

DISCOVERY OF A PROBABLE GALAXY WITH A REDSHIFT OF 3.218¹

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ABSTRACT

We report the discovery of a narrow emission line object, probably a galaxy, with a redshift of 3.218. The object is a companion to the quasar PKS 1614+051, which is at a redshift of 3.209. This is the most distant non-QSO, non-gravitationally lensed object presently known by a large margin. Its properties are consistent with those expected of a high-redshift galaxy. This object has an age of only a few percent of the present age of the universe. The object was discovered with a novel technique, which promises to push studies of distant galaxies to redshifts as high as those of the most distant quasars known, and which may eventually lead to the discovery of primeval galaxies. This discovery opens the way for studies of galaxies beyond $z = 3$, which should prove invaluable for observational cosmology.

Subject headings: cosmology — galaxies: evolution — galaxies: formation — galaxies: redshifts — quasars

I. INTRODUCTION

The study of galaxies over large look-back times is one of the main paths of observational cosmology. It is the most direct way of learning about the evolution of luminous matter in the universe, and it is a necessary step if one is to use galaxies as cosmological probes. The search for ever more distant galaxies has been one of the main tasks on the frontier of cosmological research, ever since the time of Hubble and Slipher. Inactive cluster galaxies are now known with redshifts up to 0.92 (Gunn 1982). The most distant (non-QSO) galaxies known until now were the powerful 3CR sources (Spinrad and Djorgovski 1984), with the record redshift of 1.819 for 3C 256. (We use the term “galaxy” to exclude QSOs, although we do believe that all QSOs are located in galaxies.) Many QSOs with higher redshifts are known, the most distant being PKS 2000–330, with $z = 3.78$ (Peterson *et al.* 1982). Unfortunately, QSOs are poor cosmological (and galaxy evolution) probes, because of their extreme intrinsic variability, and because their light is mainly nonthermal, generated in a poorly understood central “engine.” In this *Letter*, we report the discovery of a narrow emission line object with a redshift $z = 3.218$, whose properties are approximately those which may be expected of a galaxy at such a high redshift.

This object is a companion of the QSO PKS 1614+051 (Shimmins, Bolton, and Wall 1975). We measure the QSO redshift to be 3.209 ± 0.001 , whereas Jauncey *et al.* (1979), as quoted by Hewitt and Burbidge (1980), give $z_{\text{QSO}} = 3.208$. Its position was measured by Condon, Hicks, and Jauncey (1977), who give the finding chart, and estimate the QSO V magnitude to be 19.5. An improved radio (VLBI) position of the

QSO is given by Morabito *et al.* (1982). PKS 1614+051 is a compact radio source with an inverted spectrum (Wright 1983). The coincidence of the radio and optical positions is quite satisfactory. There is little doubt that the QSO, and not the companion, is the radio source.

The companion object was located with a new technique, which we describe below.

II. THE OBSERVATIONS AND DATA REDUCTIONS

Extremely distant galaxies are necessarily extremely faint, and devising methods to find them is an interesting problem in itself. For many years, the most distant galaxies known have been located by means of their powerful radio emission (often associated with optical line emission), and apparent optical faintness. Yet, in the spite of substantial effort, no galaxy has ever been found beyond $z = 1.82$. One possible exception is the gravitationally lensed object 2016+112 (Lawrence *et al.* 1984), with $z = 3.273$.

If we can extrapolate from common experience with low-redshift galaxies, the best place to look for a galaxy is next to another galaxy, because of pervasive galaxy clustering. (The degree of clustering must evolve, however, and it may or may not be significant at $z > 3$.) Thus, one can use the distant QSOs as “signposts” or “beacons,” and look for their putative galaxy companions. L_* galaxies (*viz.*, galaxies of a “typical” luminosity) are expected from cosmological and evolutionary considerations (see, e.g., Djorgovski and Spinrad 1985*a*) to have visible magnitudes fainter than about 23 or 24. This faintness precludes a continuum spectroscopy survey at the present time. Broad-band colors may be used as approximate redshift indicators (cf. Koo 1985*a*), but at very high redshifts ($z > 3$, say), the uncertainties in our estimates of evolutionary effects are very large. This leaves only the narrow emission line galaxies as promising targets at very high redshifts, at least at the present time. One approach suggests itself: obtain

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direct images of high-redshift QSO fields in a very narrow band centered on a suitable emission feature ($\text{Ly}\alpha$ is the obvious choice), and also in a broad band that samples the nearby continuum. Any faint objects with a notable light “excess” in the $\text{Ly}\alpha$ band are then selected as possible emission-line galaxies at the target QSO redshift.

