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OPTICAL AND RADIO STRUCTURE OF THE QUASAR PKS 0812+02

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ABSTRACT

VLA observations have resolved the quasar PKS 0812+02 ($z = 0.402$) at radio frequencies into three components. Sky-limited optical photography reveals that the quasar image is resolved and is also surrounded by several faint objects within $\sim 20''$ of the quasar. A diffuse optical object ($\sim 3'' \times 4''$) located $\sim 10''$ from the quasar has been discovered to coincide with a strong northwest radio lobe. Its surface brightness at optical wavelengths is $\mu_R \sim 23.7$ mag arcsec^{-2}, and the total radio flux is S_ν (5 GHz) ~ 0.23 Jy. A low-resolution spectrum (3400–6700 Å) of this diffuse emission region may indicate a nonthermal source with no strong emission lines. On the basis of both the radio and optical observations, we suggest that the quasar is located in the nucleus of a cluster galaxy. We also conclude that the optical emission from the northwest radio component may be one of the few examples known of an optical counterpart to a radio lobe of a quasar.

Subject headings: quasars — radio sources: general

I. INTRODUCTION

Although many radio galaxies have been mapped intensively in recent years, both the energetics and the nature of the power sources are still poorly understood. One approach to studying the nature of radio galaxies has been to search for optical counterparts of radio lobes in the hope that exploiting the large frequency range will lead to an understanding of the physics of these objects. Optical counterparts of the radio lobes of several radio galaxies have been reported (see Simkin 1978; Saslaw, Tyson, and Crane 1978; Rudnick *et al.* 1981). Saslaw, Tyson, and Crane have suggested several diagnostic tests for discriminating among different optical emission mechanisms in radio lobes. Recent work suggests that circumgalactic material may play an important role (e.g., Butcher, van Breugel, and Miley 1980).

The quasar PKS 0812+02 ($z = 0.402$) was discovered as a radio source and was subsequently optically identified (Clarke, Bolton, and Shimmins 1966; Bolton *et al.* 1966; Kinman and Burbidge 1967). The Westerbork map of PKS 0812+02 showed a resolved component at 6 cm extending northward $\sim 10''$ from the stronger component (Miley and Hartsuijker 1978). The quasar was recently included in an optical imaging survey (Wyckoff, Wehinger, and Gehren 1981) of low-redshift quasars. This survey showed not only that PKS 0812+02 is resolved in the optical region, but also that it is associated with several faint ($R \sim 20$–22 mag) diffuse objects, possibly associated cluster galaxies.

Optical and radio maps having the same spatial resolution have been obtained for PKS 0812+02. Here we report the discovery of an optical counterpart ($\mu_R \sim 23.7$ mag arcsec^{-2}) of the quasar radio lobe [S_ν (5 GHz) ~ 0.2 Jy]. In addition, an optical spectrum of the counterpart indicates that the optical radiation is probably neither dominantly thermal, nor has strong emission lines. The optical and radio observations discussed below may provide important constraints on future models of radio lobe phenomena.

II. OBSERVATIONS

a) *Radio*

Observations of PKS 0812+02 were made with the Very Large Array (VLA) 1979 December 10–11 at 1465

