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SERENDIPITOUS DISCOVERY OF A REDSHIFT 4.4 QSO[1]

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ABSTRACT

We report the serendipitous discovery of an extremely high-redshift quasar (QSO), designated Q2203+29. It was found during long-slit observations of the radio galaxy 3C 441. The QSO spectrum contains strong emission lines of Lyα, N V λ1240, and C IV λ1549, as well as weaker Lyβ, O VI λ1034, Si II λ1262, and Si IV/O IV] λ1400. There is a prominent break in the continuum level blueward of Lyα. The derived reshift is 4.406 ± 0.005, one of the highest known. Deep broad-band imaging reveals no resolved structure, as expected for a very distant QSO. The r magnitude of the QSO is 20.8. Lyα interference filter imaging shows no emission-line companions or extended emission down to surface brightness levels of 25.5 mag arcsec^{-2}. The broad-band images show a faint disk galaxy with $z = 0.2$, located 7″ away from the QSO. Our spectra do not exhibit any absorption lines produced by this foreground galaxy. The VLA observations at $\lambda = 20$ cm fail to reveal any detectable emission from the QSO to a 3 σ upper limit of 1.8 mJy beam^{-1}. This is the first serendipitously discovered QSO of any redshift in nearly 5 yr of long-slit CCD spectroscopy of radio sources at Kitt Peak and Lick Observatories.

Subject headings: quasars — radio sources: galaxies

I. INTRODUCTION

The search for, and subsequent observations of, high-redshift QSOs has probably consumed more time on large telescopes than any other program in the last decade of astronomy. Very distant QSOs are of substantial interest because they provide information about tne early universe. They are also useful as luminous beacons for the study of intervening material. As a result of intensive efforts by several groups, the number of high-redshift QSOs is now increasing quite rapidly (e.g., Hazard, McMahon, and Sargent 1986; Warren *et al.* 1987*a*, *b*; Schmidt, Schneider, and Gunn 1987). However, all search techniques, including radio, UV excess, objective prism, and multicolor, have some form of bias introduced by the selection criteria they employ.

For roughly 5 yr a number of investigators have been performing deep, long-slit spectroscopic observations of faint galaxies and QSOs with linear digital detectors, mostly CCDs. These long-slit observations can be considered as nearly unbiased surveys for faint emission-line objects. The only significant bias contained in such surveys is introduced by the restricted wavelength coverage available to CCDs. An obvious and important shortcoming, of course, is that only a minute fraction of the sky can be sampled with this technique.

In this *Letter* we report the discovery of an extremely high-redshift QSO from a survey of this type, carried out in parallel with spectroscopy of faint radio galaxies. It is quite surprising that such an unusual object should be discovered in a random survey of a very small area of the sky. Moreover, it comes at a time when intensive searches for $z > 4$ QSOs are finally yielding positive results.

[1] Based on observations obtained at the Lick Observatory, operated by the University of California.

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II. OBSERVATIONS AND RESULTS

a) Optical Spectra

The data were obtained with the Lick Observatory Shane 3 m reflector and the Cassegrain CCD spectrograph (Miller 1980). The QSO was discovered (Dickinson and McCarthy 1987) on 1987 September 25 UT during the course of long-slit spectroscopic observations of the intermediate redshift ($z = 0.707$; Perryman *et al.* 1980) radio galaxy 3C 441. The observation was set up to obtain a spectrogram of 3C 441 and an object associated with its northern radio hotspot. The discovery spectrogram was taken with the spectrograph slit centered on 3C 441 and oriented at position angle (P.A.) 145°, the radio P.A. of 3C 441. The slit size was 2″ × 2′. A grism with 420 lines mm^{-1} was used as the dispersing element, giving a spectral coverage of 4250–8600 Å with a pixel size of 5 Å × 0″.73. A 3600 s integration was made under conditions of ~1″.5 (FWHM) seeing.

