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THE DISTRIBUTION OF GAS AND GALAXIES AROUND THE DISTANT QUASAR PKS 1614+051

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ABSTRACT

We report the results of narrow-band and broad-band filter observations of the region surrounding the $z = 3.21$ quasar, PKS 1614 + 051, made under subarcsecond seeing conditions with the 3.6 m CFHT telescope at Mauna Kea. The nuclear region of the Lyα companion to the quasar is resolved with a FWHM of $\sim 0\farcs9$. A bridge of emission extending from the companion is seen at Lyα surface brightnesses typically an order of magnitude fainter. Limits on detectable continuum flux from this object suggest that it is a gas cloud interacting with the quasar, and its emission is consistent with simple photoionization by the quasar. However, the presence of several galaxies around the periphery of the quasar is noted. A search of 11 additional quasars at $z > 3$ has failed to show any other such systems. It is argued that this is consistent with the statistics of extended emission line systems in low-z quasars.

Subject headings: galaxies: clustering — galaxies: formation — quasars

I. INTRODUCTION

The discovery of a narrow emission-line companion to the quasar PKS 1614 ± 051 at $z = 3.218$ is one of the most exciting recent cosmological observations (Djorgovski *et al.* 1985). It raises the possibility of studying conditions in the neighborhood of quasars at these early epochs and of observing the feed mechanisms for the quasars. Even more dramatic is the possibility raised by Djorgovski *et al.* that continuum light is associated with the object. If this could be convincingly demonstrated, then we would be seeing an example of a fairly massive star-forming object which might perhaps be the long-sought protogalaxy. However, the morphological similarity to gaseous emission line structures around nearby quasars (cf. Stockton and MacKenty 1987) has led many to believe that the companion (hereafter PKS 1614A) is a gas cloud (possibly photoionized by the quasar) rather than a galaxy.

While two additional high-z gas clouds have recently been found in the $z = 3.273$ gravitational lens system 2016+112 by Schneider *et al.* (1986), such systems are very unusual. In a sample of 11 quasars at $z > 3$ (Table 1) surveyed with a set of 70 Å bandpass filters at and around redshifted Lyα using the 88″ UH telescope with the IFA CCD on Mauna Kea, none showed emission-line companions at the level of PKS 1614+051A. These were typically 30 minute exposures reaching limiting AB magnitudes of 23 or fainter. This is part of an ongoing survey which will be addressed in more detail in a separate paper. In some cases (e.g., Crampton 2233.9 + 1369 listed as Q2234+137 in Table 1) further observations at CFHT showed no emission-line companions even at levels more than an order of magnitude fainter. It appears that at most a few percent of high-z quasars have emission-line companions as luminous as PKS 1614 + 051 and that a substantial fraction show no companions at considerably lower levels.

As regards PKS 1614 + 051 itself, the crucial questions regarding its companion are (1) does it possess a true continuum, (2) is it spatially extended, and (3) are there any other unusual features of the region?

II. OBSERVATIONS

In the present *Letter* we report narrow-band and broad-band filter observations of the PKS 1614 + 051 region obtained at the 3.6 m CFHT in 1986 July. These observations were obtained with the Institute for Astronomy's Galileo CCD camera (Hlivak *et al.* 1982; Hlivak, Henry, and Pilcher 1984) during the course of another program when it became clear that the seeing was substantially subarcsecond ($0\farcs6$ or less) and that conditions were photometric, allowing us to address the second question raised above. With the focal reducer in place the pixel size at the Cassegrain f/8 focus was $0\farcs3$ and sampled the seeing disk at the Nyquist frequency. Four sets of composite broad-band exposures were obtained —two V bands (one of 18 minutes total duration and one of 24 minutes), one R band of 8 minutes, and one I band of 15 minutes duration. (The optics in the focal reducer have poor transmission at shorter wavelengths and no U or B images could be obtained.) Broad-band filters are on the Mould system (Butcher and Jacoby 1983). Each of these images consisted of four or more exposures shifted on the surface of the chip to minimize systematics. In addition, a 70 minute exposure was obtained through a 73 Å bandpass filter centered at 5120 Å (redshifted Lyα lies at 5125 Å for the companion and at 5118 Å for the quasar (Djorgovski *et al.* 1985, 1987)). In this case the observation consisted of one 10 minute and