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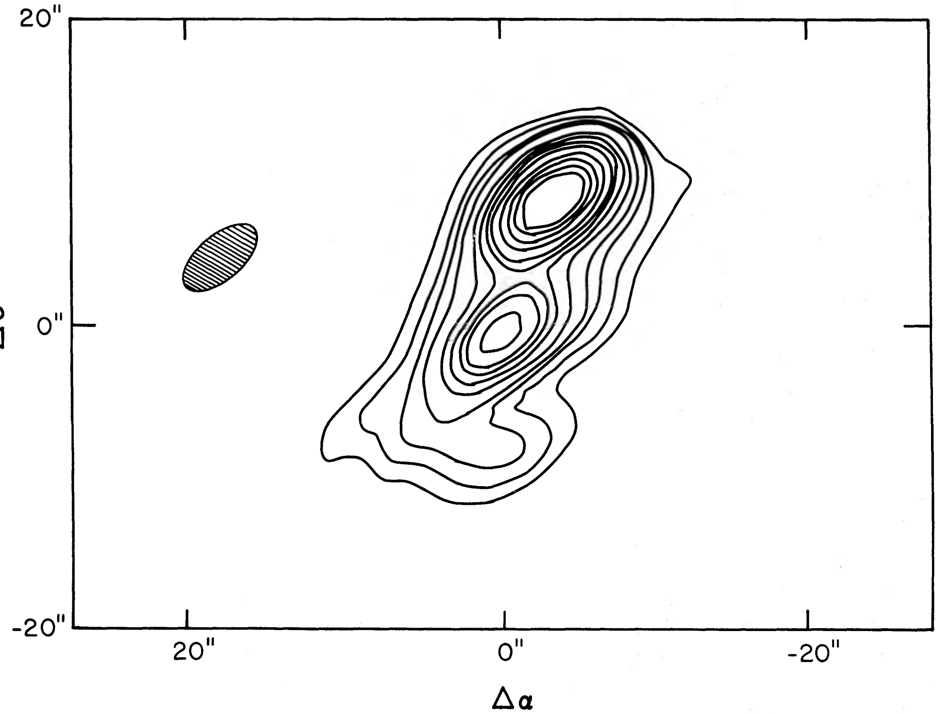

FIG. 1.—CLEANed VLA map (λ20 cm) of PKS 0812+02. This map was made with a 6 km Gaussian taper applied to the visibility data. The hatched ellipse is the beam response. The contour levels are 4%, 6%, 8%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, 60%, and 70% of the peak radio brightness of 0.760 Jy per CLEANed beam. The coordinates are offsets from α (1950) = 08h12m47s266; δ (1950) = +02°04′12″4 in arc seconds.

MHz and 4885 MHz with a bandwidth of 50 MHz using 13 antennas with spacings ranging from 0.1–17 km. The observations of PKS 0812+02 were alternated with the quasars PKS 0837−12 and PKS 0823+033 at L(1465 MHz, λ20 cm) and C(4885 MHz, λ6 cm) bands. PKS 0823+033 was assumed to be unresolved and was used to calibrate the data. The flux scale was set by observing 3C 286 which was assumed to have a flux of 14.51 and 7.41 Jy at wavelengths of 20 and 6 cm respectively (Baars *et al.* 1977). Using measurements of PKS 0823+033 over a large range of hour angles, the instrumental polarization was found to be 3.3% and 1.3% at λ20 and λ6 cm respectively. The absolute position angle of the linear polarization was found by assuming the position angle of the linear polarization of 3C 286 to be 33°.

The VLA observations resolved PKS 0812+02 into three components as can be seen in Figure 1. This figure displays a λ20 cm map with a Gaussian taper of 6 km applied to the visibility data. The λ6 cm map resulting from a 2 km Gaussian taper is displayed in Figure 2. A three-component model was fitted to the visibility data, and the resulting flux densities and polarization measurements are summarized in Table 1. The components are

TABLE 1

FLUX DENSITIES AND POLARIZATION MEASUREMENTS FOR PKS 0812+02

Source	Component	Δα	Δδ	S (mJy)	θ Major Axis	θ Minor Axis	P.A. (Major Axis)	Polarization %	Polarization P.A. (deg.)
				λ20 cm					
0812+020	NW	−3″7	+8″9	817	1″5	1″0	32° ± 10	7	−30
(Total flux = 2350 mJy)	C[a]	−0.1	−0.3	283	0	0	...	<5	60
	D	−0.6	0.5	747	19.1	9.1	160 ± 2	...	...
				λ6 cm					
0812+020	NW	−3.7	9.5	233	1.2	...	68 ± 2	...	...
(Total flux = 850 mJy)	C[a]	+0.1	−0.7	194	...	...	...	4	60
	D	−1.8	4.3	359	25.3	8.5	10 ± 2	...	...

[a] Position: α (1950) = 08h12m47s266; δ (1950) = +02°04′12″4.

