THE ASTROPHYSICAL JOURNAL, Vol. 152, May 1968

SPECTROSCOPIC AND PHOTOMETRIC DATA FOR A SAMPLE OF QUASI-STELLAR OBJECTS IDENTIFIED BY THEIR INFRARED EXCESS*

A. BRACCESI
Laboratorio Nazionale di Radioastronomia, Bologna

R. LYNDS
Kitt Peak National Observatory†

AND

A. SANDAGE
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington and California Institute of Technology

Received March 9, 1968

ABSTRACT

The criterion of infrared excess has been used to obtain a first candidate list of non-radio QSOs in a field centered at 15^h, $+35°$. Spectrographic data for objects with infrared excesses, chosen from a complete catalogue of blue objects to $B \cong 19.4$ mag, show that fifteen objects, out of sixteen candidates observed, have emission lines characteristic of QSOs. Redshifts are given for fourteen of the objects. The surface density of QSOs in this field, when compared with the results of a survey to a brighter limiting magnitude for the PHL field 1^h36^m, $+6°$, shows that the number of objects continues to increase quite steeply going to fainter magnitudes.

Following the proposal of one of us (Braccesi 1967) that the peculiar characteristics of the infrared spectrum of quasi-stellar objects (QSOs) could be used to distinguish such objects from hot stars having similar *UBV* photometric characteristics, photographic material in *UBV* and infrared has been obtained with the Palomar 48-inch Schmidt telescope for a field centered at 13^h, $+36°$, one of the original "interloper" search fields (Sandage and Véron 1965).

I. SELECTION OF OBJECTS

The two-color U and B $6°.5 \times 6°.5$ plate used by Sandage and Véron has been reexamined to construct a complete catalogue of ultraviolet objects to a limiting magnitude of $B \cong 19.4$ (Braccesi 1968). The plate has also been compared in a blink machine with an infrared plate (I-N emulsion exposed through a Wratten 89B filter—giving a range from λ7000 to the sensitivity limit of the I-N emulsion) of the same field. After experience had been gained, it was not difficult to perceive that the ultraviolet-excess objects fall into two classes according to the relative intensity of the infrared images. On the basis of a previous discussion (Braccesi 1967), we presume—as a working hypothesis—that those objects that are strong in the infrared are candidates for the QSO class and that the remainder are stars.

Of the original nine Sandage-Véron blue stellar objects (BSOs) in this field for which *UBV* photoelectric photometry exists, six (BSOs 2, 6, 7, 8, 9, and 11) seem to have a rather large infrared excess; of the three that do not, BSO 1 has only a marginal infrared excess, BSO 3 is probably an F-type subdwarf as indicated by the $U - B$ and $B - V$

* *Contributions from the Kitt Peak National Observatory*, No. 312.

† Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

colors, and BSO 5 has a very weak infrared and is presumed to be a white dwarf on the basis of the $U - B$ and $B - V$ colors. A sample of seventeen objects showing infrared excess has been chosen for further study. The sample covers a moderate range of apparent magnitude (from $V = 16.8$ to $V = 19.2$ mag) and includes BSO 1 and the six Sandage-Véron objects having infrared excesses.

II. PHOTOMETRY

The U, B, and V magnitudes of the candidates were obtained by photoelectric photometry with the 200-inch telescope at Palomar. The results are given in Table 1 for the seventeen QSO candidates. Also included in the table are *UBV* measurements for three objects predicted to be stars; two of these are BSOs and complete the tabulation of Sandage-Véron objects for this field, while the third object (B281) was mistakenly included in both the photoelectric and the spectrographic program in spite of the photometric indication that it would prove to be a subdwarf. The two-color diagram for

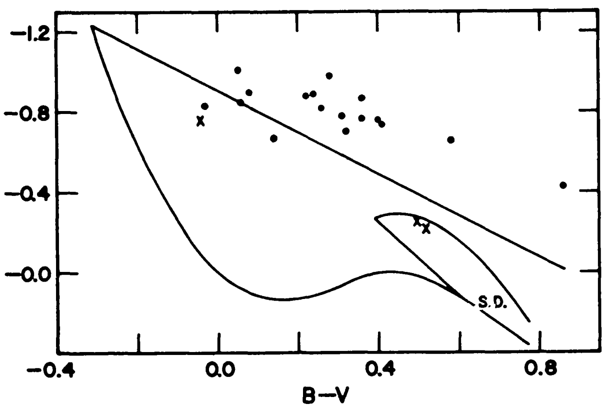

FIG. 1.—Two-color diagram for objects listed in Table 1. The three stars are shown as crosses. The remaining objects, shown as filled circles, are QSOs as judged by their spectra. The main sequence, black-body line, and subdwarf domain are shown for comparison.

the objects is shown in Figure 1. Finding charts for all of the objects are given in Figure 2 (Plates L1–L4).