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TABLE 1

LIST OF OBSERVED QUASARS

Quasar	z	Shifted Lyα	Observed Bandpasses
Q2233+132	3.218	5129	5198/78
			5102/100
			R band
Q2234+137........	3.204	5112	5102/100
			5120/73
			5198/78
			R band
			V band
Q0120+027........	3.272	5195	5198/78
			5102/100
			R band
Q0249−185........	3.21	5119	5102/100
			R band
			V band
			I band
Q0642+449........	3.40	5350	5382/70
			R band
Q0905+151........	3.157	5055	5120/73
			5045/79
			V band
			R band
Q1017+109	3.171	5072	5045/79
			5120/73
			V band
Q1400+115........	3.174	5076	5045/79
			5120/73
			V band
Q1402+045........	3.202	5110	5120/73
			V band
Q1451+124........	3.256	5175	5198/78
			V band
			R band
Q1600+285........	3.24	5156	5120/73
			V band

one 60 minute exposure. All the images were flat-fielded using exposures of the illuminated dome and were calibrated on the AB system of equivalent visual magnitudes using observations of a number of standard stars (Stone 1977) interspersed among the observations of the object.

After reduction, the 24 minute V band exposure was rejected as being of substantially inferior quality owing to focus and guiding problems. Measured FWHMs on the remaining final composite images were 0''.8 on the Lyα frame, 0''.85(V), 1''.0(R), and 1''.2(I). No attempt was made to cosmetically clean bad regions in order to avoid introducing artifacts. These regions were marked and are noted on the displays. The data are presented in several ways in Figures 1–3. Figure 1 shows the central 30'' × 30'' region centered on the quasar in Lyα (Fig. 1a) and V band (Fig. 1b). PKS 1614A is the object at 6''.0 to the NE of the quasar connected to the quasar on the Lyα frame by the somewhat patchy filamentary structure. The remaining objects are foreground galaxies and stars which can also be seen in the V band image. PKS 1614A can also be clearly seen in the V band image owing to the presence of the Lyα line at the edge of the V bandpass. However, in the R bandpass (a 10'' × 10'' portion around the quasar is shown as the upper left inset) PKS 1614A can hardly be seen. As we shall discuss later, even the low-level features can be accounted for by the weak C IV 1549 and He II 1640 emission within the R band. A second inset shows the V band image of a nearby star (which is about a magnitude brighter than the quasar) at the same contour levels as the main figure. This object was used to measure FWHMs for the various images.

In Figure 2 we show the Lyα light (with the continuum subtracted) overlaid on V band continuum contours where the Lyα contamination has been removed. Once again it should be noted how weak the PKS 1614A continuum is. Finally, Figure 3a shows cuts across the quasar and the reference star. The quasar is unresolved in both continuum and Lyα light. Figure 3b shows the same comparison for the quasar and PKS 1614A, which is clearly resolved.

Rough equivalent visual magnitudes for all the objects near the quasar are given in Table 2. Each corresponds to the background-subtracted flux in a box of the given aperture. The galaxies near the quasar have been further corrected for contamination by the quasar light. Uncertainties are typically about 0.3 mag from background correction and aperture choice. The magnitudes do not agree particularly well with those quoted in Djorgovski *et al.* (1985) or more recent results in Djorgovski *et al.* (1987). In particular, in the narrow-band observations (1985 paper) the quasar is brighter by 0.9 mag and the companion fainter by 0.9 mag. This may be caused in part by the slightly different bandpasses (5120/73 vs. 5139/90), but the present filter observations should have been well centered on the companion's Lyα. R band magnitudes for the quasar are consistent with both the 1985 and 1987 Djorgovski *et al.* values. However, R magnitude estimates for the fainter companion are 1.5 mag fainter than the 1987 Djorgovski *et al.* value (itself about a magnitude brighter than the original 1985 determination). Only ~ 0.1–0.2 mag of this discrepancy can be attributed to color system corrections (Djorgovski 1985), and the reason for this discrepancy is unclear. We shall argue in § IV that adoption of either measured continuum value does not change our conclusions on the physical nature of the emission mechanism.

