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THE EXISTENCE OF Ca II ABSORPTION LINES IN THE SPECTRUM OF THE QUASAR 3C 232 DUE TO THE GALAXY NGC 3067

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ABSTRACT

We have discovered Ca II H and K absorption lines in the spectrum of the quasar 3C 232 (z_{em} = 0.5303) at the same redshift as that of the galaxy NGC 3067, which lies 1′.9 away on the plane of the sky. The H and K lines have a velocity of (1406 ± 11) km s^{-1}, in excellent agreement with the 21 cm neutral hydrogen absorption line found in the system by Haschick and Burke. The 21 cm line is much narrower than are the Ca II lines. We present arguments that the H and K lines and the 21 cm line are produced in the outer halo rather than the outer disk of NGC 3067. The implications of our discovery concerning the nature of QSO absorption lines in general are discussed.

Subject headings: galaxies: redshifts — galaxies: structure — quasars

I. INTRODUCTION

Burbidge *et al.* (1971) and others have drawn attention to several examples of quasars lying close to bright galaxies on the plane of the sky. One such case is that of 3C 232 (also known as 4C 32.33 and Ton 469), which lies 1′.9 away from NGC 3067. The quasar 3C 232 has a redshift z_{em} = 0.5303 (our value), while the redshift of NGC 3067 is z = 0.0050. Haschick and Burke (1975) discovered 21 cm neutral hydrogen absorption in the radio spectrum of 3C 232/NGC 3067 close to the mean redshift of NGC 3067. They supposed that this absorption was due to neutral hydrogen lying in the outermost parts of NGC 3067. However, with their large beam size (8′) Haschick and Burke were unable to determine the location of the absorbing cloud with certainty. Their results were later confirmed by Grewing and Mebold (1975).

Here we report the discovery of Ca II H and K absorption lines in the spectrum of 3C 232 at the same redshift as the 21 cm line found by Haschick and Burke. Our observation shows that the optical absorption lines do arise in the outer regions of NGC 3067 and strongly suggests that the 21 cm line also does. In this paper we derive some physical parameters for the region which produces the H and K absorption lines and discuss whether the lines are likely to arise in the outer disk or in the halo of NGC 3067. Finally, we consider some of the implications of our discovery for the question of the origin of quasar absorption lines in general.

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II. OBSERVATIONS

Spectra of 3C 232 were obtained in 1977 April with the University College London image photon counting system (IPCS) mounted at the 36 inch (91 cm) camera of the coudé spectrograph of the Hale telescope. The device was used approximately in the manner described by Boksenberg and Sargent (1975). Observations were made in three wavelength ranges with a slit width of 1″ or 1″.5, as specified in Table 1. The IPCS was used in a mode giving 1024 channels spread over

TABLE 1

3C 232: JOURNAL OF OBSERVATIONS

Date (1977)	Wavelength Region (Å)	Grating Order	Slit Width (arcsec)	Instrumental FWHM (Å)	Integration Time (minutes)
April 8........	3810–4120	3	1.0	0.7	150
April 9........	5680–6130	2	1.5	1.3	140
April 10.......	3810–4120	3	1.5	0.9	100
April 11.......	3800–4100	3	1.0	0.7	50
April 11.......	3800–4100	3	1.5	0.9	50
April 11.......	4080–4380	3	1.5	0.9	100