Three infrared plates obtained with the 48-inch Schmidt telescope have been measured by using the Becker iris photometer in Asiago. An approximate magnitude scale has been established assuming a black-body spectrum for the three real stars in Table 1. Intercomparison of the results for the three plates leads to the conclusion that the infrared magnitudes have an average rms error of 0.06 mag. The uncertainty of the calibration of the magnitude scale is more difficult to estimate, but it should be of the same order of magnitude. The infrared excess was defined as the observed infrared magnitude *minus* the infrared magnitude of a black-body radiator having the given U and B magnitudes. The relation used to compute the infrared magnitude for a black body is

$$I = U - 3.14\,(U - B)\,, \quad (1)$$

assuming the relevant effective wavelengths of the U, B, and infrared bands to be 3600, 4400, and 7950 Å, respectively. The infrared excess for each QSO candidate is given in Table 1.

III. RADIO EMISSION

Accurate positions of all QSO candidates have been measured from a 48-inch Schmidt plate using a Mann double-screw comparator at the Mount Wilson Observatory. The

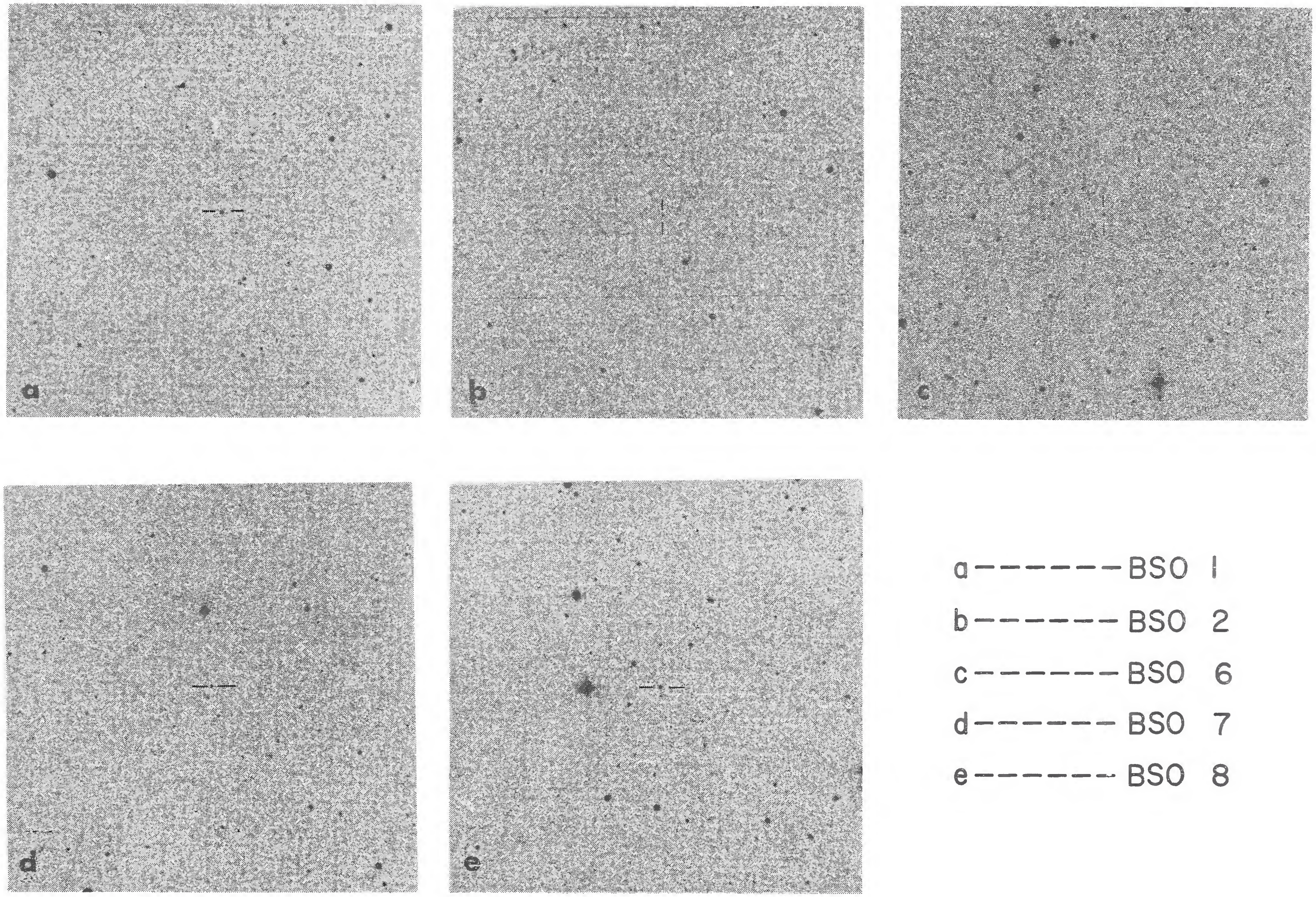

FIG. 2.—Finding charts for objects listed in Table 1. The charts are 10′ square, with north at the top and west to the right; they are reproduced from a photovisual plate obtained with the Palomar 48-inch Schmidt telescope.