III. DESCRIPTION

a) *Lyman-Alpha*

These moderately high-resolution observations show PKS 1614A to be extended and somewhat elongated in a north-south direction (cf. Fig. 1a). It is connected to the quasar by a bridge which splits into two filaments near the quasar (cf. Fig. 1a and Fig. 2). The quasar itself is unresolved in both the continuum and in Lyα (except toward PKS 1614A) while the nuclear region of PKS 1614A is clearly resolved (Fig. 3b) and after deconvolution of the seeing disk has a FWHM of approximately 0''.9 ($3h^{-1}$ kpc, $6h^{-1}$ kpc).[2] The outer Lyα isophotes of PKS 1614A can be traced to at least 1''.5 radius. In a 2''.4 × 2''.4 square aperture centered on the nucleus, we measured a Lyα flux of 10^{-15} ergs cm^{-2} s^{-1}. (This is a value

[2] Following Djorgovski *et al.* (1985) we quote scale sizes and luminosities for both $q_0 = 0$ and $q_0 = 1/2$ in a Friedmann cosmology with $h = H_0/100$ km s^{-1} Mpc^{-1}.

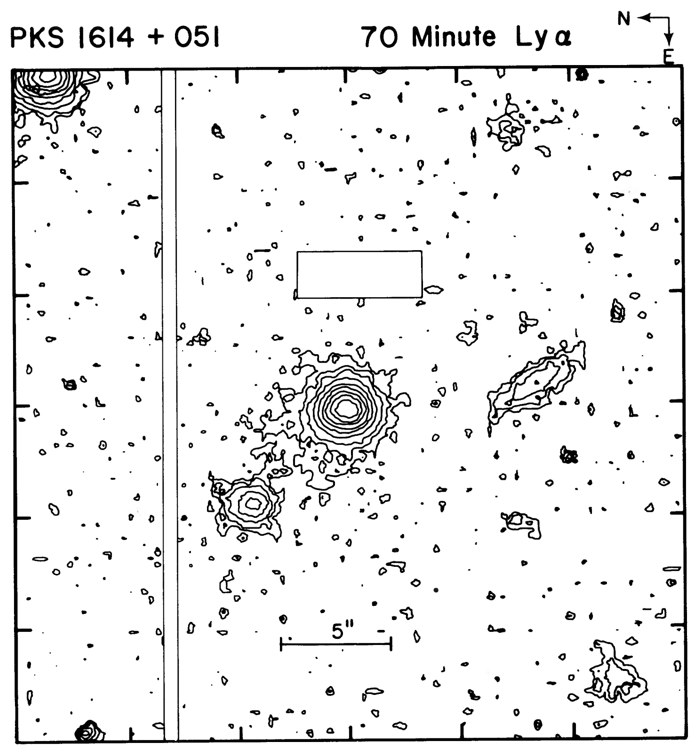

FIG. 1*a*

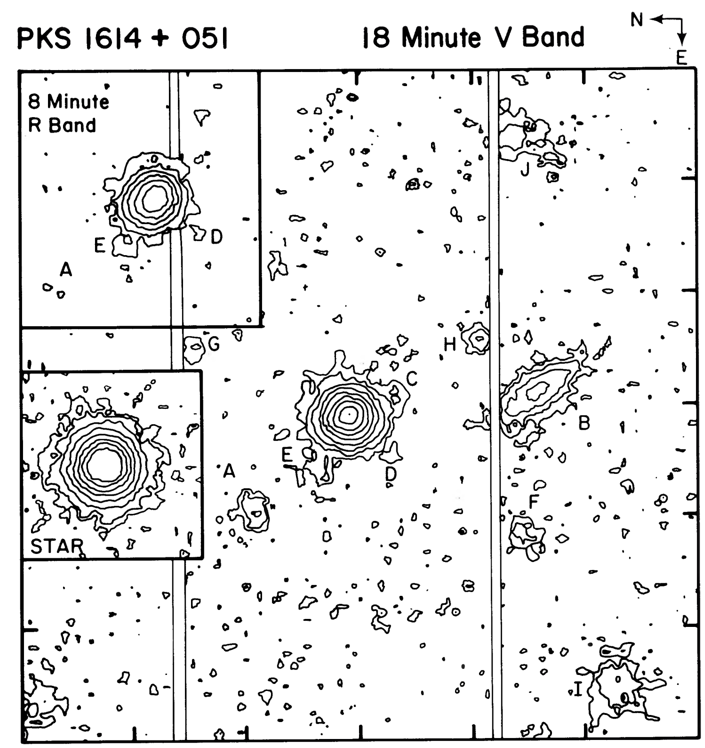

FIG. 1*b*