This is precisely what we have done. We used an interference filter centered at $\lambda = 5139 \text{ \AA}$, with a $\text{FWHM} = 90 \text{ \AA}$, corresponding to a $\text{Ly}\alpha$ redshift of 3.226. From the catalog of Véron-Cetty and Véron (1984) we then selected all QSOs in the appropriate redshift range observable from Lick in the 1985 July dark run. Out of five such QSOs, PKS 1614+051 was judged to be the best initial choice. For the continuum comparison band, we used the r_s band ($\lambda_{\text{eff}} = 6890 \text{ \AA}$), which is defined by Djorgovski (1985).

All observations were done with the Cassegrain CCD system (Miller 1983; Lauer *et al.* 1983) on the Lick Observatory 3 m Shane telescope. The discovery images were obtained on the night of 1985 July 18 UT, in good seeing conditions ($\text{FWHM} \approx 1''.5$). Two $\text{Ly}\alpha$ images with exposure times of 1200 s each and two r_s images with exposure times of 300 s each were obtained; all images were taken in the position angle (PA) of 90° . The telescope was offset a few arcsec between adjacent exposures; this practice assures the repeatability of detected objects as they are imaged with different portions of the CCD each time, and it also improves the flat-fielding. It was immediately apparent that there was a strong $\text{Ly}\alpha$ “excess” object next to the QSO. Three additional

direct r_s images with exposure times of 200 s each were obtained on the night of 1985 July 19 UT, in equally good seeing conditions, and $\text{PA} = 43^\circ$. Three more direct r_s images with exposure times of 207 s each were obtained on the night of 1985 August 15 UT, and two images of 207 s and one of 345 s, on the night of 1985 August 16 UT, all in $\text{FWHM} \approx 1''.2$ seeing conditions, and with $\text{PA} = 201^\circ$. (The odd PAs were dictated by the spectroscopy.)

The flat-fielding of the broad-band images was accomplished using a sky median frame for the appropriate night (Djorgovski 1984). The narrow-band images were flat-fielded with exposures of the twilight sky, a permissible practice for narrow-band CCD imaging. The images were interpolated to twice the original sampling (to a new pixel size of $0''.365$) by bilinear interpolation, digitally rotated if necessary, and then registered and stacked together. Images of the flux standard Feige 98 (Stone 1977) were used both for the monochromatic ($\lambda 5139$) and r_s magnitude calibrations. Digital stacks of the appropriately rotated and shifted images are shown in Figure 1 (Plates L1 and L2).

Spectroscopic observations were initially obtained on the night of 1985 July 19 UT. The seeing FWHM was about $1''-1''.5$ at the start but deteriorated somewhat as the objects began to set. The transparency also gradually deteriorated, because of a variable high-altitude smoke aerosol. The Cassegrain spectrograph slit was rotated to $\text{PA} = 43^\circ$, to cover both the QSO and the companion. One 3600 s spectroscopic exposure with a low-resolution ($420 \text{ grooves mm}^{-1}$) grism,

