). With one exception, all the sources are listed as empty fields to the limit of the Palomar Sky Survey. The source 1413+135 was identified with a 20th mag red stellar object (Condon, Hicks, and Jauncey 1977). The positions of stars near the radio sources were measured with an accuracy of $\sim 0\farcs7$, using the SAO catalog for reference star positions. At the telescope these positions were used with an offset guider to center the infrared beam on the radio position with a total error of $\sim 1\farcs5$. In most cases, the radio positions themselves had accuracies of 1″ or better, although a few sources (0040+51, 0102+48, and 0223+34) had considerably larger positional errors. Beam diameters of $\sim 8''$ were used in the infrared; therefore the radio sources with the most accurate positions should have fallen near the center of the infrared beam, but positional errors may lead to a lower detection rate for the sources with relatively inaccurate radio positions. The positions of the two brightest sources, 0406+121 and 1413+135, were determined independently in the infrared and found to lie within $1\farcs5$ of the original telescope settings.

The infrared observations were obtained with the University of Arizona 2.25 m (90 inch) and 1.54 m (61 inch) telescopes, beginning at the K band (2.2 μm). If a definite detection was obtained, additional measurements were made at H (1.6 μm) and J (1.25 μm) (except for 0348+049, because observing conditions deteriorated). Despite the increase in background noise, the best signal-to-noise ratio on these sources was always obtained at 2.2 μm. The first source discovered, 0406+121, has been observed occasionally over a period of 6 months; during this time, it decreased in brightness by a factor of more than 4, including a significant change in 1 month. The object 1413+135 has also faded significantly in a period of a month. Our infrared observations are summarized in Tables 1 and 2.

Calibrated deep plates were obtained at the prime focus of the Mayall 4 m telescope for four of the fields containing infrared sources, using Eastman Kodak IIIa-F emulsions with a Schott GG495 filter.[4] The plates were calibrated using photometric standards in

[1] Steward Observatory and Lunar and Planetary Laboratory, University of Arizona. Alfred P. Sloan Fellow.

[2] Steward Observatory, University of Arizona.

[3] Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

[4] This plate-filter combination has a response which approximates to $V-0.25(B-V)$. The V magnitude was determined iteratively from a $B-V$ calculated by assuming a power-law spectrum fitted to the observed K and estimated V magnitudes.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1979ApJ...232L.151R

TABLE 1

MEASUREMENTS OF DETECTED SOURCES

Source	Date (UT) (mo/d/yr)	Flux (mJy) 0.55 μm	1.25 μm	1.6 μm	2.2 μm
0026+34........	9/11/78	...	...	0.13±0.06	0.40±0.07
	11/29/78	0.010±0.003	...	...	...
0348+049.......	10/31/78	...	...	...	0.13±0.03
	11/29/78	≤0.004	...	...	...
0406+121.......	8/26/78	...	...	...	1.81±0.36
	8/28/78	...	0.45±0.11	0.78±0.09	1.32±0.16
	9/11/78	...	...	0.39±0.13	1.18±0.20
	11/29/78	0.025±0.008	...	...	...
	2/10/79	...	0.17±0.07	0.44±0.08	0.69±0.08
	3/08/79	...	...	...	≤0.35
0602+67........	12/10/78	...	...	0.13±0.03	0.20±0.03
1413+135.......	2/10/79	≤0.06	0.46±0.10	1.17±0.10	3.32±0.10
	3/07/79	...	...	...	1.72±0.12
	3/08/79	...	...	...	1.98±0.18
2255+41........	11/19/78	...	...	0.18±0.06	0.33±0.07
	11/29/78	0.006±0.002	...	...	...

TABLE 2

TWO SIGMA UPPER LIMITS AT 2.2 MICRONS

Source	Upper Limit (mJy)
0040+51...........	0.57
0102+48...........	0.43
0108+38...........	0.16
0223+34...........	0.77
0332+078..........	0.12
0458+138..........	0.14
0539−057..........	0.19
0931−114..........	0.17
1100+223..........	0.16
1107−187..........	0.11
2047+098..........	0.22

the range $12 < v < 16$, and these sequences were extended 7 mag using a Racine auxiliary prism. The images were measured with a PDS microphotometer to give V magnitudes for which the overall error should not exceed ±0.3 mag. Sections covering 2′.5 × 2′.5 of these plates centered on the positions of the infrared sources are reproduced in Figure 1 (Plate L2). Faint objects lie at the positions of three of the sources and probably also at that of the fourth. The object with a marginal optical identification is also the faintest of the detected sources in the infrared. The optical and radio positions are compared in Table 3. In addition to these four sources, the position of 1413+135 was observed with a sensitive acquisition TV system in a dark sky. No object was found to a limit of $V \sim 19.5$.