FIG. 1.—(*a*) Composite Lyα image of the PKS 1614 + 051 field. Shown here is a 30″ × 30″ field of view. Bad columns and a region where dust could not be removed in flat-fielding have been blanked out and indicated on the figure. No smoothing has been applied. Contours are at 25.0 mag arcsec^{-2}, 24.5 mag arcsec^{-2}, etc., calibrated on the Oke AB (equivalent visual) magnitude scale. (*b*) Composite *V* band exposure of the PKS 1614 + 051 field. Same scale as for Fig. 1*a*. Contour levels extend from 25.5 mag arcsec^{-2}, 24.7 mag arcsec^{-2}, and increment thereafter in −0.75 mag arcsec^{-2} intervals. For comparison purposes, the inset at left shows the image of a star, somewhat brighter than the quasar, contoured at the same levels. Also shown in inset to scale is an *R* band image of the quasar region (*upper left*). Nearby objects have been labeled with letters, with "A" denoting the Lyα companion. Some of these objects in the vicinity of the quasar (e.g., object E, 2″.7 from the quasar) are discussed in more detail in the text.

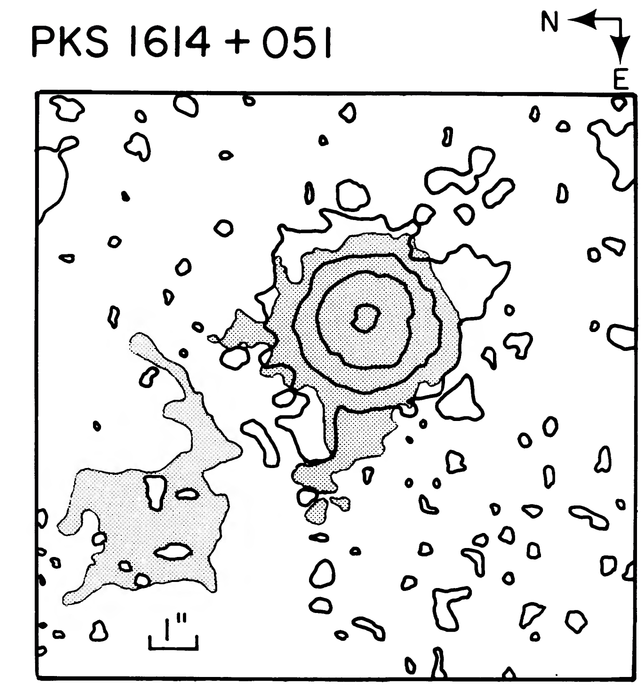

FIG. 2.—Lyα emission (*shaded region*) is shown superposed on continuum image of quasar and companion. Note "bridge structure" extending between PKS 1614A and quasar which is also visible in Fig. 1*a*.