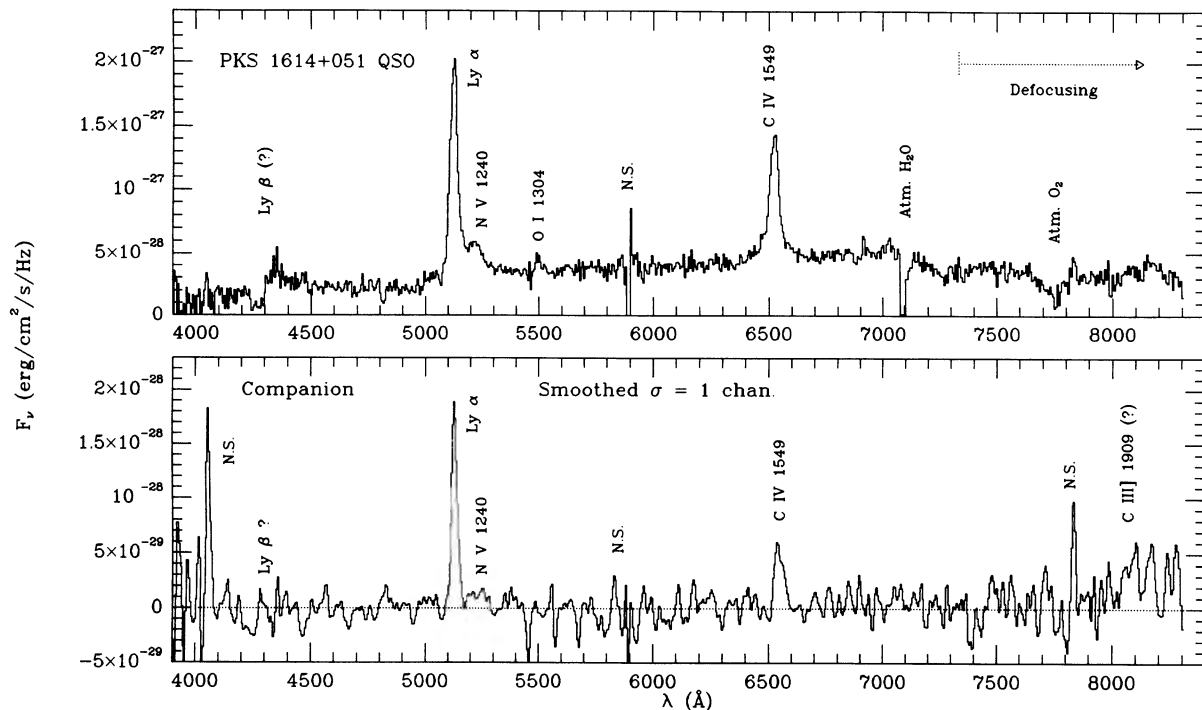


FIG. 2.—Spectra of the PKS 1614+051 QSO (*top*) and its companion object (*bottom*). The QSO spectra are from the July data only, and the companion spectra are a quality-weighted average of July and August data. The companion object spectrum was smoothed with a narrow Gaussian filter in order to suppress the pixel-to-pixel noise; this smoothing also causes some artificial broadening of the emission lines. Dubious line identifications are indicated with a question mark (?). Spurious features caused by imperfect night sky subtraction are indicated (N.S.). CCD defocusing in the red causes spurious dimming of the QSO continuum, some of which spills over to the companion object’s spectrum, and biases the companion continuum.