Figure 2 compares the spectra of five of the six detected sources with spectra of two of the reddest QSOs known previously, 3C 68.1 and AO 0235+164, with the spectrum of a typical elliptical galaxy, and with that of one of the reddest known active emission-line galaxies with flat radio spectra, NGC 1275. The infrared spectrum for 0406+121 corresponds to its brightness level when first detected by us; the visual brightness has been adjusted upward by one-half the difference observed in the interval between 1978 August/September and 1979 February. A visual magnitude of 20 ± 0.5 was assumed for 1413+135. It is to be noted that, although the visual colors of these objects may not differ markedly from those of a normal E galaxy, their spectrum over the $V - K$ wave band is completely different.

III. DISCUSSION

The Palomar Sky Survey nearly suffices for the complete identification of the blue QSOs detected in existing radio surveys; it is not sufficiently deep to identify all of the galaxies, however (see, e.g., Bolton 1969; Kristian 1977). Therefore, two hypotheses have been put forward regarding radio sources in empty

TABLE 3

COMPARISON OF OPTICAL AND RADIO POSITIONS

Source	Optical Positions α (1950)	δ (1950)	Optical-Radio Δα	Δδ
0026+34........	00ʰ26ᵐ34ˢ.78±0ˢ.03	+34°39′55″.5±0″.5	−0ˢ.07	−2″.4
0348+049.......	03 48 15.32±0.03	+04 57 21.5±0.5	(−0.2)	(+0.4)
0406+121.......	04 06 35.62±0.06	+12 09 49.5±1.0	+0.22	−1.7
2255+41........	22 55 04.72±0.03	+41 38 13.5±0.5	+0.07	−0.1