about 3 times lower than would be inferred from Djorgovski *et al.* 1985.) The typical Lyα surface brightness in the bridge is about 3×10^{-17} ergs cm^{-2} s^{-1} arcsec^{-2} compared to a nuclear surface brightness about an order of magnitude higher. The Lyman-α luminosity is $(6 \times 10^{43}\ h^{-2}, 1.6 \times 10^{43}\ h^{-2})$ ergs s^{-1}.

b) *Continuum*

While PKS 1614A is clearly seen in the *V* band owing to the presence of the Lyα line in the band, it is extremely faint in the *R* and *I* bands (e.g., Fig 1*b*). Our measured equivalent visual magnitudes at *R* of 25.2 and at *I* of 24.2 are quite marginal detections. Indeed, all three broad-bandpass filters contain some strong emission lines which contribute much or all of the signal. From estimates on the degree of line contamination to each bandpass using the spectrum given in Djorgovski *et al.* (1985) in combination with our measured Lyα flux, the *R* and *I* bands provide the strongest constraints on continuum emission and suggest that any continuum that is present must be well below 25th mag. Even adopting a weakened upper limit of 24 (based on the faint continuum detection reported in Djorgovski *et al.* 1987) on the equivalent visual magnitude in the *V* band, the Lyα equivalent width exceeds 2000 Å.

In contrast, there are a number of faint objects visible in the continuum around the periphery of the quasar itself (cf.

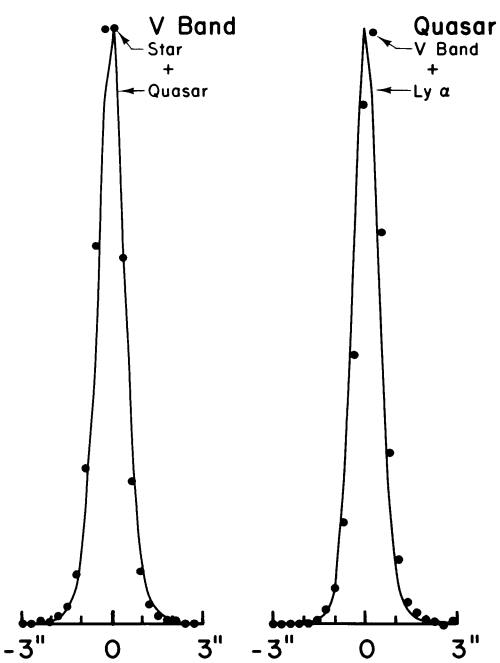

FIG. 3*a*

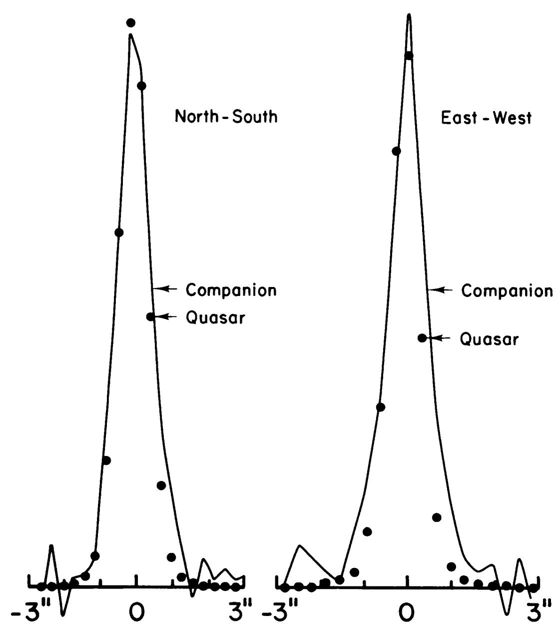

FIG. 3*b*

FIG. 3.—(*a*) Profiles comparing sample cuts through the quasar with a stellar profile. Similar profile cuts through the quasar in *V* band and Lyα light show the quasar images to appear stellar in both bandpasses. (*b*) Profiles comparing sample cuts through the quasar (*dots*) and Lyα companion (*solid line*) PKS 1614A. Note the extended nature of PKS 1614A as seen in row (north-south) and column (east-west) cuts through the object in Lyα light. The contribution of the "bridge" extension to the west of the companion may be seen in the east-west cut. The typical size of the brighter regions of PKS 1614A is ~ 0''.9.