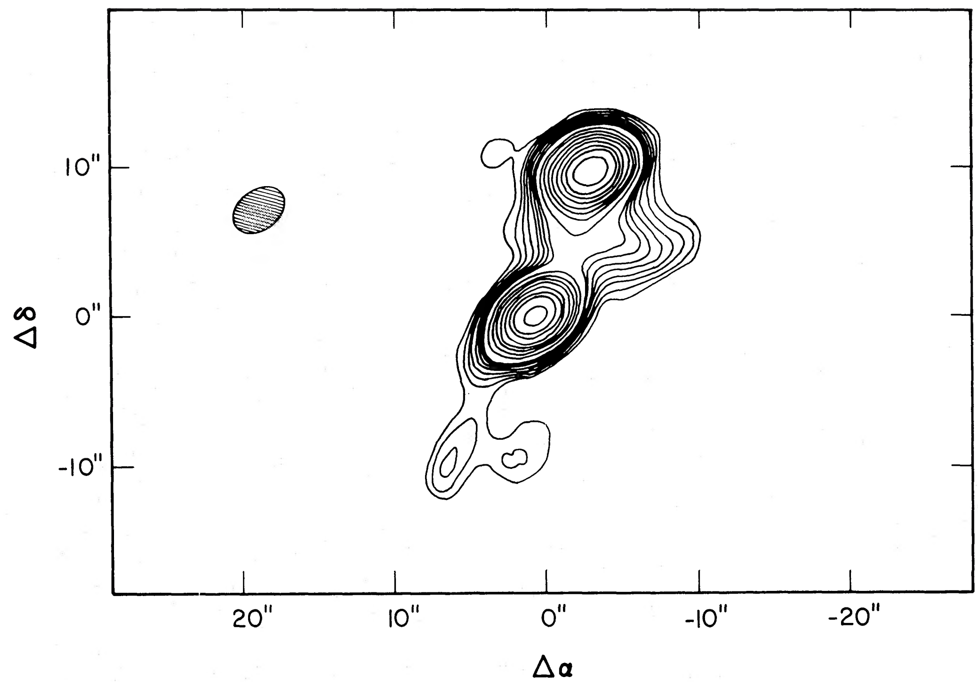

FIG. 2.—CLEANed VLA map (λ6 cm) of PKS 0812+02. The map was made applying a 2 km Gaussian taper to the visibility data. The hatched ellipse is the beam response. The contour levels are 3%, 4%, 5%, 6%, 7%, 8%, 9%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, 60%, and 80% of the peak radio brightness of 0.260 Jy per CLEANed beam. The coordinates are offsets in arc seconds from the position listed in Fig. 1.

denoted by NW (northwestern), C (center), and D (diffuse). The last component consists of diffuse emission from the entire radio source with an estimated size of 19″ × 9″ at λ20 cm. Its centroid roughly coincides with the quasar. These three components are an adequate but not unique representation of the source. The source sizes (θ) in Table 1 were determined from Gaussian fits to the synthesized VLA beam at each frequency.

The λ20 cm map displayed in Figure 1 looks typical for a quasar with a compact central component and asymmetrical radiation distributed on either side (Miley and Hartsuijker 1978). The overall spectral indices ($S \sim \nu^{\alpha}$) of the components are also typical, −0.3 for the central component, and −1.0 and −0.6 for the two outer lobe components, NW and D, respectively. These steep spectral indices for the two outer lobe components are typical of outer components associated with quasars. The diffuse nature of much of the emission and its roughly symmetric distribution around the central radio source are, however, unusual. The total flux of the model fitting compares well with the short spacing flux at λ6 cm, i.e., 850 ± 80 mJy versus 786 ± 80 mJy, but falls short at λ20 cm, i.e., 2.35 ± 0.23 Jy versus 1.85 ± 0.19 Jy. This discrepancy at λ20 cm is probably due to a background source in the field.

We see quite a different picture in the λ6 cm map made with the full resolution of the VLA (Fig. 3). This map is superposed on an optical photograph of the PKS 0812+02 field. Only two components appear in the radio emission, the NW and C components. Most of the total flux at λ6 cm of the NW component appears to be in this compact feature. The NW component is coincident (±1″) with a diffuse optical object ($R \sim 22$ mag). From an inspection of Figure 3, the NW radio lobe appears to be resolved along a position angle of 68°. This is almost precisely perpendicular to the Gaussian fit to the synthesized VLA beam at λ6 cm for these observations (1″.4 × 0″.6 P.A. = −29°). The simplest model at λ6 cm for the NW radio lobe is a double source, each unresolved by the synthesized beam and separated by 0″.6 along P.A. ∼ 70° with a flux ratio of 2:1.