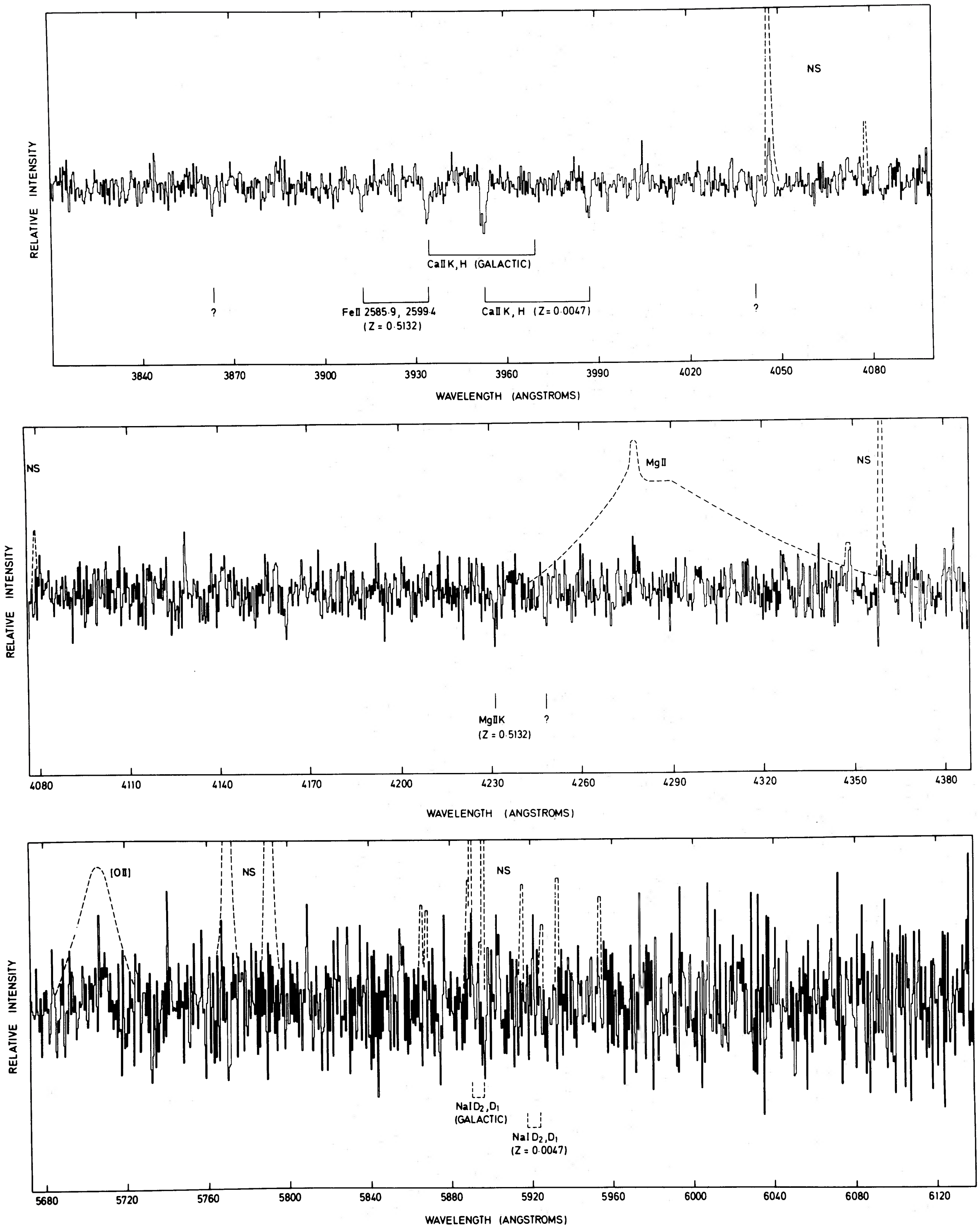

FIG. 1.—Sky-subtracted spectra of the three wavelength regions observed in 3C 232. In all cases the spectra are divided by a smooth curve delineating the observed continuum and emission features to give a flattened continuum for the absorption lines. The original main emission features are shown in broken outline; from [O II] λ3727 and the sharp feature in Mg II, assumed to be λ2795.5, we obtain $z_{em} = 0.5303$ (heliocentric vacuum value). The main night-sky lines also are shown in broken outline. All certain and possible lines are marked, and are given the identifications listed in Table 2 and discussed in the text. Those lines which appear to be present but are unmarked were unconvincing when examined on separate spectra. The expected positions of the undetected Na I D lines are indicated.