TABLE 2

PHOTOMETRY OF OBJECTS NEAR PKS 1614 + 051

Object	AB_{5120}	AB_V	AB_R	AB_I	Aperture
Quasar:					
PKS 1614	18.2	19.4	19.4	19.4	4″2
Companion:					
PKS 1614A	21.0	23.5	25.2	24.2	2″4
Peripheral galaxies:					
PKS 1614C	24.9	24.8	25.4	...	0″9
PKS 1614D	24.6	25.3	24.7	25.6	1″2
PKS 1614E	23.0	24.0	23.7	23.0	1″8
Neighbor galaxies:					
PKS 1614B	21.7	21.9	21.6	21.7	4″2
PKS 1614F	23.7	24.1	23.4	23.5	2″4
PKS 1614G	24.7	24.9	24.8	25.7	1″2
PKS 1614H	...	24.7	23.3	22.4	1″8

Fig. 1*b*, objects C, D, E). We consider that only objects D and E are reliable detections since C is significant only in the V band. From Table 2 it appears initially that object E has a significant Lyα flux since the equivalent visual magnitude is 23.01 in the 5120/73 band and is a magnitude brighter than the continuum. However, the physical association of this gas with the object is much less clear if one overplots the Lyα emission on the continuum as in Figure 2. Here the emission appears to correspond to the filament running down the side of object E. Despite this caveat, the morphological position of E is very suggestive of an association with the quasar-gas system, and it is very close to the quasar indeed (2″7). However, it is also possible that E is simply a change projection of a foreground galaxy. In particular it could be a member of the foreground cluster which lies in this direction (Djorgovski *et al.* 1985).

In this context it is noteworthy that Table 2 suggests that object D may also have very weak Lyα emission associated with it though this is a very marginal result. Once again inspection of the overlay Figure 2 suggests this may be contamination of the aperture by the quasar rather than emission associated with the galaxy. Therefore this object could also be a projected foreground galaxy, though once again the morphology may suggest otherwise.

IV. INTERPRETATION

The structure of the PKS 1614A suggests that we are seeing a gas cloud tidally interacting with the quasar and its underlying galaxy and that this interaction may be fueling the quasar activity.

However, it is clear that PKS 1614A *is not* a protogalaxy where the gaseous emission is excited by hot member stars. The measured equivalent width is ≥ 2000 Å in the Lyα line whether we use our own data or that of Djorgovski *et al.* and is almost an order of magnitude too high to be consistent with protogalaxy predictions of about 400 Å (Meier 1976). This discrepancy would become worse if the gas cloud had dust in it and Lyα was preferentially destroyed with respect to the continuum.

The emission of the cloud *is* consistent with simple photoionization by the quasar. The nuclear regions of the system cover approximately a fraction, ϕ, of 10^{-3} of a spherical surface around the quasar. If the quasar spectrum followed an $f_\nu \approx \nu^0$ dependence and each ionizing photon beyond the Lyman-continuum break striking the cloud produced one Lyα photon, then the magnitude of PKS 1614A in our narrow-band exposure of width $\Delta\lambda$ relative to the continuum V band magnitude of the quasar is given by

$$m_{\mathrm{Ly}\alpha,\,\mathrm{comp}} - m_{v,\,\mathrm{qso}} = -2.5 \log \left[\phi(1+z) \frac{\lambda_{\mathrm{Ly}\alpha}}{\Delta\lambda} \ln \frac{\nu_{\max}}{\nu_{Ly\ \mathrm{limit}}} \right]$$

which translates to a difference of about 2 mag while the observed value is 1.9. The agreement is fortuitously good but does suggest that photoionization is the most natural mechanism for producing the observed emission. However, dynamical energy input from the tidal interaction or from compression by surrounding higher-pressure gas could also contribute through shock heating. Alternatively, the presence of a mildly active galactic nucleus such as described in Djorgovski *et al.* (1987) could supply part of the ionization. We suggest that these processes are of secondary importance in view of the photoionization arguments given above.