The distance between the central quasar and the NW component is 10″.1. Assuming these objects are at cosmological distances with $z = 0.402$, $H_0 = 75$ km s^{-1} Mpc^{-1}, and $q_0 = 0.1$ (to be used throughout this paper), the projected separation on the sky is 47 kpc. The projected linear size for the two components making up the NW lobe is ∼7 kpc.

b) Optical

A 60 minute photograph (IIIaF emulsion + 0G550 filter) of PKS 0812+02 was taken 1979 March 23 (seeing disk FWHM measured from the plate of ∼1″.5) at the prime focus of the European Southern Observatory 3.6 m telescope. Analysis of the surface brightness profile of the quasar image and removal of the point-spread function has revealed resolved underlying structure associated with the quasar (Wyckoff, Wehinger, and Gehren 1981), with a measured diameter of ∼7″ at the surface brightness level, $\mu_R \sim 26$ mag (arcsec)$^{-2}$, corres-

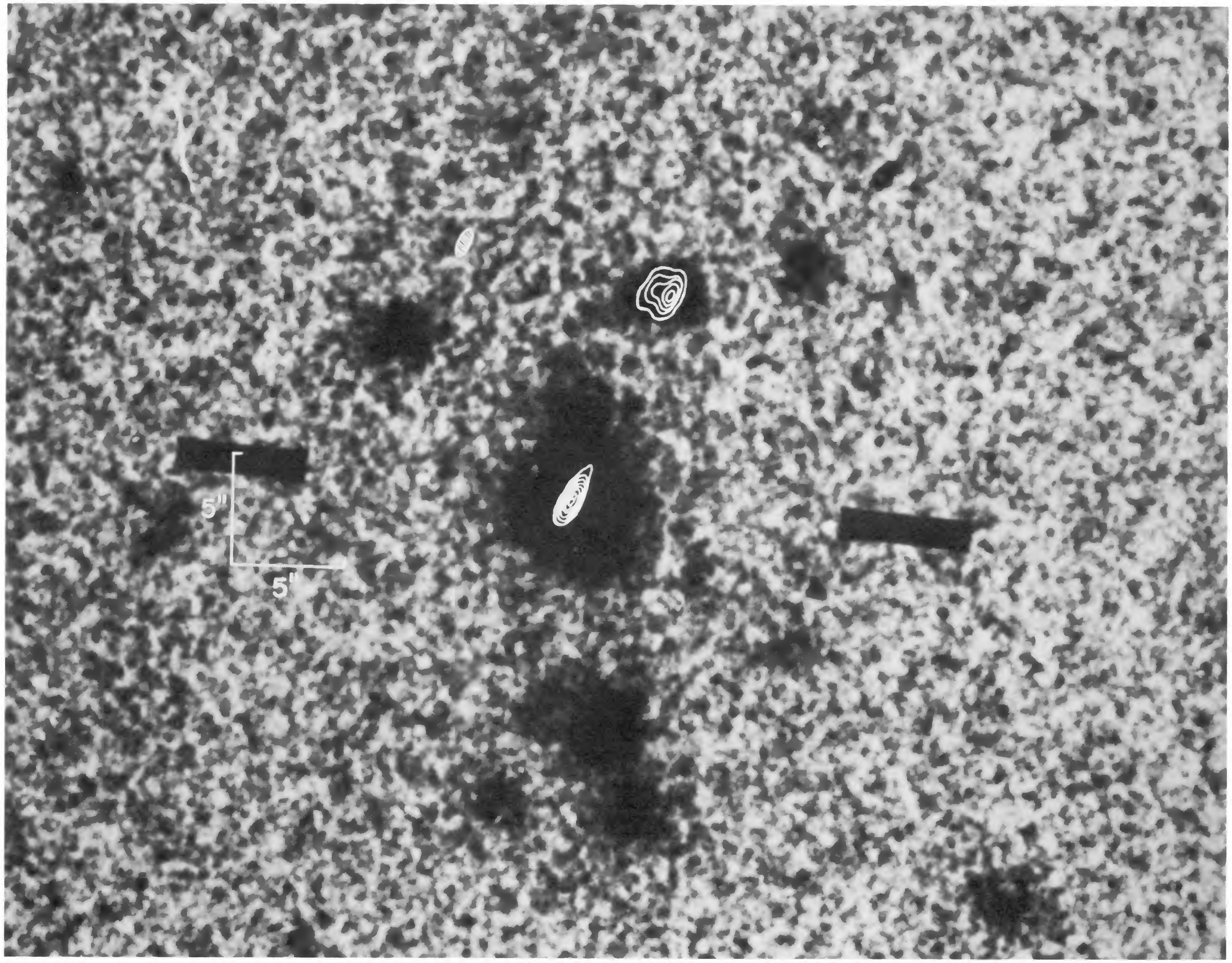

FIG. 3.—CLEANed VLA map (λ6 cm) superposed on an ESO 3.6 m photograph of PKS 0812+02. The strong central component is centered on the 18th magnitude quasar; the strong northwest radio lobe coincides within the positional accuracy (~1") with a diffuse (3" × 4") optical emission region. North is up, east to the left. The beam response is 1".4 × 0".6, P.A. = −29°. The interval between contours is 10% of the peak flux density 0.214 Jy per CLEANed beam central component starting at the 10% level.