The QSO appeared along the slit displaced 51″ northwest of 3C 441. Direct images previously obtained with the same instrument (1987 August 23) revealed a faint stellar object at the approximate location of the QSO. The telescope was then offset to place this object on the slit, and an 1800 s exposure was made with the slit at P.A. = 90°. This spectrogram confirmed our identification of the faint stellar object as the QSO. Observations of standard stars from Stone (1977), as well as comparison lamps and flatfield exposures, were made to calibrate the data. The reductions were performed using standard techniques. The average of our two discovery spectra is shown in Figure 1.

Subsequent spectroscopic observations were made at Lick Observatory on 1987 September 28 and 29 UT and on 1987 November 20 UT, with the Cassegrain grating spectrograph. The 2″ slit was placed at P.A. = 144°. Two exposures of approximately 1 hr duration each were obtained with a 300 line mm^{-1} grating blazed at 4200 Å, giving 4 Å pixels covering the wavelength range λλ3100–6280. Two integrations of about 1 hr duration each were also made with a 300 line mm^{-1} grating blazed at 7500 Å, giving 4 Å pixels covering the range λλ6830–10050. Spectra of higher resolution in the region around Lyα were obtained with a 600 line mm^{-1} grating blazed at 7000 Å, giving 2 Å pixels over the range λλ5890–7520. Two integrations of 1 hr duration each were made with this grating.

Figure 2 shows the average of all our spectra of Q2203+29. Strong emission lines of Lyα, N v λ1240, and C IV λ1549 are present. Weak emission lines of O VI λ1034 and Lyβ are also marked in Figure 2. A weak blend of Si IV and O IV] λ1400 is visible at ~7570 Å. We determine very approximate line widths of FWHM $\gtrsim$ 5000 km s^{-1} from C IV λ1549 and Lyα (after crudely subtracting the contribution of N V λ1240). In Table 1 we list the observed emission lines, their equivalent widths (in the observed frame), and the redshifts derived from them. The line widths and equivalent widths are not atypical of high-redshift QSOs, although the Lyα/C IV ratio is higher than usual. The average redshift of the strong lines is $z = 4.406 \pm 0.005$. The low-dispersion spectra include the expected location of He I λ586. We do not convincingly detect any emission there, our 3 σ upper limit on (He I Lyα)/(H I Lyα) being 0.07. We observe some continuum flux blueward of the QSO's Lyman limit (λ912 redshifted to 4930 Å). Although the signal-to-noise ratio is poor, it appears that the continuum is cut off by a Lyman limit absorption system at ~4500 Å, or $z = 3.93$. The continuum redward of Lyα shows no evidence of reddening, being quite flat (in f_ν units). This may bear on models of the number density fall-off based on increasing obscuration at large redshifts (e.g., Heisler and Ostriker 1987).

Our higher resolution spectrum of Lyα is illustrated in Figure 3. The spectrum clearly shows emission from Si II λ1262. Several narrow absorption features are also visible, including one that is nearly centered on the Lyα emission line. The redshift that we derive for this absorption line (assumed to be Lyα) is 4.402, the highest redshift ever observed for a narrow absorption line. In Table 2 we list the strongest absorption lines, their equivalent widths, and their redshifts; all are presumed to be Lyα.

The spectrogram taken with the slit oriented east-west also recorded the faint galaxy to the east of Q2203+29 and the faint stellar object immediately to the west. These data show that the stellar object to the west is a dM star, and that the galaxy 7″ east of the QSO has strong emission lines of Hα,

TABLE 1

EMISSION LINES OBSERVED IN Q2203+29

Line	$\lambda_{\rm observed}$	W_λ (Å)	z
Lyα λ1216	6568	440	4.402
N v λ1240	6703	160	4.405
Si II λ1262	6824	40	4.407
C IV λ1549	8375	180	4.406