Knowing the surface brightness s of the object, we can infer an emission measure of $4\pi s(1+z)^4/(\alpha h \nu_{\mathrm{Ly}\alpha})$ where α is the recombination rate to the second level and above. This gives a value of 2×10^4 cm^{-6} pc. If $C = \langle n_e^2 \rangle / \langle n_e \rangle$ then this translates to $\langle n_e \rangle = 3\ C^{-1/2}\ h^{1/2}$ cm^{-3} for a dimension of $6h^{-1}$ kpc, with a column density of $5 \times 10^{22}\ C^{-1/2}\ h^{-1/2}$ cm^{-2} and a mass of $8 \times 10^9\ h^{-3/2}\ C^{-1/2}\ M_\odot$ in ionized gas.

Turning finally to the companion galaxies PKS 1614D and E we note that if, as suggested by the morphology, they do lie near the quasar that they are very luminous ($M_v \approx -23$) galaxies with flat spectra to near the Lyman-continuum break. *These*, as opposed to PKS 1614A, may be protogalaxies and the crucial diagnostic is to obtain U colors of these objects to see if the Lyman-continuum break is present. If it is, then we could be seeing a cluster or group in the process of formation.

V. DISCUSSION

What is PKS 1614A? The most obvious analogs are the extended emission-line systems seen around many low-z quasars (cf. Boroson, Persson, and Oke 1985; Stockton and MacKenty 1987) which are suspected to be caused by cooling flows or by tidal interactions. Some of these cases (e.g., the companion to 0205 + 024 in Stockton and MacKenty) bear a striking similarity to PKS 1614A in almost all aspects (size, separation from the quasar, morphology, etc.). [O III] luminosities in the Stockton and MacKenty catalog extend up to $5 \times 10^{42}\ h^{-2}$ ergs s^{-1} with typical values around 10^{41} h^{-2} ergs s^{-1} on detected systems. Hβ fluxes are typically a factor of several less (Boroson *et al.* 1985), suggesting that Lyα luminosities should lie in the $10^{42}\ h^{-2}$ ergs s^{-1} range with the most luminous around 5×10^{43} ergs s^{-1} being similar to PKS 1614A.

Many of the Stockton-MacKenty systems also show distorted and extended continuum emission as well as extended ionized gas. The continuum emission seldom follows the pattern of ionized gas. It is tempting to associate objects D and E with similar distortion of the underlying quasar galaxy.

It seems unlikely, given the low dust content that would be inferred from the escape of Lyα photons, that PKS 1614A is caused by tidal interaction, and this would seem to favor a cooling flow interpretation for this case.

Finally, we can ask if the detection rate is reasonable in this interpretation. In a subsample of 47 quasars biased toward extended line systems and chosen from an original sample of 58 quasars, Stockton and MacKenty found 11 systems with [O III] luminosities in excess of 2×10^{41} h^{-2} ergs s^{-1} and four systems with luminosities in excess of 6×10^{42} h^{-2} ergs s^{-1}. If $L(\mathrm{Ly}\alpha)/[\mathrm{O\ III}] \approx 10$ this would suggest that about 7% of high-z quasars should have emission-line companions as luminous as PKS 1614A and about 20% should have companions with luminosities about an order of magnitude lower. These numbers are quite consistent with the null results of both the survey quoted above and others which have been conducted in the past year. They do suggest that extending the surveys to a larger sample should begin to turn up a small number of additional cases.

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