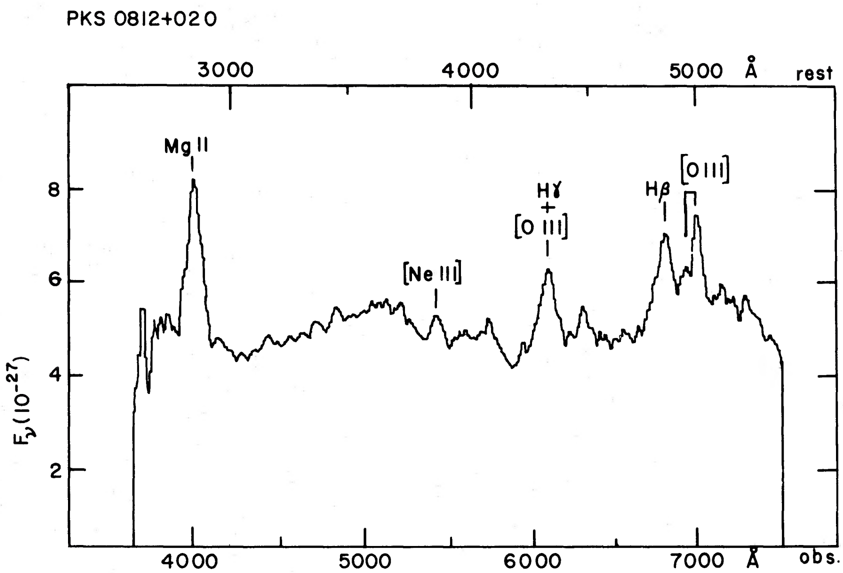

FIG. 4.—CTIO SIT vidicon spectrum of the quasar PKS 0812+02, $z = 0.407$. Resolution ~15 Å. The abscissa is the wavelength in Å; the ordinate is the flux, F_ν, in ergs cm^{-2} s^{-1} Hz^{-1}.

ponding to a linear diameter of ~65 kpc. The optical object ($R \sim 22$ mag) located ~10″ northwest of the quasar (Fig. 3) appears diffuse (3″ × 4″) with its centroid coinciding with the northwest radio lobe. The optical photometric calibrations were derived from the quasar V-magnitude and an assumed color, $V - R = 0$, as discussed elsewhere (Wehinger, Gehren, and Wyckoff 1980; Wyckoff, Wehinger, and Gehren 1981). Hence the optical magnitudes and surface brightnesses of PKS 0812+02 and associated objects should be considered approximate with errors of ~ ±0.5 mag, depending on the actual $V - R$ colors and the variability of the quasar.

In addition to resolving the optical quasar image, several optical objects were noted in the vicinity of the quasar, as shown in Figure 3. (The object approximately 4″ north of the quasar was not included in the surface brightness profile analysis mentioned above.) The remaining approximately 10 objects are located ~10″–20″ from the quasar and appear to be prime candidates for cluster galaxies associated with PKS 0812+02 since several are diffuse. These diffuse objects ($R \sim 22$–24 mag) are not visible on either the blue or red Palomar Sky Survey prints.