BRACCESI (*see* page L106)

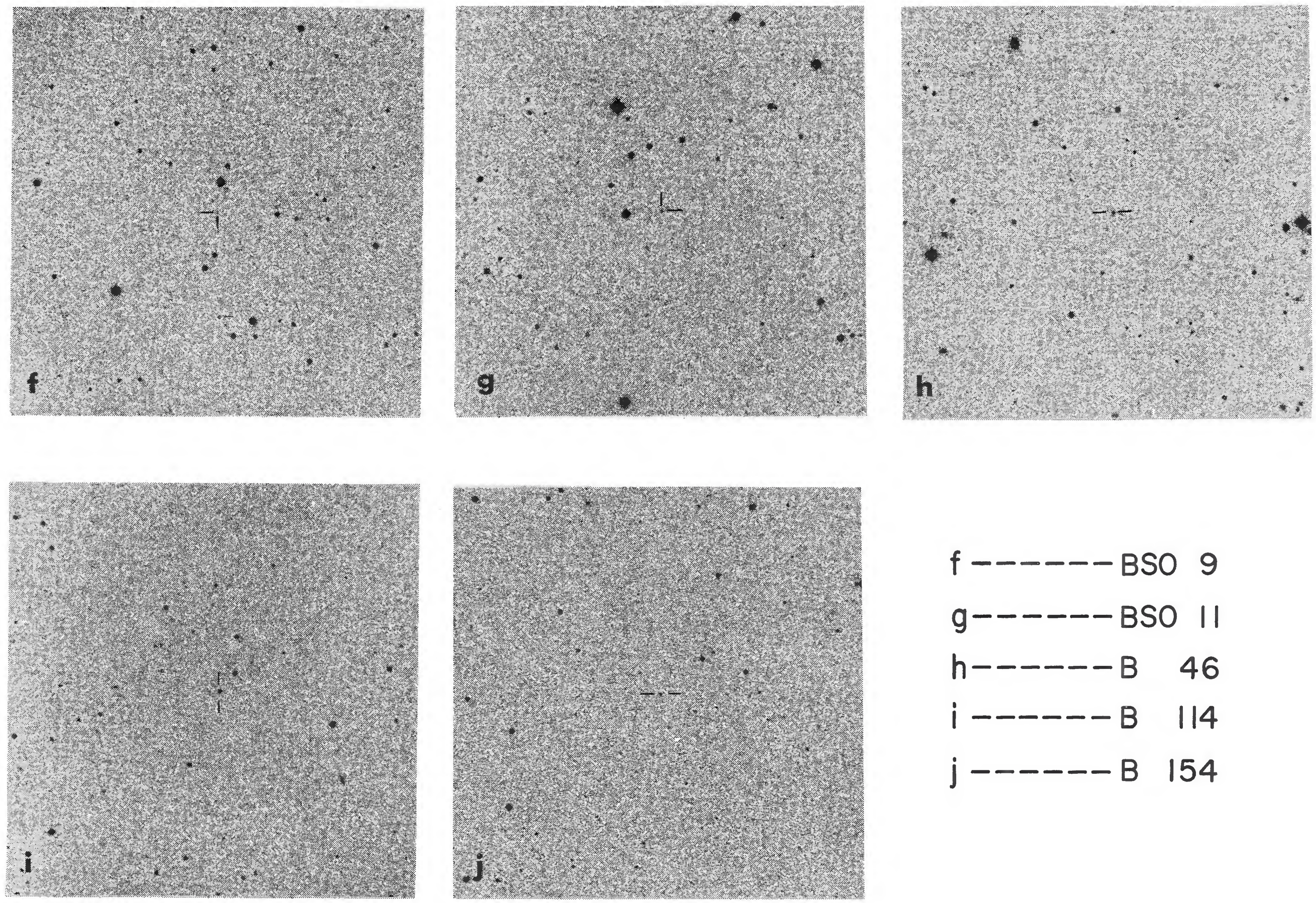

Fig. 2.—*Continued*

Braccesi (*see* page L106)