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1979ApJ...232L.151R

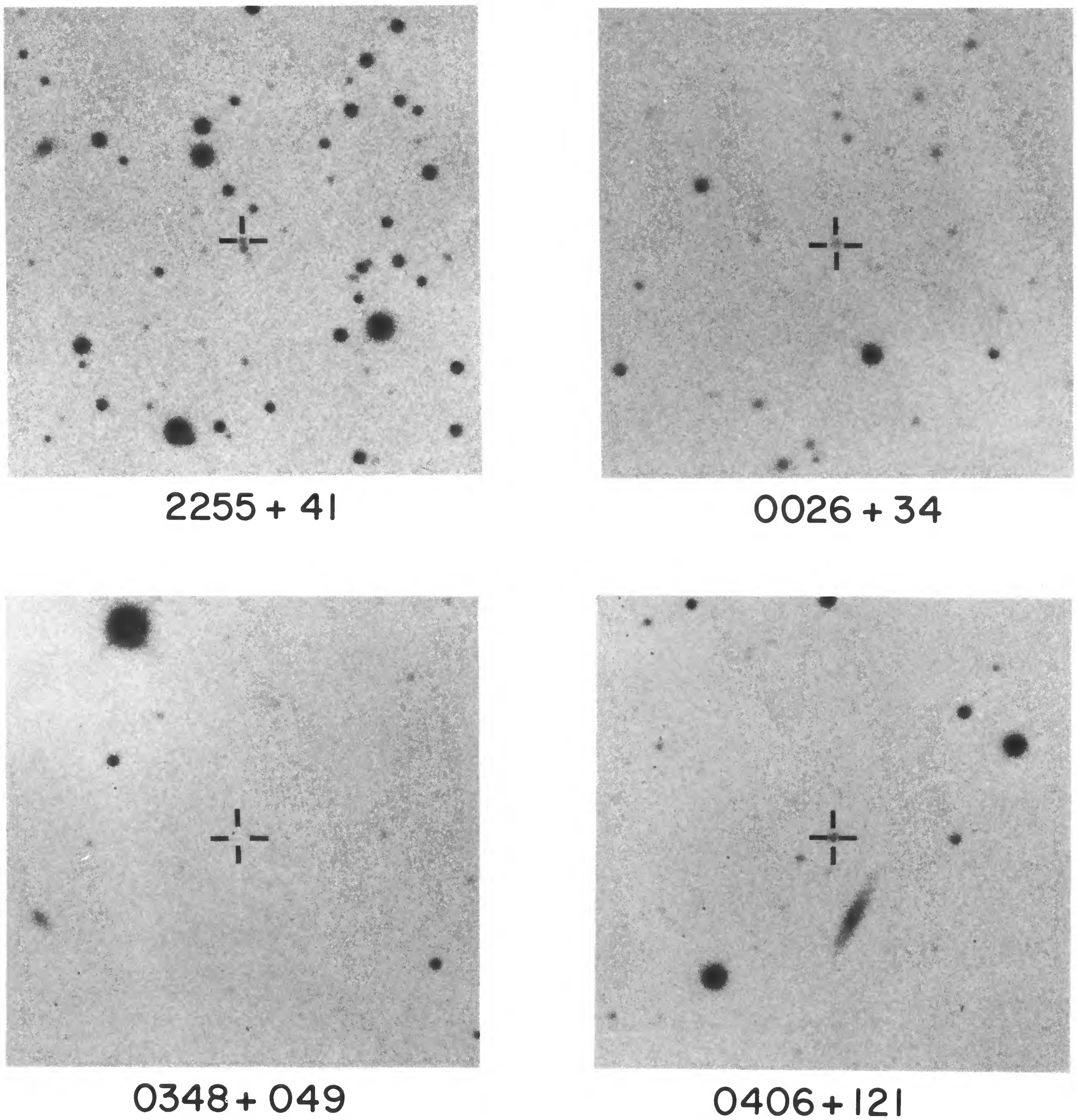

FIG. 1.—Deep plates at the positions of four newly identified sources. Sections of the plates 2.5 arcmin square are reproduced with north at the top and east at the left. The positions of the radio sources are marked.

RIEKE *et al.* (*see* page L152)

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1979ApJ...232L.151R

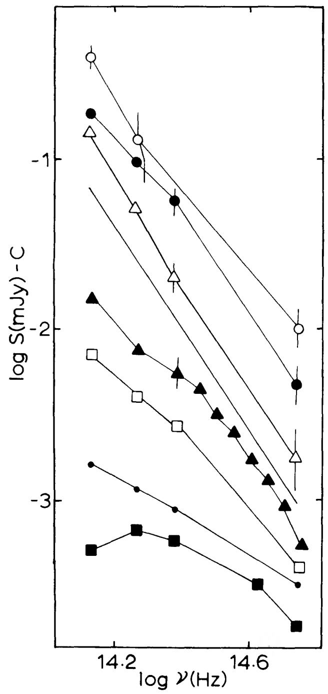

FIG. 2.—Optical-to-infrared spectra of newly identified sources and other red extragalactic objects. The object 0026+34 is represented by open circles and has a normalization constant $C = 0$; 0406+121 by filled circles and $C = 0.85$; 1413+135 by open triangles and $C = 1.35$; a power law ν^{-3}; 3C 68.1 by filled triangles and $C = 1.9$; AO 0235+164 by open squares and $C = 4.0$; and NGC 1275 by dots and $C = 4.8$. Filled squares indicate the colors of a typical elliptical galaxy, arbitrarily normalized. The data for 3C 68.1 are from Neugebauer *et al.* 1979; for AO 0235+164 from Rieke *et al.* 1976, near maximum; and for NGC 1275 from our unpublished measurements.

fields on the Palomar plates: (1) they are faint galaxies; or (2) they are variable QSOs similar to the brighter identifications but which happened to be fainter than the Palomar limit when the survey was made. Although these two hypotheses undoubtedly account for some of the empty fields, our work demonstrates that at least one additional effect is involved, at least for the flat-spectrum sources. Many of the empty fields have missed detection because the sources are exceedingly red.

The importance of this third effect can be estimated in a preliminary way. We have observed a total of 17 empty fields. For three of these (0040+51, 0102+48, and 0223+34) the radio positional errors were sufficiently large that it is questionable whether the source lay within our beam; in addition, we did not obtain deep limits for these sources. If we exclude them from the sample, we detected six of 14 sources, or ~40%. Three of the detected sources are within a factor of 2 in infrared flux of typical upper limits in our survey, indicating that a deeper survey would result in an even larger percentage of detections.

Infrared-to-optical spectral information is available for five of the six detected sources. Judged by the $V - K$ color, *all five* are as red as or redder than the reddest previously known QSOs or active galaxies (see Fig. 2). They are much redder ($V - K \sim 6$) than a typical elliptical galaxy ($V - K \sim 3$). Even if K-corrections appropriate to $z = 1$ are applied to the active and normal galaxy spectra, the five sources are *all* redder, particularly in $H - K$ and $J - H$ where these colors have been measured. These sources therefore represent either a new type of object or a substantial extension in the properties of a previously known class of object.