A spectrum (3600–7500 Å, resolution ~15 Å) centered on the quasar PKS 0812+02 was obtained 1980 February 25 with the SIT vidicon using the 4 m CTIO telescope. The calibrated spectrum of the quasar is shown in Figure 4, and the emission line fluxes are given in Table 2. The redshift was measured to be $z = 0.407$ in good agreement with the previous determination, $z = 0.402$ (Kinman and Burbidge 1967). The weak He II (3203 Å) line mentioned by Kinman and Burbidge is

TABLE 2

OBSERVED EMISSION-LINE FLUXES: PKS 0812+02

Line λ (Å)[a] (observed)	Ident. Element	F (ergs s^{-1} cm^{-2})[a] × 10^{-14}	W_λ (Å)[a]	l_ν (ergs s^{-1}) × 10^{42}
2815	Mg II	6.54	74 ± 1	20.2
2945	...	0.33	4	1.02
3136	...	0.19	3	0.59
3349	...	0.20	3	0.62
3424	Ne V	0.26	4	0.80
3865	Ne II	0.43	9	1.33
4085	Hδ	0.17	4	0.53
4339	Hγ + O III	1.54	43	4.76
4508	Fe II	0.28	8	0.87
4826	Hβ	1.01	30	3.12
4941	O III	0.08	2	0.25
5007	O III	0.33	9	1.02
5100	Fe II	0.04	1	0.12

[a] Rest frame.

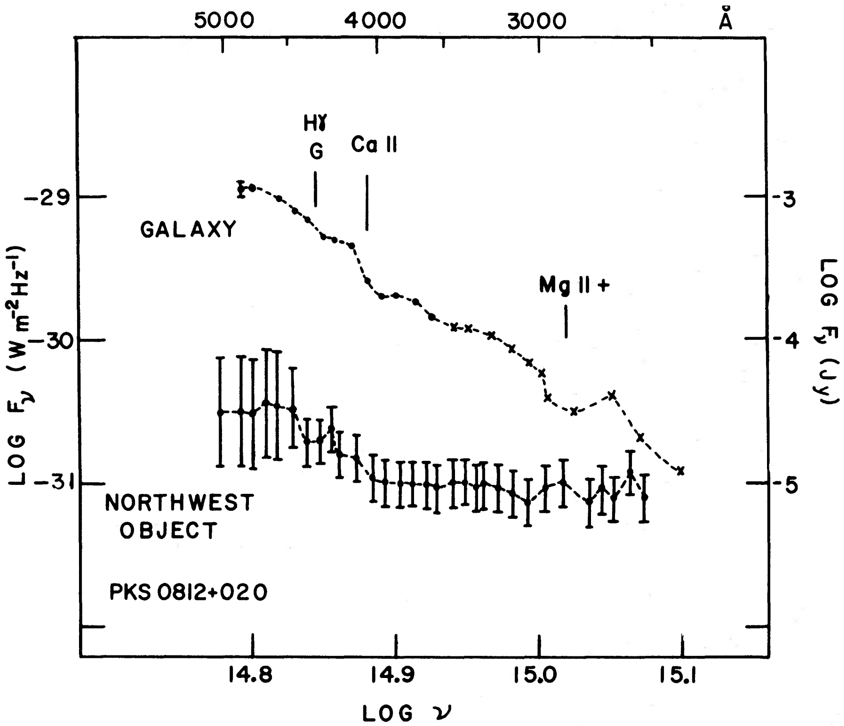

FIG. 5.—ESO IPCS dereddened spectrum of the optical emission region $\sim 10''$ northwest of the quasar. The spectrum has been binned in 100 Å intervals. The galaxy spectrum is a composite (*dots*, NGC 4472; $\times$ = Spinrad galaxy; $z = 1.1$). Note the change in slope at $\sim$4000 Å (rest frame) in the northwest object.

weak or absent in our SIT spectrum. The emission features at 4510 Å and 5100 Å could be Fe II emission.