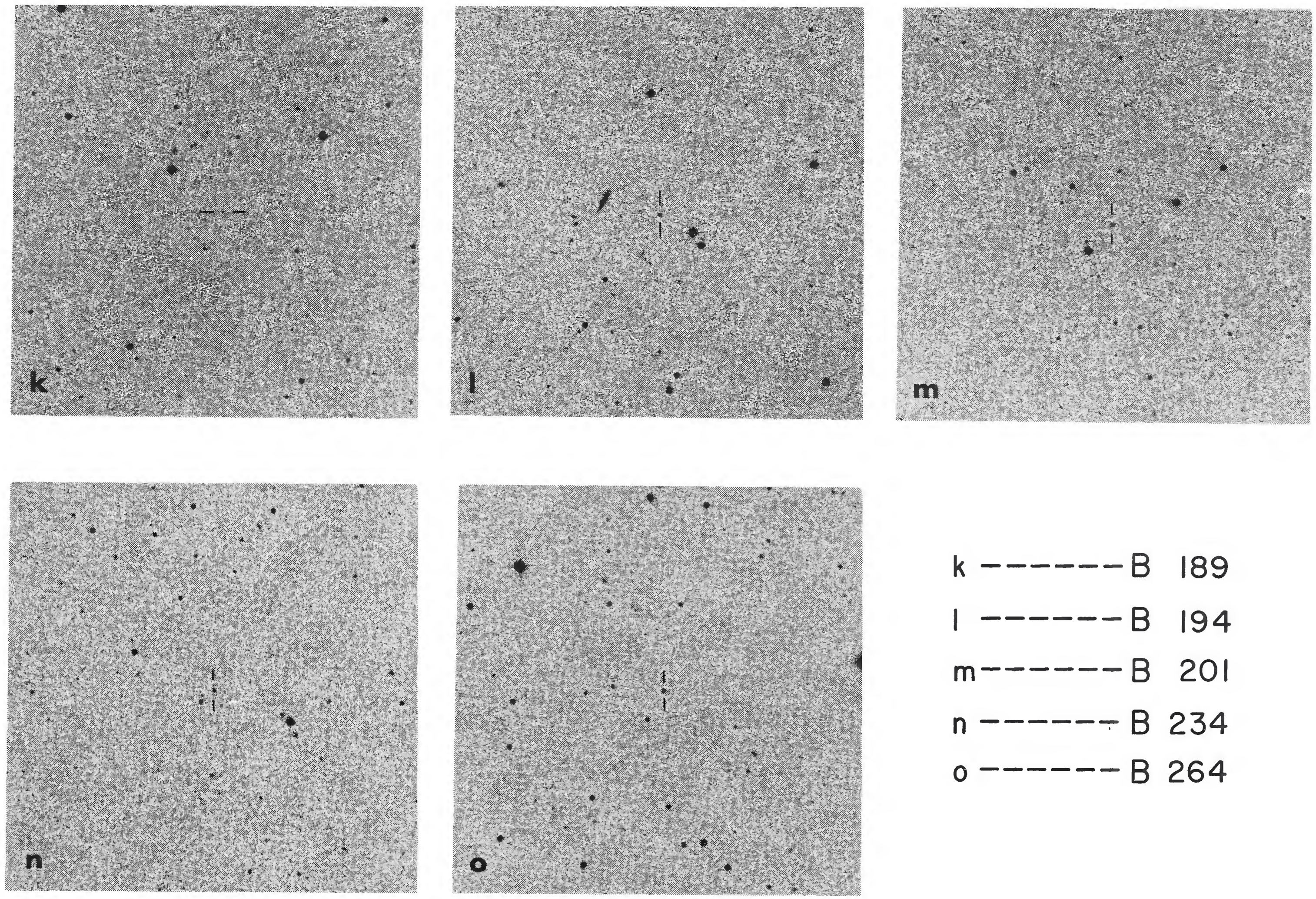

FIG. 2.—*Continued*

BRACCESI (*see* page L106)