TABLE 2

Absorption Lines in the Spectrum of 3C 232

λ (Å)	W_λ (observed) (mÅ)	Identifications
B 3863.3 ± 0.2.......	150 ± 40	...
B 3912.7 ± 0.2.......	180 ± 40	Fe II λ2585.88, $z_{abs} = 0.5130 \pm 0.0001$
A 3933.9 ± 0.2.......	370 ± 40	Ca II K galactic, $v = (-6 \pm 15)$ km s^{-1}; also Fe II λ2599.40, $z_{abs} = 0.5132 \pm 0.0001$
A 3952.5 ± 0.2.......	430 ± 40	Ca II K, $v = (1413 \pm 15)$ km s^{-1}
B 3969.2 ± 0.3.......	100 ± 40	Ca II H galactic, $v = (30 \pm 23)$ km s^{-1}
A 3987.3 ± 0.2.......	260 ± 40	Ca II H, $v = (1399 \pm 15)$ km s^{-1}
B 4041.6 ± 0.2.......	160 ± 30	...
B 4231.1 ± 0.3.......	270 ± 50	Mg II λ2795.53, $z_{abs} = 0.5134 \pm 0.0001$
B 4248.1 ± 0.3.......	180 ± 40	...

Notes.—(1) All wavelengths are air values. Definite lines are designated A; possible lines, B. (2) All derived redshifts and velocities are heliocentric vacuum values. (3) The quoted errors in W_λ are rms values due to noise. (4) The system of mean velocity (1406 ± 11) km s^{-1} is indicated $z = 0.0047$ in Figs. 1 and 2.

300 Å in the third order, and 450 Å in the second. In all cases the slit width projected to at least two channels on the detector, and the spectral resolution is essentially optically limited. The full widths at half-maximum (FWHM) of the resolution profiles also are given in Table 1. Four integrations, with a total exposure time of 350 minutes, were made on the wavelength region containing the Ca II H and K lines at the velocity of NGC 3067, which also includes the galactic lines. One integration lasting 140 minutes in relatively poor conditions was made on the corresponding Na I D-line region, and one integration lasting 100 minutes covered the wavelength region $\lambda\lambda$4080–4380 which includes the Mg II emission line in 3C 232.

III. RESULTS

Sky-subtracted spectra of the three wavelength regions observed in 3C 232 are shown in Figure 1. The four runs including the Ca II lines have been added over the common region $\lambda\lambda$3810–4100. The wavelength scales were obtained from polynomial fits to spectra of a hollow cathode Ar-Fe arc. In all cases the spectra were divided by a smooth curve delineating the observed continuum and emission features in 3C 232 to give a flattened continuum for the absorption lines. The original main emission features, [O II] λ3727 and Mg II $\lambda\lambda$2796, 2803, are shown in broken outline. The main night-sky lines are similarly shown to mark regions having extra noise or spurious residuals in the subtracted spectra. Continuum emission and moonlight contributions to the night-sky spectrum are not indicated directly but add a general noise component. The total relative noise at any point in the "continuum" can be gauged from the channel-to-channel statistical variation.

The spectra in Figure 1 show certain and possible absorption lines, which are listed in Table 2. The region containing the certain lines is shown expanded in Figure 2. The line at λ3933.9 seems at first sight to be the galactic Ca II K line at heliocentric velocity (−6 ± 15) km s^{-1}. The corresponding H line appears