A low-resolution spectrum (3400–6700 Å) of the diffuse optical object coincident with the northwest radio lobe of the quasar (see Fig. 5) was obtained on 1980 March 14 using the Image Photon Counting System (IPCS) and the ESO 3.6 m telescope. The total integration time was 100 minutes. Equal integration times were obtained with the object located alternately at two spectrograph slit positions $\pm 10''$ from the slit center. The slit had an east-west orientation. The slit width of $\sim 3''$ projected on the sky determines the spectral resolution which for the grating used was 2.4 Å per channel at 5000 Å. The extent of the optical object east-west was 4″, as determined from the optical isophotes and detection limit of the IPCS plus 3.6 m telescope. Hence, the effective entrance aperture was $3'' \times 4''$ at each slit position.

The reduction of the IPCS data was carried out using the Tololo-Vienna Reduction System (Albrecht 1979) at Cerro Tololo Observatory. All spectra were corrected for flat field, converted to a linear wavelength scale, reduced to absolute flux, and co-added. Due to the low signal-to-noise ratio in the final spectrum, it was binned in 100 Å intervals (observed frame). The spectrum of the diffuse object northwest of the quasar as shown in Figure 5 has been corrected for galactic reddening by adopting a column density of neutral hydrogen in the direction, $l^{\rm II} = 220°$, $b^{\rm II} = +22°$, of $N(\text{H I}) \sim 6 \times 10^{20}$ cm^{-2} (Dickey, Salpeter, and Terzian 1978). From the correlation between color excess and N(H I) of Bohlin, Savage, and Drake (1978), we find $E(B-V) = 0.1$ for the direction of PKS 0812+02. The low-resolution spectrum of the optical emission coincident with the northwest radio lobe is shown in Figure 5 where the error bars represent $\pm 1\ \sigma$ rms deviations from the mean. For comparison, a composite of two standard galaxy spectra is also shown. The binned spectrum (also 100 Å intervals) of the low-redshift galaxy, NGC 4472, was obtained with the IPCS and the ESO 3.6 m telescope. A high-redshift ($z = 1.1$) galaxy spectrum showing the UV region was kindly supplied by H. Spinrad. This spectrum is approximately the same resolution as the binned IPCS spectrum and has been arbitrarily shifted in flux to match the UV end of the spectrum of NGC 4472.

In Figure 5, strong absorption features in the spectra of the standard galaxies are indicated. The most prominent absorption dips are the H and K lines of Ca II and a broad feature between 2700 Å and 2900 Å due to Mg II 2800 Å lines plus a blend of several other absorption lines (cf. Johnson 1979). There is no evidence in the northwest object spectrum for absorption features. In particular, the dip in the 2700–2900 Å region is not present in the northwest object. The spectral index of this object is ~ -1 in the optical and radio regions,

TABLE 3

OBSERVED SPECTRAL INDICES

Spectrum	PKS 0812+02 Quasar	Northwest Object
$\alpha^{\text{opt a}}$	−0.52	−1.1[b]
$\alpha^{\text{opt c}}_{\text{radio}}$	−0.51	−0.86
$\alpha^{\text{radio d}}$	−0.31	−1.0

[a] 3600–5600 Å.
[b] Note there is a break in the spectrum at 4000 Å.
[c] 4500 Å to 6 cm (4885 MHz).
[d] 20 cm–6 cm.

which is significantly different from that of a galaxy and may indicate, therefore, a nonthermal origin for the optical continuum of the object.

In Table 3 the observed spectral indices are summarized for the quasar and the northwest object. The indices are calculated for the optical, the optical-radio, and the radio spectral regions.

III. DISCUSSION

a) *Morphology of 0812+020*

Although this radio source is typical of quasars in many ways (i.e., overall structure, size, and luminosity), it differs in two important respects. First, this quasar appears to be dominated by two radio components, with one component centered on the quasar position. If one compares this morphology with typical quasars with symmetrical radio lobes located on opposite sides of the optical quasar, then the ratio of peak surface brightness between the two lobes is ~50:1 with arc second resolution at λ6 cm. This ratio is larger than for any of the 105 3C sources discussed by Neff and Rudnick (1980) based on λ6 cm Cambridge 5 km maps. Only 3C 123 and 3C 351 have ratios $\gtrsim$15:1. This large ratio may point to the special nature of the northwest radio lobe of PKS 0812+02. The second distinction is the unusual amount of low surface brightness emission. Structures of this type are more commonly found among low-luminosity and cluster radio sources.