Among known types of object, these sources resemble optically violently variable (OVV) sources (either with emission lines [QSOs] or without [BL Lacertae-type]), or objects at very high redshift. The uniform distribution with galactic latitude also indicates that the sources are extragalactic. The radio (Condon, Hicks, and Jauncey 1977) and infrared variability of 0406+121 and 1413+135 imply membership in the OVV category. Members of this category are thought to have steeper optical-IR spectra than do nonvariable QSOs (Kinman 1975; Neugebauer *et al.* 1979). If this association is correct, theoretical work on this type of source must accommodate very steep spectra in addition to the difficulties already posed by the other characteristics of the sources; naive synchrotron emission theory would suggest an electron energy spectrum of the form $N(E) \propto E^{-7}$ [where E is the electron energy and $N(E)$ is the number of electrons per energy interval] for a source with power-law spectral slope $\alpha = -3$. Such a steep slope suggests a cutoff in the electron spectrum. It is therefore of interest to find out whether the newly discovered objects are a distinct subcategory of QSOs or whether spectral indices are more or less uniformly distributed from values where no cutoff is suspected to the values found here.

Our results also indicate that there is a class of QSO that is strongly discriminated against with current optical search techniques even if identifications are made without regard to color. This bias arises fundamentally because much of the optical-to-infrared luminosity of a QSO is emitted at wavelengths longer than 1 μm. Objects like 3C 68.1 and AO 0235+164 are detected in existing surveys in part because their infrared slopes are not particularly steep, even though they are relatively red at wavelengths short of 1 μm. In contrast, the small group of infrared-selected QSOs discussed here appear to have very steeply falling spectra over the whole range of 2.2 to 0.5 μm. Any optically selected sample of QSOs can be expected to be biased against strong infrared emitters; for example, the recent study by Neugebauer *et al.* (1979) will tend to underestimate the role of the infrared in a typical QSO.

Fortunately, with an adequate investment of telescope time, modern infrared instruments can be used to remove this bias. In fact, these instruments are now competitive with any other technique known to us for confirming the nonstellar nature of a proposed identification for a radio source. However, it may be difficult to search in the infrared for very steep spectrum counterparts to steep spectrum radio sources, since for these sources the identification is often displaced from the radio position. Thus it will be inefficient to integrate

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1979ApJ...232L.151R

at a single position, as was done for the flat-spectrum radio sources, and the use of two-dimensional detectors sensitive to $\lambda \lesssim 1$ μm may be the best approach.

IV. CONCLUSION

We have carried out a small survey for infrared counterparts of flat-spectrum radio sources that are empty fields to the limit of the sky survey. We have found:

1) A large percentage of these sources are detectable in the infrared and have been missed in the optical because of their very steep optical-to-IR spectra.

2) These sources are probably related to previously known highly variable QSOs and BL Lacertae-type objects. Additional theoretical and observational initiatives will be needed to define this relationship.

3) The known sample of QSOs, found through optical search techniques, is biased against sources bright in the infrared. This bias is only partially removed by making identifications without regard to color.

4) Infrared techniques are now sufficiently advanced to start removing this bias.

We thank C. Thompson and C. T. Mahaffey for helping to measure plates, E. F. Montgomery for assistance in constructing the infrared photometer, and C. Heller and G. Will for helping with some of the observations. This work was supported in part by the National Science Foundation.

REFERENCES

Bolton, J. G. 1969, *A.J.*, **74**, 131.
Condon, J. J., Hicks, P. D., and Jauncey, D. L. 1977, *A.J.*, **82**, 692.
Condon, J. J., Jauncey, D. L., and Wright, A. E. 1978, *A.J.*, **83**, 1036.
Kinman, T. D. 1975, in *IAU Symposium No. 67, Variable Stars and Stellar Evolution*, ed. V. E. Sherwood and L. Plaut (Dordrecht: Reidel), p. 573.
Kristian, I. 1977, in *IAU Symposium No. 74, Radio Astronomy and Cosmology*, ed. D. L. Jauncey (Dordrecht: Reidel), p. 151.
Neugebauer, G., Oke, J. B., Becklin, E. E., and Matthews, K. 1979, *Ap. J.*, **230**, 79.
Pauliny-Toth, I. I. K., Witzel, A., Preuss, E., Kuhr, H., Kellermann, K. I., Fomalont, E. B., and Davis, M. M. 1978, *A.J.*, **83**, 451.
Rieke, G. H., Grasdalen, G. L., Kinman, T. D., Hintzen, P., Wills, B. J., and Wills, D. 1976, *Nature*, **260**, 754.

T. D. KINMAN: Kitt Peak National Observatory, Box 26732, Tucson, AZ 85726

M. J. LEBOFSKY and G. H. RIEKE: Steward Observatory, University of Arizona, Tucson, AZ 85721

© American Astronomical Society • Provided by the NASA Astrophysics Data System