TABLE 2

ABSORPTION LINES OBSERVED IN Q2203+29

Line	$\lambda_{\rm observed}$	W_λ (Å)	z
Lyα	6568	2	4.403
Lyα	6530	3	4.371
Lyα	6514	6	4.359
Lyα	6438	17	4.296
Lyα	5313	20	3.37
Lyα	5410	50	3.45

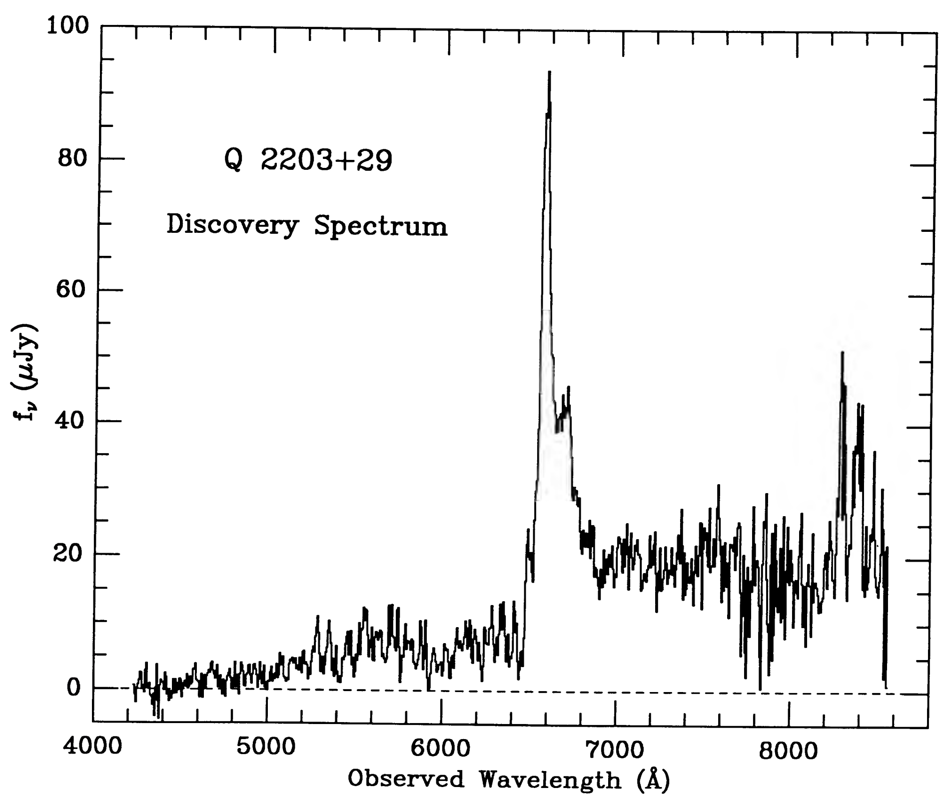

FIG. 1.—Discovery spectrum of Q2203+29, taken on 1987 September 25. The pixel size is 6 Å, and the mean resolution is 12 Å. The total integration time was 1.5 hr. Note the strong break in the continuum shortward of Lyα emission.