1968ApJ...152L.105B

PLATE L4

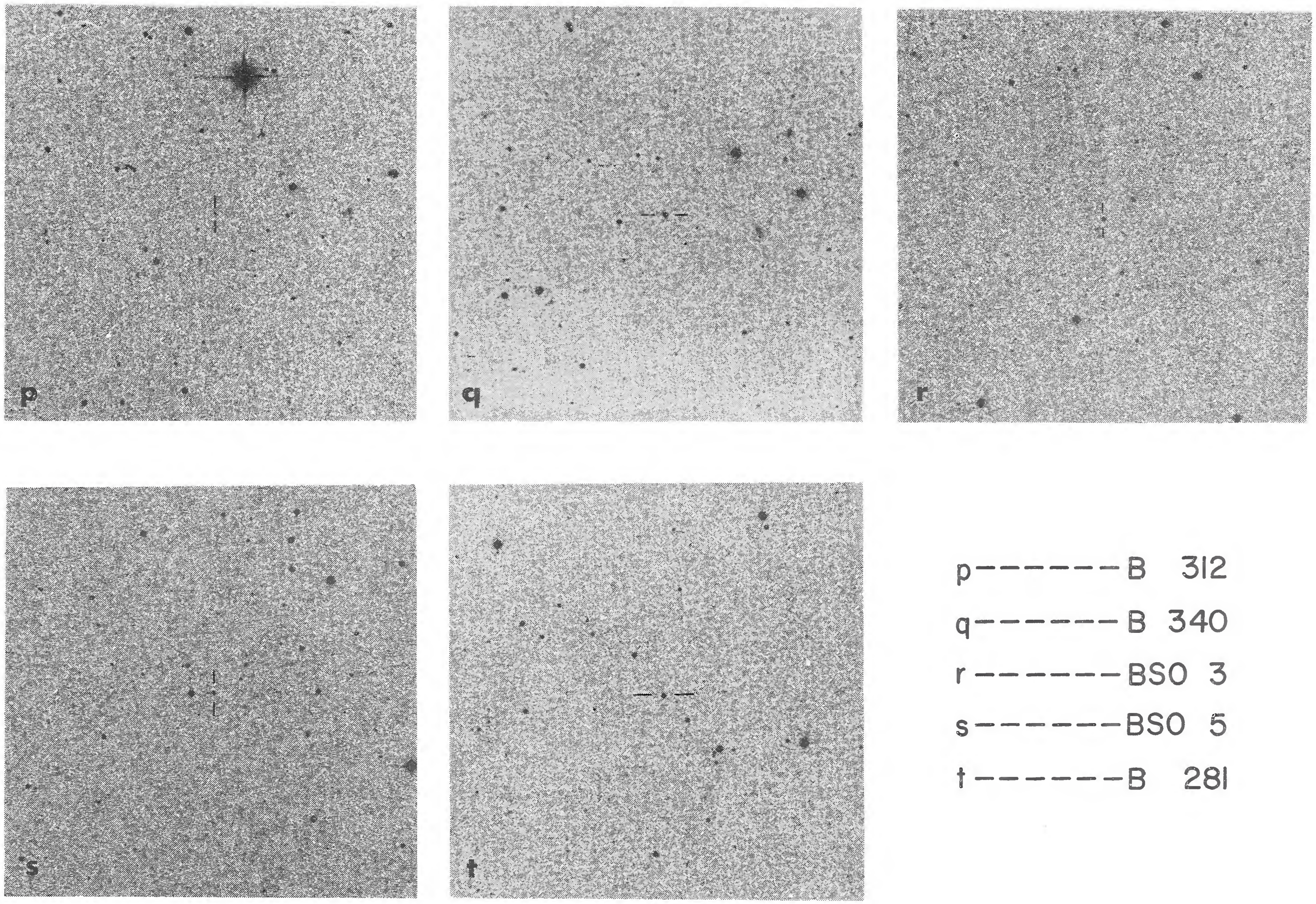

FIG. 2.—*Continued*

BRACCESI (*see* page L106)

accuracy of these measurements is probably better than 1″. Two special radio surveys of the region, one at 408 MHz with the east-west arm of the Bologna cross radio telescope and the second at 2800 MHz with the Owens Valley radio interferometer, have failed to detect radio emission from any of these objects. Furthermore, none of the objects appear to correspond with sources in the fourth Cambridge catalogue (4C) of radio sources. Therefore, the following limits can be set to the radio emission: 178 MHz, $<2.0 \times 10^{-26}$; 408 MHz, $<0.5 \times 10^{-26}$; and 2800 MHz $<0.2 \times 10^{-26}$ W m^{-2} (c/s)$^{-1}$. The objects are "radio-quiet" to these limits of detection.

IV. SPECTRA

Previous spectroscopic data exist for two of the objects discussed here (Sandage 1965). BSO 1 has a redshift of 1.241 and has no large infrared excess. BSO 8 was previously reported to have a featureless spectrum, but Kitt Peak observations, described below, show the presence of several emission lines.

Spectrograms of BSOs 8 and 14 of the fifteen candidates having no previous spectroscopic material have been obtained by Lynds and Braccesi using the 84-inch telescope at Kitt Peak. None of the objects appear to be stars. With the exception of one that

TABLE 1

PHOTOMETRIC AND SPECTROSCOPIC DATA

No.	α(1950)	δ(1950)	V	$B-V$	$U-B$	I_{ex}*	Redshifts and Remarks
				QSOs			
BSO 1....	12^{h}46^{m}28^s.7	+37°47′01″	16.98	+0.31	−0.78	−0.3	1.241, absorption line
BSO 2....	12 48 17.7	33 47 04	18.64	+ .28	0.98	1.6	0.186 (?)
BSO 6....	12 59 30.5	34 27 15	17.87	+ .05	1.01	1.2	1.956
BSO 7....	13 07 05.6	35 55 58	18.34	+ .22	0.88	1.0	Continuous spectrum
BSO 8....	13 09 15.2	34 03 08	17.43	+ .36	0.77	0.5	Emission lines
BSO 9....	13 11 13.5	34 45 21	19.10	+ .26	0.89	1.5	No spectrogram
BSO 11...	13 11 22.1	36 16 30	18.41	+ .06	0.85	1.5	2.084, absorption lines (?)
B46†.....	12 46 29.2	34 40 49	17.83	+ .36	0.87	1.3	0.271, $V-R$=0.58‡
B114.....	12 52 57.7	35 55 26	17.92	+ .08	0.90	1.2	0.221 (?)
B154.....	12 55 02.1	35 21 21	18.56	+ .32	0.70	1.2	0.183 (?)
B189.....	12 56 51.1	36 48 10	19.22	− .03	0.83	1.5	2.075
B194.....	12 56 07.8	35 44 56	17.96	+ .40	0.76	1.5	1.864, absorption lines
B201.....	12 57 26.6	34 39 34	16.79	+ .26	0.82	1.0	1.375
B234.....	13 00 43.2	36 07 48	17.52	+ .86	0.43	0.4	0.060, sharp lines
B264.....	12 59 30.9	32 21 58	16.89	+ .58	0.65	0.5	0.095
B312.....	13 04 53.1	37 29 33	19.08	+ .14	0.67	1.5	0.450 (?)
B340†....	13 04 47.1	+34 40 39	16.97	+0.41	−0.74	−1.7	0.184, $V-R$=0.64‡
				Stars			
BSO 3....	12^{h}49^{m}21^s.1	+36°08′32″	17.30	+0.52	−0.22	....	
BSO 5....	12 57 02.5	36 35 36	17.48	− .04	.77	....	
B281.....	13 02 01.6	+36 13 36	16.34	+0.50	−0.26	....	Absorption lines—subdwarf

* Infrared excess, as defined in the text.

† Fuzzy visual appearance with both the 84-inch and 200-inch telescopes.