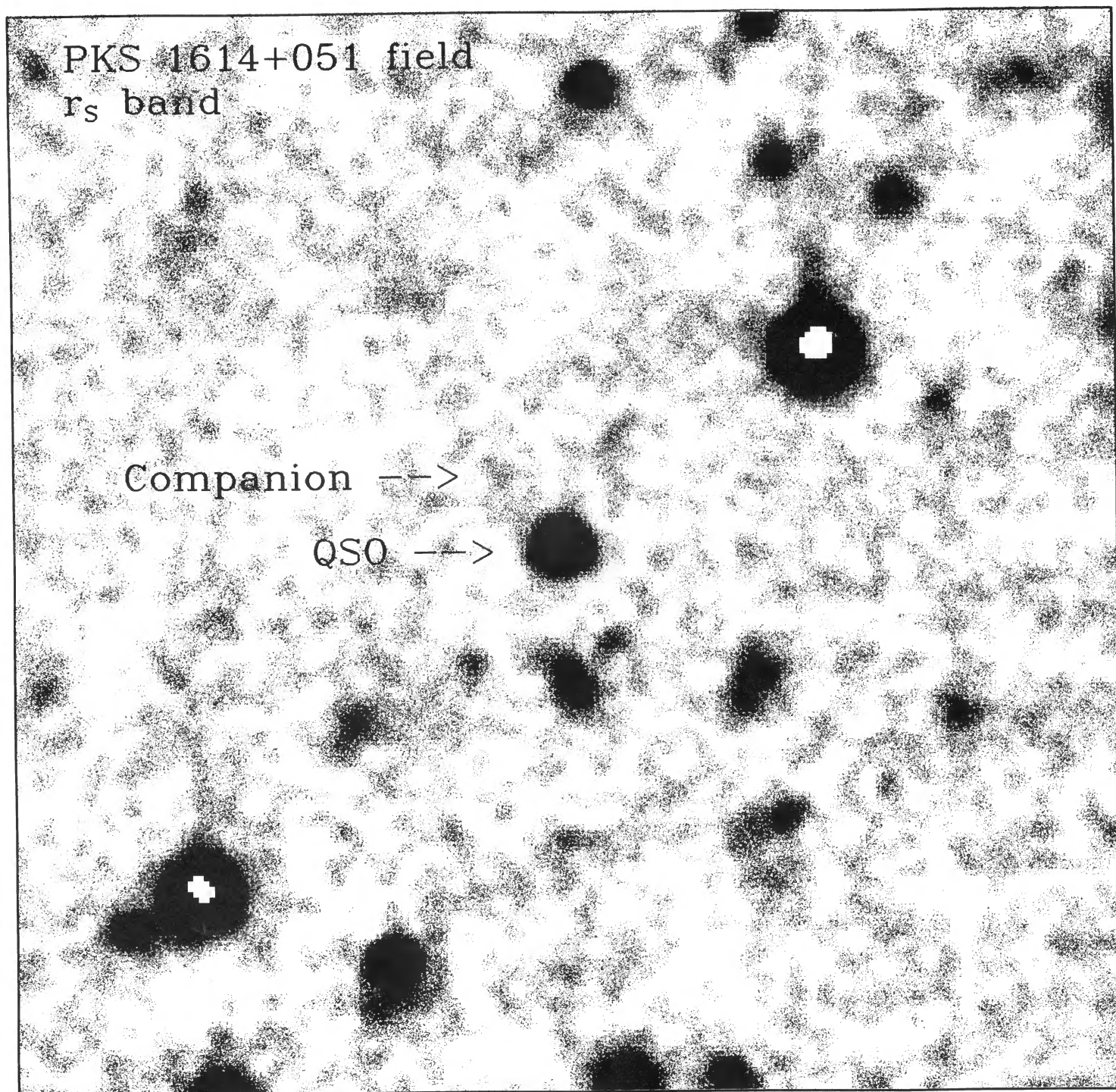


FIG. 1a

FIG. 1.—Stacked CCD images of the PKS 1614+051 QSO field. North is at the top, east to the left, and the fields are 73 arcsec^2 . The QSO coordinates are: $\alpha = 16^{\text{h}}14^{\text{m}}09^{\text{s}}.1$, $\delta = 05^{\circ}06'54''$ (1950); (a) Broad-band red image; the companion is barely detected. Many faint, red (almost certainly foreground) galaxies are present. The data are from both July and August runs. (b) $\text{Ly}\alpha$ image; note the prominence of the companion object. The data are from the July run only.