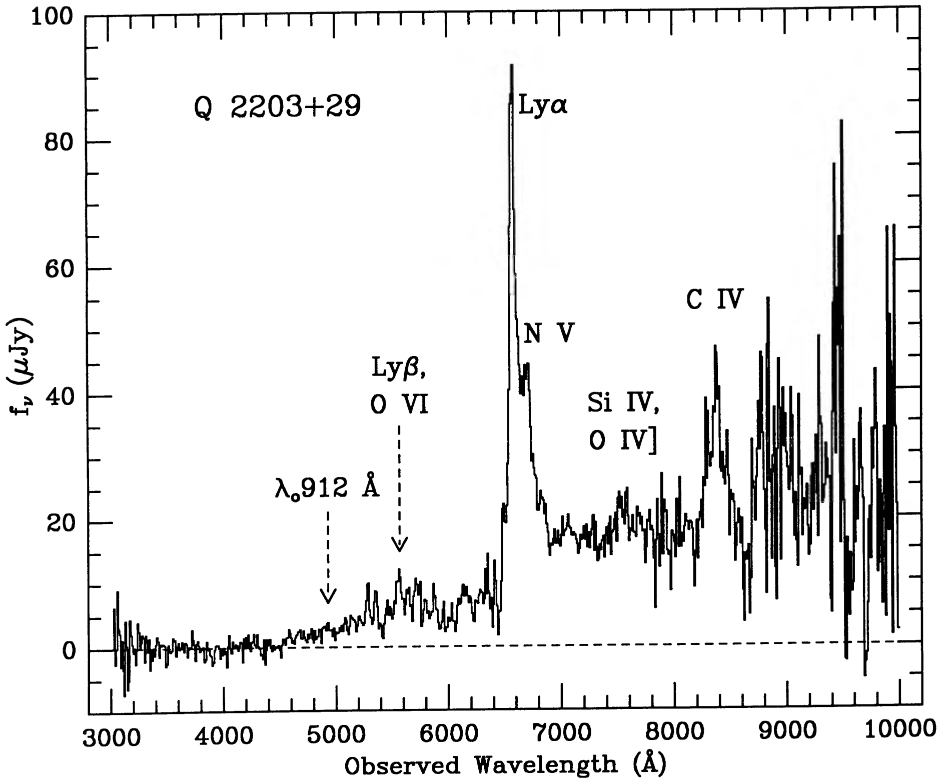

FIG. 2.—Average of all our spectra of Q2203+29. The individual spectra have been rebinned to 10 Å pixel^{-1} and co-added. The total integration time was roughly 2 hr in most portions of the spectrum, except near Lyα where it was ~4 hr. The atmospheric absorption bands have been removed through division by the normalized spectrum of a standard star.