‡ R is a red magnitude defined by Sandage and Smith (1963).

seems to have a continuous spectrum, all objects have emission lines characteristic of QSOs. Redshifts for fourteen objects have been determined; four of these are provisional. The redshifts are given in Table 1. Supplementary comments on the individual objects follow.

BSO 2.—The tentative redshift of 0.186 is based on a definite emission line at 4415 Å and a very diffuse feature near 4070 Å, identified as [Ne V] λ3426 and [O II] λ3727, respectively. Although the redshift determination is not definitive, the QSO nature of the object is nearly certain.

BSO 6.—This object has a very strong emission-line spectrum closely resembling that of PHL 1305[1] (Lynds 1967). The usual resonance lines are present and include Ly-α, N V λ1240, Si IV λλ1394, 1403, and C IV λ1549. A spectrogram of this object is reproduced in Figure 3, *a* (Plate L5).

BSO 7.—The presence of spectroscopic features is not conclusively indicated by either of the two spectrograms of this object.

BSO 8.—Although the redshift of this object is indeterminate, there is a definite emission line at 3873 Å and possible lines at 3734, 4276, and 5719 Å.

BSO 9.—No spectrogram was obtained for this object.

BSO 11.—The emission lines present include Ly-α and C IV λ1549, both of which are fairly strong, and N V λ1240. There are indications of the presence of absorption lines in the spectrum.

B46.—The redshift is based on emission lines at 3552, 3728, 4734, and 6363 Å; identified as Mg II λ2798, [Mg V] λ2931, [O II] λ3727, and [O III] λ5007, respectively. The line identified as λ2798 is the only really strong line, but the line at 6363 Å is much too strong to be attributable to the airglow feature near the same wavelength.

B114.—The tentative redshift is based on a definite but very broad emission line near 3420 Å, identified as Mg II λ2798, and two possible features at 4174 and 5940 Å, identified as [Ne V] λ3426 and Hβ, respectively. Although the redshift determination is not definitive, the QSO nature of the object is not in doubt.

B154.—The provisional redshift of 0.183 is based on weak emission lines at 4413 and 5921 Å, identified as [O II] λ3727 and [O III] λ5007, respectively. Although the redshift determination is not definitive, the QSO nature of the object is nearly certain.

B189.—The redshift of 2.075 is probably not very accurate because of the great width (approximately 150 Å) of one of the two observed emission lines. However, there is no reasonable basis for doubting the general value of the redshift. The two observed lines are identified with Ly-α and C IV λ1549, the latter being the broad line.

B194.—The emission lines that are identified include Ly-α, N V λ1240, and C IV λ1549; all are moderately strong. In addition, there is definite emission at the position of Si IV λλ1394, 1403. There are absorption lines in the spectrum, but their study is not yet complete.

B201.—The redshift is well determined from two moderately strong emission lines identified as C IV λ1549 and C III] λ1909. There is also a broad emission feature at the expected position of Si IV λλ1394, 1403.

B234.—The spectrum of this object is unique among those of QSOs studied thus far at Kitt Peak. The usual emission lines seen in objects of small redshift, namely, forbidden lines and the Balmer series of hydrogen, are observed; but they are extremely narrow. A spectrogram of the object is reproduced in Figure 3, *b*. For purposes of comparison, a spectrogram of B264 is reproduced in Figure 3, *c*. B264 has a redshift similar to that of B234 but displays line profiles more nearly representative of those usually encountered in QSO spectra. A higher-dispersion spectrogram of B234 shows that the lines are unresolved to a spectral resolution of about 1 Å. It is also of interest to note that the intensity ratio of the λ3727 doublet indicates an electron density below 10^{-2} cm^{-3}.

[1] A spectogram of PHL 1305 is reproduced in Burbidge and Burbidge (1967).