The radio source appears to be a double radio source embedded in a large "halo-like" component (the latter denoted D in Table 1). The source classification resembles a D2 (asymmetrical double) quasar (cf. Miley 1971) in that the spectral index of the northwest component is very steep, and it is "resolved" into two compact components. Approximately one-third of all quasars display this type of structure (Perley, Fomalont, and Johnston 1980). Normally, the radio emission coincident with the optical QSO in a D2 quasar is the dominant emission at 5 GHz. In PKS 0812+02, however, the intensity of the northwest object is equal to that of the central radio source at 5 GHz.

Since the radio structure appears to have a slight curvature and, optically, the quasar appears to be in a faint galaxy cluster, it is useful to compare PKS 0812+02 with cluster sources whose properties are summarized by Rudnick and Owen (1977). The radio structure of PKS 0812+02 would put it into the wide tail category. Its physical extent of ~120 kpc is similar to that of other wide tail cluster sources. Rudnick and Owen (1977) found that the wide tail sources occur almost exclusively in clusters with a single dominant galaxy.

The optical observations support the radio evidence that PKS 0812+02 is a cluster source as mentioned in § II*b*. The quasar is surrounded by about 10 diffuse objects which appear to be cluster galaxies. Also, the optical image of the quasar is resolved with the diameter of the underlying nebulosity corresponding to about 65 kpc and the integrated absolute magnitude $M_R \sim -21$ (Wyckoff, Wehinger, and Gehren 1981). Hence, the optical observations indicate that the quasar, PKS 0812+02, is seated in a galaxy located in a cluster of galaxies. We note further that the radio power of PKS 0812+02 exceeds that of a typical cluster radio source by a factor of ~20. The extended emission in PKS 0812+02 may arise as a result of interaction with an intracluster medium.

b) *Nature of Northwest Object*

The region of optical emission in the northwest object measures 14 × 19 kpc, while the overall size of the radio emitting region at 5 GHz is 120 × 40 kpc (25″ × 8″). This is approximately the size of a radio galaxy. With this in mind, we may compare the ratio of the optical to radio emission of the optical counterparts of radio lobes in the radio galaxies 3C 33, 3C 285, and 3C 390.3 and also of M87 and its jet (Butcher, van Breugel, and Miley 1980; Saslaw, Tyson, and Crane 1978; Rudnick *et al.* 1981). The luminosity in both the optical and radio emission regions is more than an order of magnitude greater for the quasar radio lobe than for the radio galaxy lobe or the jet in M87. This comparison might imply that the total power radiated in the radio and optical lobes is correlated with the power in the central source.

In regard to the nature of the northwest object, it is possible to rule out a dominant thermal contribution based on the continuum slope of the optical spectrum (Fig. 5). The absence of strong emission lines in the spectrum also rules out the presence of significant amounts of hot thermal gas with a temperature of ~10^4 K.

Optical polarization measurements of the northwest object could establish whether the optical emission is merely an extension of the radio synchrotron emission provided that the optical and radio counterparts are truly physically associated. As pointed out by many authors (e.g., Saslaw, Tyson, and Crane 1978), the detection of optical synchrotron emission would place severe constraints on the energy-generating mechanism in the radio and optical lobes due to the extremely short lifetimes of the optical synchrotron electrons.

Finally, we note that if the QSO is physically associated with the northwest object, it is the most optically luminous radio lobe known. Its steep spectral index, -1.0, may rule out the possibility that the northwest object is a background BL Lacertae object.

IV. CONCLUSIONS

VLA observations of the quasar PKS 0812+02 have resolved it into three components: (*a*) a flat spectrum radio source coinciding with the quasar, (*b*) a northwest radio lobe which is resolved into two components separated by 0".6 along P.A. $\sim 70°$ with an overall spectral index of -1.0, and (*c*) a diffuse component of size $25'' \times 8''$ at $\lambda 6$ cm with a spectral index of -0.6. The high ratio of peak surface brightness between the two lobes of the radio source and the extensive low brightness emission are unusual for quasars. The northwest radio lobe coincides with a diffuse optical ($\mu_R \sim 23.7$ mag arcsec^{-2}) object. The low-resolution spectrum of the northwest object may indicate a dominant nonthermal emission source. If the northwest radio lobe and optical object are physically associated, this would be one of the first detections of optical emission from a quasar radio lobe.

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