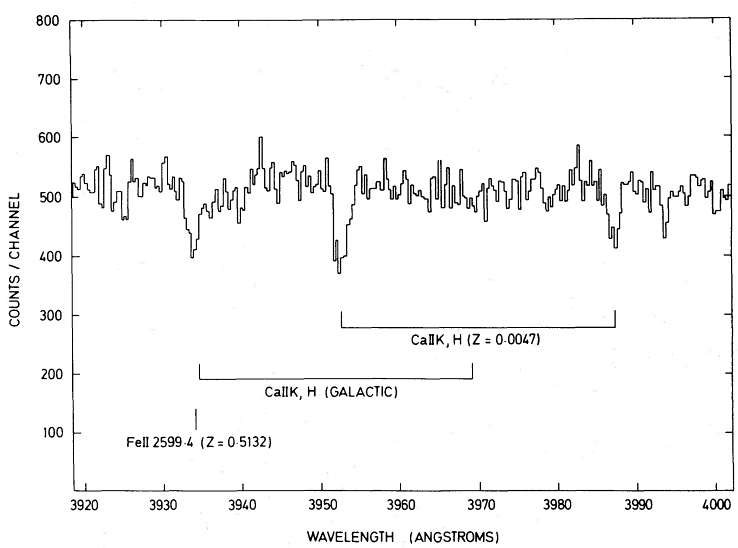

Fig. 2.—An expanded section of the region containing the Ca II lines

as a possible feature at λ3969.2 [with rather uncertain heliocentric velocity (30 ± 23) km s^{-1}] but is much too weak relative to K. However, this discrepancy is resolved, if we include with the line at λ3933.9 a contribution from Fe II λ2599.40 at $z_{abs} = 0.5132$, close to the emission redshift. Then we find the possible lines at λλ3912.7, 4231.1 fit acceptably well with Fe II λ2585.88 ($z_{abs} = 0.5130$) and Mg II K ($z_{abs} = 0.5134$), where all redshifts are heliocentric vacuum values. The apparent absence of Mg II H, if it is half the strength of Mg II K, is not inconsistent with the limitation set by noise in the continuum. Assuming the galactic Ca II lines are completely unsaturated, then assigning the K line with twice the observed equivalent width of H, i.e., (200 ± 80) mÅ, we obtain with sufficient accuracy the value (170 ± 90) mÅ for Fe II λ2599.40 from the total of (370 ± 40) mÅ for the observed line at λ3933.9. Then we get the value 0.9 ± 0.6 for the ratio of equivalent widths Fe II λ2599.40 to Fe II λ2585.88, and 1.5 ± 0.4 for Mg II K to Fe II λ2585.88. These come well within the expectation for these ratios and add to the credibility of this weak system. With this interpretation, the heliocentric velocity obtained for the Ca II K line is rendered more uncertain than indicated above; we note, however, that there is a slight extension to the red wing of the λ3933.9 line, which, if taken to represent part of the actual Ca II K contribution, tends to bring its velocity more into line with that obtained for H.

There are very convincing lines at λλ3952.5, 3987.3 which correspond to Ca II K and H at observed velocities of 1437 and 1423 km s^{-1}, respectively. The mean heliocentric velocity of these lines is (1406 ± 11) km s^{-1}; this is in excellent agreement with the velocity of (1418 ± 2) km s^{-1} measured by Haschick and Burke for the 21 cm absorption feature. However, the K and H lines have a mean full width at half-maximum of (90 ± 15) km s^{-1} (when we take into account the instrumental width), compared with the value less than or equal to 5.5 km s^{-1} found by Haschick and Burke for the 21 cm line; in fact, the 21 cm line falls well within the Ca II velocity profile. The K and H lines are weak, and it is possible that they have substructure. The equivalent widths for the K and H lines are (430 ± 40) mÅ and (260 ± 40) mÅ, respectively.

There are no detectable features at the expected wavelengths of the Na I D lines either at the galactic velocity or at that of NGC 3067. The upper limits are 500 mÅ for the former, which have extra noise due to the subtracted Na I night-sky emission, and 250 mÅ for the latter.

Other possible absorption lines in the observed region of the spectrum of 3C 232 are at λλ3863.3, 4041.6, and 4248.1. We have not been able to identify any of these.

Dr. H. C. Arp generously allowed one of us (W. S.) to inspect several excellent large-scale direct photographs of the region around 3C 232 and NGC 3067. These included two IIIa-J plates with a Wr 2c filter and exposures of 70 minutes, a 50 minute exposure with 098-04 emulsion and an ORI filter, and two 098-02 + ORI plates with exposures of 50 and 60 minutes—all obtained at the prime focus of the Hale telescope. Two IIIa-J + GG 385 plates obtained on the Kitt Peak 4 m telescope with exposure times of 35 and 45 minutes were also examined. None of these photographs show extensions of NGC 3067 in the vicinity of 3C 232. Thus there are no faint spiral arms or other optical features associated with the absorbing material. NGC 3067 appears to be sharply bounded like many disk galaxies. On the E side it is crossed by a complex network of dust lanes which presumably gave rise to Markarian's (1963) classification of the system as an Irr II galaxy. However, on Arp's photographs NGC 3067 looks more like a disturbed object of class Sc or Sb—it has only a small nuclear bulge, and the disk, where there are no dust lanes, does not have the smooth amorphous characteristic of Irr II systems.