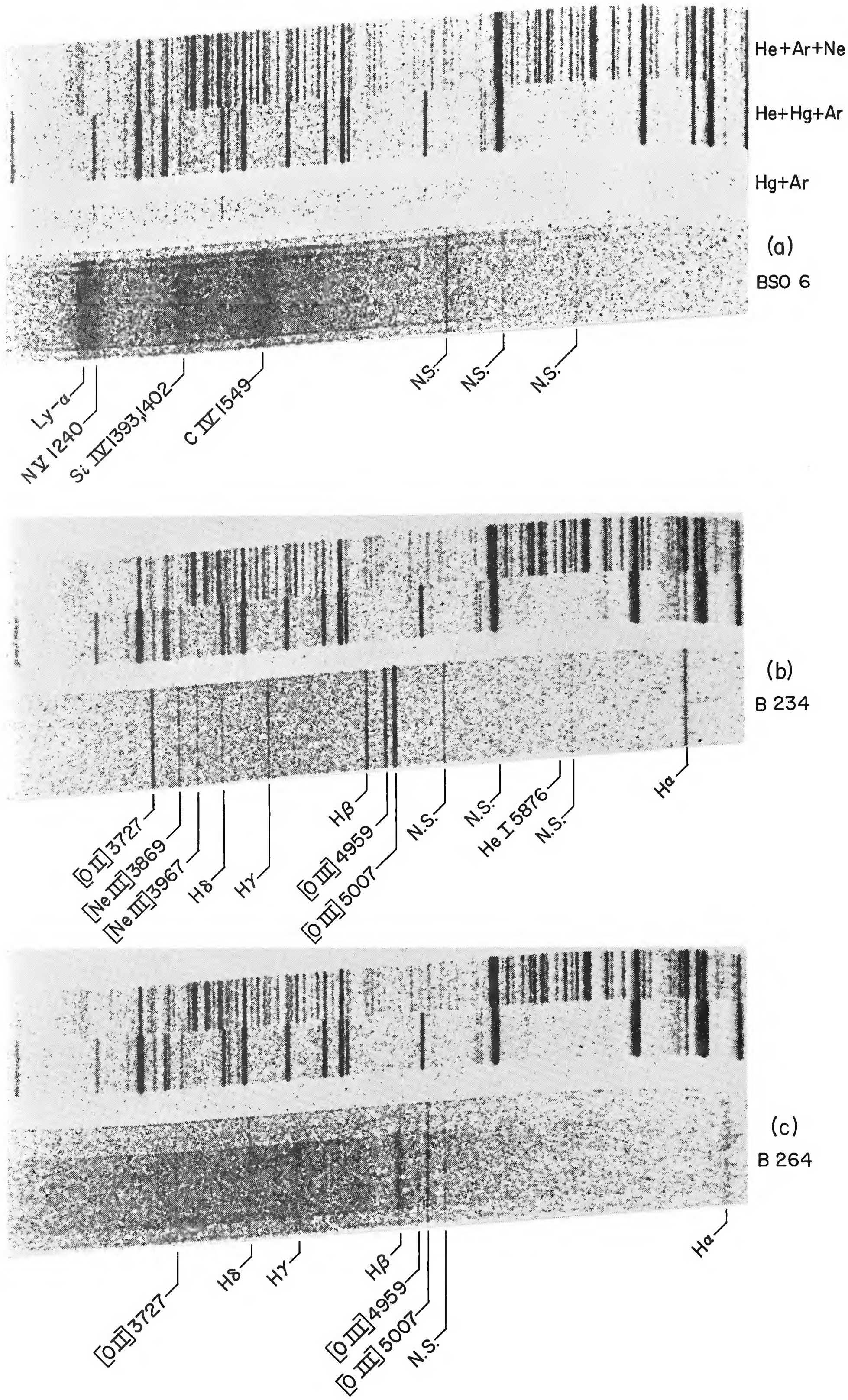

FIG. 3.—Spectrograms of selected objects from Table 1. BSO 6, B234, and B264 appear in parts *a*, *b*, and *c* of the illustration, respectively. Note especially the differences between the spectra of B234 and B264. The spectrograms were obtained with the image-tube spectrograph of the Kitt Peak 84-inch telescope.

BRACCESI (*see* page L108)

B264.—The line identifications and redshift determination are straightforward. The spectrum is illustrated in Figure 3, *c*, and is discussed in connection with B234.

B312.—Two spectrograms covering the spectral range from 3100 to 8000 Å fail to reveal the certain presence of more than one moderately strong emission line at 4057 Å, with the possible exception of a weak feature occurring near the position expected for [Ne v] λ3426, provided that the strong line is identified as Mg II λ2798. Although the tentative redshift cannot be described as certain, the nature of the available spectroscopic material is such as to virtually rule out an alternative interpretation.

B340.—The redshift is based on emission lines observed at 3310, 4040, 5178, 5755, and 5931 Å, identified as Mg II λ1798, [Ne v] λ3426, [O III] λ4363, Hβ, and [O III] λ5007, respectively. All of the lines are moderately weak, the strongest being those identified as λλ2798 and 5007.

It is important to note that the redshifts of the objects range from 0.06 to 2.1 and that, with the exception of B234, the spectra appear to be indistinguishable from those of quasi-stellar radio sources. This similarity extends even to the presence of absorption lines in the spectra of two of the objects. From Table 1 it is seen that three objects (BSO 2, B154, and B340) have nearly the same redshift of 0.184. However, the objects show no special geometrical arrangement on the sky; and, because two of the redshifts are provisional, the suggestion of clustering cannot be supported at the present time.

In connection with the unique spectrum of B234, it is interesting to note in Figure 1 that the position of the object in the two-color diagram is also unique for the present sample of objects. As a matter of fact, the photometric characteristics of the object are similar to those of the so-called N-type galaxies (Sandage 1967). On the other hand, the photometric characteristics of B234 are undoubtedly controlled by the very intense emission lines and are, therefore, of questionable value for purposes of classification. Finally, B234 appears quite stellar at both the 84-inch and 200-inch telescopes, and available photographic material does not provide any evidence of fuzziness or nebulosity. The true significance of B234 is still open to question. B340 and B46, two objects that do look fuzzy at both the 84-inch and 200-inch telescopes, have typical spectra for QSOs, and their position in the two-color diagram is normal. It should be noted that B340 appears to be extended in the infrared (Figure 4, Plate L6), being 4″ long in position angle 90°.

V. CONCLUSIONS

The sample of objects that has been observed is essentially free of contamination by stars. The next points to be investigated are (1) the way in which the selection based on the infrared excess is influenced by the redshift and (2) the variance of the infrared excess from object to object.