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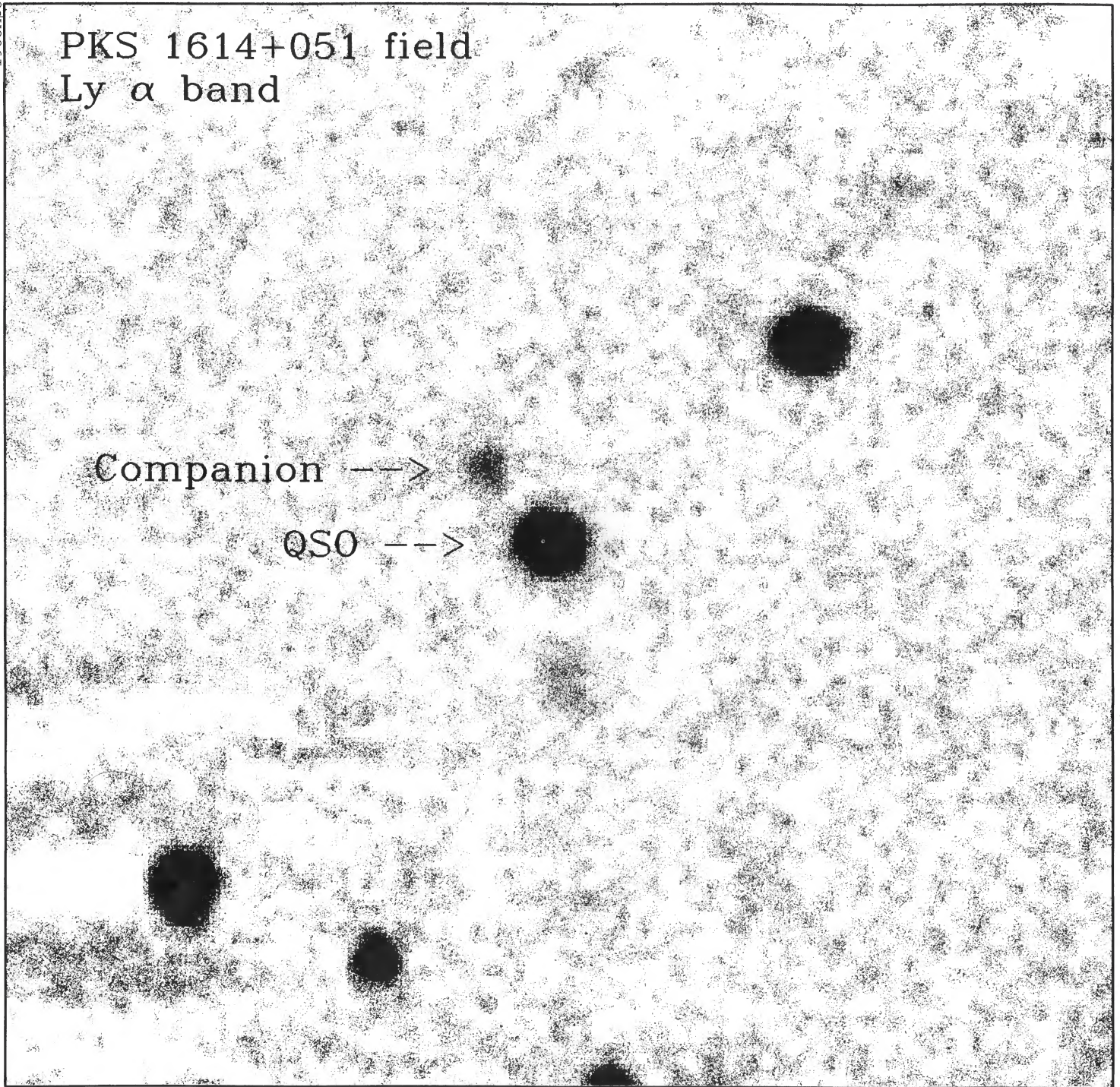


FIG. 1b

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and one 3600 s exposure with a medium-resolution ($600 \text{ grooves mm}^{-1}$) grism were obtained. In this way the spectroscopic features were sampled with different dispersers and different positions on the CCD. The wavelength calibrations have rms errors of about 5 \AA and 1 \AA , respectively; we used the high-resolution data to measure the redshifts. The spectral resolutions of the two grisms are $\text{FWHM} \approx 15 \text{ \AA}$ and 10 \AA , respectively. Additional spectroscopic exposures were obtained on the nights of 1985 August 15 UT (2480 s integration), and 1985 August 16 UT (2760 s integration). Both of these exposures used the "420" grism, and the slit PA = 201° , centered on the companion object and the red galaxy just south from the QSO (see Fig. 1). The seeing was excellent, with $\text{FWHM} \approx 1''.2$.