IV. INTERPRETATION

On the plane of the sky 3C 232 lies 1'.9 away from the center of NGC 3067. The mean heliocentric velocity of NGC 3067 is (1494 ± 20) km s^{-1} (Haschick and Burke 1975). Thus the line of sight to 3C 232 passes 16.5 kpc out from NGC 3067 at its closest point, if $H_0 = 50$ km s^{-1} Mpc^{-1}. On the other hand, NGC 3067 is highly inclined, and the line of sight intersects the plane of the galaxy at a radial distance of about 61 kpc, where we have taken the value given by Haschick and Burke but adjusted it for $H_0 = 50$ km s^{-1} Mpc^{-1}. These authors found the neutral hydrogen column density for the absorption feature $N_H \leq 2.7 \times 10^{17} T_S$ cm^{-2}, where T_S is the spin temperature of the absorbing region. Putting $T_S = 100$ K, typical for cool, dense clouds in the disk of our Galaxy, gives $N_H \leq 2.7 \times 10^{19}$ cm^{-2}. Our values for the equivalent widths of the Ca II K and H lines give the doublet ratio 1.65 ± 0.30. Using the tables published by Strömgren (1948), we find for the Ca^+ column density the value $[6(+4, -2)] \times 10^{12}$ cm^{-2}. The corresponding value for the Doppler parameter is $b = [21(-12, +190)]$ km s^{-1}. The upper limit for b gives a full width at half-maximum (for a Gaussian profile) of 350 km s^{-1}, which greatly exceeds the observed value; the lower limit for b gives 13 km s^{-1} for the width. A b-value of 54 km s^{-1}, appropriate for the observed Ca II profiles, also is consistent with the measured equivalent widths. However, for relatively unsaturated lines there is always great uncertainty in the value of the Doppler parameter; furthermore, the lines here almost certainly have several unresolved components, and a true description of the velocity profile cannot be obtained from the simplified treatment we have used. On the other hand, the result for the total column density is relatively insensitive to the detailed velocity profile (with the assumption of optically thin material for all the components).

For the column density of galactic Ca^+ we obtain $(1.9 \pm 0.8) \times 10^{12}$ cm^{-2}, using the observed equivalent width for the H line and assuming a doublet ratio of 2.0.

We obtain upper limits for Na^0 in the material associated with NGC 3067 and the Galaxy of 2.3×10^{12} cm^{-2} and 4.5×10^{12} cm^{-2}, respectively, from our observed upper limits for the equivalent widths and again assuming the doublet ratio is 2.

V. DISCUSSION

The main question is to decide where in NGC 3067 the Ca II absorption lines are produced. In the solar neighborhood a K-line equivalent width of 430 mÅ would require a path length of about 1.3 kpc in the galactic plane (Allen 1973). However, there is now ample evidence that strong K lines can be produced in the inner galactic halo (Münch and Zirin 1961; Sargent 1967; Greenstein 1968; Cohen and Meloy 1974; Rickard 1972). In particular, Greenstein showed that the equivalent width of the K line in the spectra of horizontal-branch stars in the globular clusters M13, M15, and M92 averaged about 300 mÅ. Moreover, Münch and Zirin, Cohen and Meloy, and other authors have shown that the ratio $N(\mathrm{Ca}^+)/N(\mathrm{Na}^0)$ generally is much larger in the halo than in the galactic disk, and a comparison of Ca II K profiles with 21 cm profiles by Rickard showed that there is consistently good correlation between the shapes of these lines for gas in the galactic plane but not for distant gas out of the plane. For the latter, the K-line profiles are generally much broader than the corresponding 21 cm profiles and show many negative velocity features frequently extending to about 50 km s^{-1}. From a viewpoint outside the Galaxy the velocity profile for the full line of sight through such material would correspond well with our observation for NGC 3067.