Our data show that at every redshift there are objects that have infrared excess. There are, however, QSOs that have little or no infrared excess (BSO 1 is an example). Consequently, although the presence of an infrared excess is an important criterion for the selection of candidates, it may not distinguish all such candidates.

The average infrared excess for the present sample is about −1.2—slightly larger than is expected from the mean composite continuum spectrum discussed elsewhere (Sandage 1966). It must be remembered, however, that the objects have been selected for their infrared excess and that this selection introduces a bias.

The objects studied here comprise only a small fraction of the complete catalogue of this region. In a 6°5 × 6°5 field approximately five hundred ultraviolet stars have been identified down to $B \simeq 19.4$ mag, of which about three hundred show an infrared excess. If a majority of the infrared-excess objects prove to be QSOs, as the present results seem to indicate, there will be something of the order of three hundred QSOs in this one field alone. Several candidates, in addition to the present list, have already been observed spectroscopically by Lynds with positive results; the program is being continued.

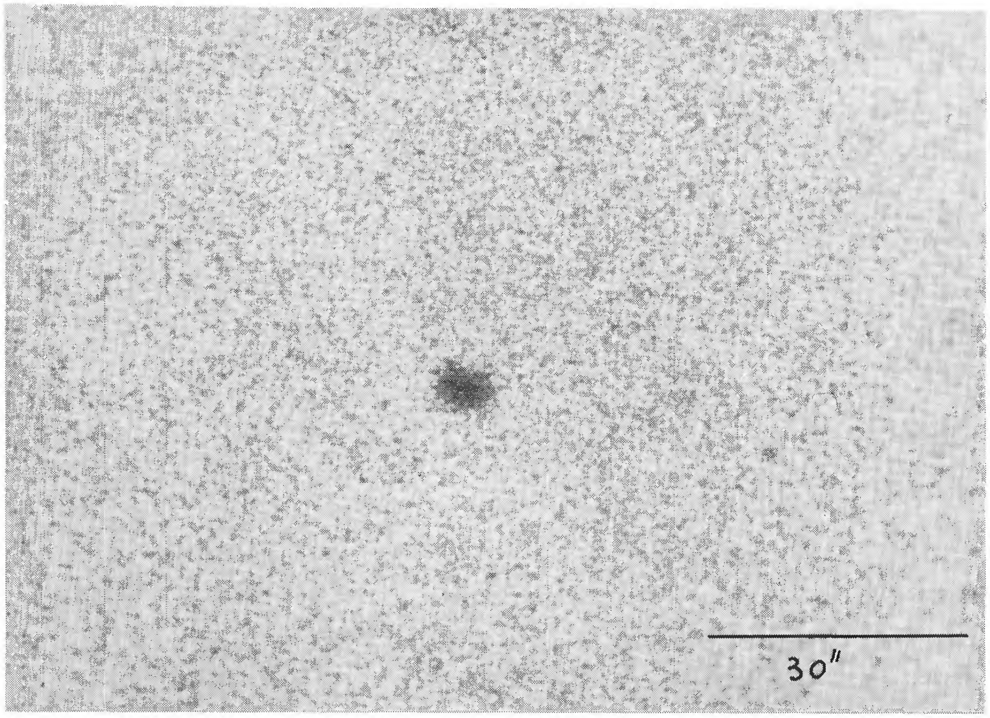

FIG. 4.—Enlargement, from an infrared plate, showing the elongation of the image of B340. The plate was obtained with the Palomar 48-inch Schmidt telescope.

BRACCESI (*see* page L109)

It can be stated that, to $B \simeq 19.4$ mag, the surface density of "radio-quiet" QSOs is very large in this field, substantially greater than that found by Sandage and Luyten (1967) to $B = 18.1$ mag in the PHL field at 1^h36^m, $+6°$. We may conjecture from this result that the $N(m)$ relation for QSOs is a steeply rising function of apparent magnitude and that a previous estimate of 10^5 such objects over the sky to $B = 19.7$ mag is likely to be conservative.

The interest in the infrared criterion lies primarily in the possibility of studying the $N(m)$ relation in this and in other fields to faint limiting magnitudes. The power of the technique will depend to a large extent on the practicality of separating QSOs from white dwarfs on a purely photometric basis.

One of us (A. Braccesi) wishes to thank the Director of the Mount Wilson and Palomar Observatories for the privilege of using the facilities of the Observatories.

REFERENCES

Braccesi, A. 1967, *Nuovo Cimento*, Ser. 10, **49**, 148.
———. 1968, manuscript catalogue.
Burbidge, G. R., and Burbidge, M. E. 1967, *Quasi-stellar Objects* (San Francisco, Calif.: Freeman & Co.), Pl. 5.
Lynds, C. R., 1967, *Ap. J.*, **147**, 837.
Sandage, A. 1965, *Ap. J.*, **141**, 1560.
———. 1966, *ibid.*, **146**, 13.
———. 1967, *Ap. J.* (*Letters*), **150**, L9.
Sandage, A., and Luyten, W. J. 1967, *Ap. J.*, **148**, 767.
Sandage, A., and Smith, L. L. 1963, *Ap. J.*, **137**, 1057.
Sandage, A., and Véron, P. 1965, *Ap. J.*, **142**, 412.