The spectra were reduced with the methods described in Djorgovski and Spinrad (1983), and flux-calibrated with the exposures of Feige 98 (Stone 1977). The averaged spectra are shown in Figure 2. The reality of the weak emission-line features in the spectrum of the companion was verified by direct visual examination of the two-dimensional, sky-subtracted spectroscopic frames.

III. THE RESULTS

From our direct images, we obtain magnitudes for the QSO and the companion:

$$r_{S, \text{QSO}} = 19.69 \pm 0.01, \quad m(5139)_{\text{QSO}} = 17.09 \pm 0.01,$$

$$r_{S, \text{COMP}} = 24.56 \pm 0.5, \quad m(5139)_{\text{COMP}} = 20.12 \pm 0.02,$$

where $m(5139)$ pertains to the whole $\text{FWHM} = 90 \text{ \AA}$ band, and the positional offsets:

$$\Delta\alpha_{\text{COMP-QSO}} = +4''.20 \pm 0''.05,$$

$$\Delta\delta_{(\text{COMP-QSO})} = +5''.04 \pm 0''.05,$$

corresponding to a separation of $6''.55$ and a position angle of 40° . Taking the QSO position from Morabito *et al.* (1982), we obtain the position of the companion object (1950 epoch):

$$\alpha = 16^{\text{h}}14^{\text{m}}09^{\text{s}}.37, \quad \delta = +05^\circ06'58''.9,$$

with estimated total errors of about $0''.7$ in each coordinate, which includes our $0''.05$ offset errors, and $0''.6$ – $0''.7$ positional errors from Morabito *et al.*

Surface brightness profiles for the QSO and the companion object are shown in Figure 3. Apparently, the companion is unresolved in both bands, although the signal is poor in the r_s band.

The measured redshift for the companion object is $z_{\text{COMP}} = 3.2182 \pm 0.0005$, based on the $\text{Ly}\alpha$ line. The peak of the C IV line gives $z_{\text{COMP}} = 3.219$, in good agreement with the $\text{Ly}\alpha$ redshift, but this line is broadened in its red wing, probably due to a noise spike. This agreement of redshifts suggests that the $\text{Ly}\alpha$ line is not significantly self-absorbed in its blue wing, as is the case with the QSO. The other lines, as indicated in Figure 2, are too weak for reliable measurement. The measured equivalent width of the $\text{Ly}\alpha$ line in the compa-

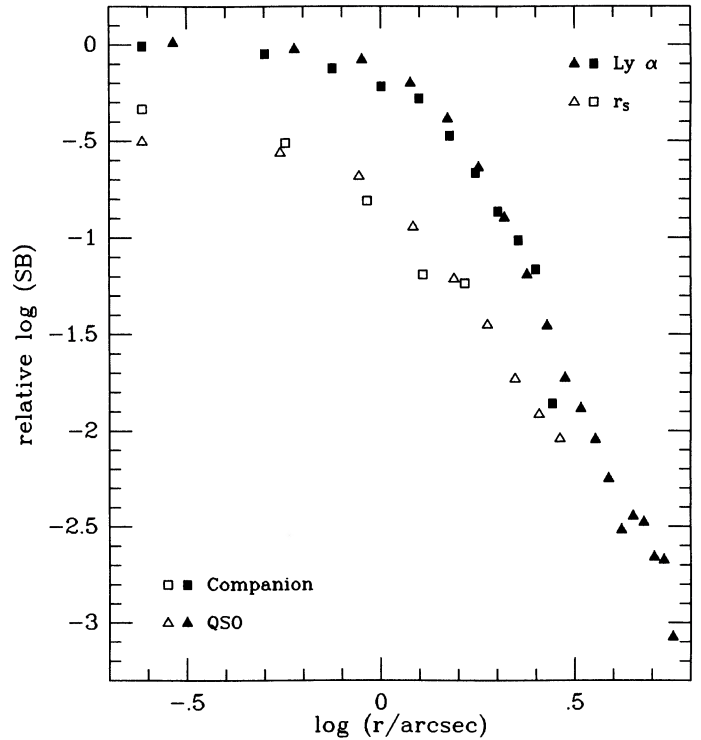


FIG. 3.—Surface brightness profiles for the QSO (triangles) and the companion object (squares), obtained in the redshifted $\text{Ly}\alpha$ band (solid symbols) and the broad-band red continuum (open symbols). The curves were shifted along the Y-axis so that the surface brightnesses for the two objects roughly match in each band. Red profiles were shifted down by 0.5 dex, for clarity. $\text{Ly}\alpha$ band data are from the July run only, and the red data are from both July and August runs.