Because of the large observed lower-limit value for $N(\mathrm{Ca}^+)/N(\mathrm{Na}^0)$ in the gas associated with NGC 3067 and also the large width of the Ca II lines relative to the 21 cm line, we are inclined to the view that they arise in gas situated in the outer halo of that galaxy, not the disk. However, the arguments in favor of this hypothesis are not strong. In particular, large values for $N(\mathrm{Ca}^+)/N(\mathrm{Na}^0)$ also exist for high-velocity gas in the plane of the Galaxy (Siluk and Silk 1974). Clearly it will be desirable to probe the interstellar gas in the halos and outer disks of other, nearby spiral galaxies before attempting to reach a definite conclusion. One possibility would be to study the galactic interstellar lines in the spectra of the brighter quasars, BL Lacertae objects, and Seyfert nuclei. In addition to the present detection of galactic Ca II, we observed this at high latitudes in the spectra of the Seyfert galaxy NGC 4151 and the BL Lacertae object 0735+178 (paper in preparation). Galactic Ca II also was noted in the spectrum of NGC 4151 by Boksenberg and Penston (1976). Another, more direct approach would be to conduct a similar study of the interstellar gas in the halo of M31 through the interstellar lines in the spectra of quasars around that galaxy; a special survey of quasars around M31 would, of course, be required.

According to de Vaucouleurs *et al.* (1976), NGC 3067 has a diameter $D_{25} = 2'.46$ (this is the diameter out to an isophote of $B = 25$ mag arcsec^{-2}). The line of sight to 3C 232 passes well beyond the corresponding radius $R_{25} = 1'.23$. Haschick and Burke have pointed out that the line of sight intercepts the disk of NGC 3067 at about 4 Holmberg radii from the center of the system. We have found evidence for heavy elements in the interstellar gas at a large distance from the center in either the disk or the halo of this one spiral. This discovery adds credence to the suggestion of Bahcall and Spitzer (1969) that the QSO absorption lines in general arise in the extended halos of galaxies and to the suggestion of Bahcall (1975) that the absorption-line splittings described by Boksenberg and Sargent (1975) also arise in this manner.

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REFERENCES

Allen, C. W. 1973, *Astrophysical Quantities* (3d ed.; London: Athlone Press), p. 266.
Bahcall, J. N. 1975, *Ap. J.* (*Letters*), **200**, L1.
Bahcall, J. N., and Spitzer, L. 1969, *Ap. J.* (*Letters*), **156**, L63.
Boksenberg, A., and Penston, M. V. 1976, *M.N.R.A.S.*, **177**, 127P.
Boksenberg, A., and Sargent, W. L. W. 1975, *Ap. J.*, **198**, 31.
Burbidge, E. M., Burbidge, G. R., Solomon, P. M., and Strittmatter, P. A. 1971, *Ap. J.*, **170**, 233.
Cohen, J. G., and Meloy, D. A. 1974, *Ap. J.*, **198**, 545.
de Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H. G. 1976, *Second Reference Catalogue of Bright Galaxies* (Austin: University of Texas Press).
Greenstein, J. L. 1968, *Ap. J.*, **152**, 431.
Grewing, M., and Mebold, U. 1975, *Astr. Ap.*, **42**, 119.
Haschick, A. D., and Burke, B. F. 1975, *Ap. J.* (*Letters*), **200**, L137.
Markarian, B. E. 1963, *Soob. Byurakan Obs.*, **34**, 19.
Münch, G., and Zirin, H. 1961, *Ap. J.*, **133**, 11.
Rickard, J. J. 1972, *Astr. Ap.*, **17**, 425.
Sargent, W. L. W. 1967, *Ap. J.* (*Letters*), **148**, L147.
Siluk, R. S., and Silk, J. 1974, *Ap. J.*, **192**, 51.
Strömgren, B. 1948, *Ap. J.*, **108**, 242.

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