nion object is about 200 \AA in the rest frame, similar to that found in high-redshift radio galaxies (Spinrad *et al.* 1985). The continuum is very weak, and this number should perhaps be regarded as a lower limit. Its intrinsic width (corrected for the instrumental resolution) is about $900 \pm 300 \text{ km s}^{-1}$ FWHM in the rest frame, which is appropriate for a mildly active galaxy. The overall spectrum appearance is very similar to that of high-redshift radio galaxies (Spinrad and Djorgovski 1984; Spinrad *et al.* 1985). The poor signal-to-noise ratio and troublesome sky subtraction should not be too surprising: at $24^{\text{m}}5$, this is probably the faintest object for which a conclusive spectrum has ever been obtained.

The QSO has a normal, high-redshift QSO spectrum. We measure its redshift from the $\text{Ly}\alpha$ line to be $z_{\text{QSO}} = 3.214$. The $\text{Ly}\alpha$ line may be self-absorbed in its blue wing and has perturbing N V 1240 emission in its red wing. From the C IV 1549 line, we find a redshift $z_{\text{QSO}} = 3.209$. Thus, the companion object is redshifted with respect to the QSO by some 300 km s^{-1} in the rest frame if the QSO $\text{Ly}\alpha$ redshift is used, or about 660 km s^{-1} if the C IV line QSO redshift is used, with errors of about 90 km s^{-1} .

Note that the line ratios and equivalent widths are quite different in the QSO and the companion object: the $\text{Ly}\alpha$ to C IV line energy ratios are 1.96 and 3.5 for the QSO and the companion, respectively, and the QSO lines have the rest

frame FWHM of $\sim 2000 \text{ km s}^{-1}$. The redshift difference (which is also very apparent in the spectroscopic CCD frames, at least for Ly α), along with the differences in line widths and ratios, rules out the possibility that we are seeing yet another example of gravitational lensing.

Our spectra of the red galaxy just south from the QSO are still too poor to yield a redshift; no emission lines are present. The galaxy is almost certainly a foreground object. The number of faint galaxies in our red CCD frames suggests a possible foreground cluster.

IV. DISCUSSION AND CONCLUSIONS

The companion object is certainly young, because of its high redshift. In a $q_0 = 0$, $\Lambda_0 = 0$ Friedman-Lemaître cosmology, the look-back time to this system is 0.763 of the age of the universe (= the Hubble time), whereas in a $q_0 = 1/2$, $\Lambda_0 = 0$ cosmology, it is 0.855 of the age of the universe (= $2/3$ of the Hubble time). If the galaxies formed at $z = 5$ (which currently seems to be a reasonable guess), we are seeing this system at an age of only 8.4% or 5.0% of the present galaxian age, for the two cosmological models above. If galaxies formed at $z = 10$, these numbers become 16.1% and 9.1%, respectively. The corresponding numbers for PKS 2000–330 (the most distant QSO known, at $z = 3.78$) differ from these by only a couple of percent.

What is the nature of the companion object? Its spectrum is definitely not that of the QSO/Seyfert 1 type, and it is not very different from those of radio galaxies with $z \approx 1.5$ – 2 . The Ly α line to local continuum ratio is very high, in contrast to ratios seen in the QSO/Seyfert 1 spectra. The fact that it is unresolved in our direct images should not be surprising: at such a high redshift, only the central parts of galaxies should be observable, since relativistic $(1+z)^4$ surface brightness dimming suppresses their faint envelopes, even though stellar population evolution would make the envelopes brighter (by a poorly known amount). One possibility is that we are seeing an equivalent of the nuclear starburst disk of NGC 1068 (Weedman and Huenemoerder 1985). We may have to wait for the Hubble Space Telescope in order to resolve the morphology of this object. It is certainly possible that this object is a marginal Seyfert 2, or a LINER. It does possess a faint red continuum, which may well be due to starlight. Note the presence of carbon and possibly nitrogen lines in its spectrum—some reprocessing of gas has already happened.

Djorgovski and Spinrad (1985a) have found that the colors and magnitudes of 3CR galaxies (presumably giant ellipticals) at high redshifts are described well by the continuous, exponentially decaying star formation models of Bruzual A. (1981, 1983). The “best” models (Bruzual $\mu = 0.5$ – 0.7) predict red magnitudes of the order of 22–23 for these very luminous galaxies at $z \geq 3$. If such models can indeed be extrapolated and applied in this case (a very tenuous assumption), we may be seeing an actively evolving L_* galaxy; if milder evolution is assumed, the galaxy should be of a brighter kind. The conclusion is that nothing more dramatic than a moderately luminous galaxy (e.g., like our Galaxy) is required. The distance moduli ($m - M$) at this redshift, for the two cosmological models mentioned above, are 46.99 and 45.56, respectively, for $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$; one must still

subtract the K -corrections and evolutionary effects from these numbers.

The projected separation between the QSO and the companion corresponds to 45 or 23 $h_{100}^{-1} \text{ kpc}$ for the two cosmologies above. Their relative velocity is typical of that observed in moderately rich clusters or rich galaxy groups at low redshifts. Two objects do not a cluster make, but the possibility of clustering at such high redshifts is very intriguing—it is a fundamental test for the theories of large-scale structure and galaxy formation.

Another possibility is that the companion is a gas-rich galaxy, with the narrow-line emission excited by the QSO’s radiation field. This is very seldom the case for QSO companion galaxies at low redshifts (Filippenko 1985; Heckman *et al.* 1984; Djorgovski and Spinrad 1985b). If more such galaxy companions to high-redshift QSOs are found in the future, we may be able to address this possibility. Another possibility is that we are seeing a high-redshift equivalent of Minkowski’s object (van Breugel *et al.* 1985; Brodie, Bowyer, and McCarthy 1985), a gas-rich galaxy excited by a radio jet. A modern VLA map could check the latter possibility. Measurements of its near-infrared continuum would also be very valuable, in order to constrain its stellar content.

The prominent Ly α emission in this object (and the equally prominent emission found in $z \approx 1.5$ – 2 radio galaxies by Spinrad *et al.* 1985) gives new hope for primeval galaxy searches. The pessimistic predictions of Hartman, Huchra, and Geller (1984) about Ly α quenching are based on low-redshift, gas-rich dwarfs; these authors may still be right about the spectroscopic dullness of some or even most primeval galaxies, but there are clearly galaxies at high redshifts with very prominent Ly α emission. The models of Meier (1976) and Cox (1985) predict an early Ly α -luminous phase of primeval galaxies. The properties of primeval galaxies predicted by Meier (1976), viz., compact appearance and strong Ly α , agree well with our observations of the companion object. (See also the reviews by Davis 1980 and Koo 1985b on how to recognize a primeval galaxy.) It now appears that the fall-off in the number density of QSOs beyond $z = 3$ is real (Schneider, Schmidt, and Gunn 1984). If the appearance of QSOs reflects the appearance of galaxies, i.e., if galaxies formed at $z \leq 4$, then we may have discovered a good approximation to a primeval galaxy.

Perhaps the most important result of the present work is the proof of the method: it is possible to find extremely distant, young galaxies, using interference filter imaging of high-redshift QSO fields (and perhaps even “blank” fields). Unless we are victims of improbable good luck, we should be able to find more such distant objects. If so, we will have succeeded in pushing the studies of distant galaxies well into the “realm of the quasars.” The next step, of course, is a search for (primeval?) galaxies at $z = 4$, and beyond. One such experiment is now being carried out by C. Pritchett and D. Hartwick (C. Pritchett, private communication).

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