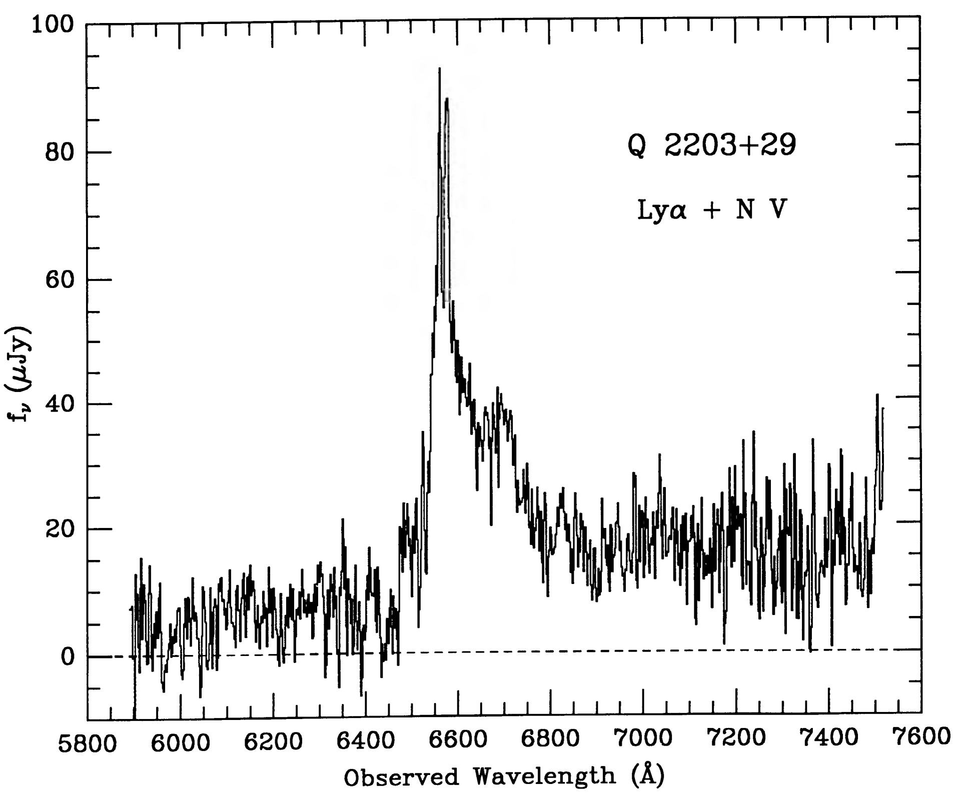

FIG. 3.—Moderate dispersion spectrum of the region around Lyα. The pixel size is 2 Å, and the resolution is 5 Å. Note the sharp cutoff in the blue wing of Lyα, the narrow absorption line at λ6560, and the deep absorption line at λ6430. The total integration time for this spectrum was 2 hr.

[O III] λ5007, Hβ, and [O II] λ3727 at a redshift of 0.202. The relative line strengths are typical for galaxies having bright H II regions. We therefore expect that the galaxy, whose projected separation from the line of sight to the QSO is $15h^{-1}$ kpc (where $h = H_0/[100 \text{ km s}^{-1} \text{ Mpc}^{-1}]$), may be capable of producing a metal-line absorption system (e.g., Cristiani 1987). Our spectra do not exhibit any features identifiable with the $z = 0.2$ system, Na D at $\lambda_{\text{obs}} = 7080$ Å being, in principle, the most easily observable line. Further high-resolution spectroscopy would be warranted to search for such features, as well as to perform the Gunn-Peterson test at a large redshift (e.g., Steidel and Sargent 1987).

b) Optical Images

The CCD spectrograph can also be used in a direct imaging mode by removing the dispersing element from the beam and opening the slit jaws. This gives a $2' \times 2'$ field of view with $0''.73 \times 0''.73$ pixels. Four broad-band r_S (Djorgovski 1985) images of 300 s duration were taken centered on the QSO. On 1987 September 25, after determining the redshift of the QSO from the Lyα and N V λ1240 emission lines at the telescope, we placed a rest wavelength Hα ($\lambda_c = 6563$; $\Delta\lambda = 70$ Å) interference filter in the beam to take images in the light of redshifted Lyα (e.g., Djorgovski *et al.* 1985). Two exposures were made with the interference filter, one of 1800 s duration and one of 1200 s duration. The separate images in each filter were shifted into registration and co-added. We removed the continuum from the Lyα image by subtracting a scaled version of the r_S image, after eliminating the sky from both. Observations of the twilight sky were used to remove sensitivity variations of the CCD for the Lyα images. The broad-band images were flattened using a dark-sky median technique. Observations of spectrophotometric standards from Stone (1977) were used to flux calibrate the images.

Figure 4 (Plate L1) shows our r_S image of the field around Q2203+29. The position of the QSO is marked, as are the adjacent disk galaxy ($z = 0.2$) and the dM star. The r_S magnitude of the QSO is 20.78 ± 0.09, fainter than the $z > 3.5$ QSOs recently discovered by radio, color, and objective prism techniques (Peterson *et al.* 1982; Hazard, McMahon, and Sargent 1986; Warren *et al.* 1987*a*, *b*), but comparable to the $z = 4.04$ QSO selected optically by Schmidt, Schneider, and Gunn (1987). The r_S filter contains the Lyα emission line; thus, our r_S magnitude does not measure the continuum alone. Applying synthetic V and I filters to the spectrum yields continuum magnitudes of $V = 22.0 \pm 0.3$ and $I = 21.1 \pm 0.3$ (atmospheric absorption bands not removed).

Our Lyα imaging observations failed to reveal any extended emission or companion objects down to a surface brightness level of 25.5 mag per square arcsecond.

Several prediscovery images of Q2203+29 exist, both in the literature and in private plate collections. The plate of 3C 441 in Longair and Gunn (1975) shows Q2203+29, as does the image-tube plate in Riley, Longair, and Gunn (1980). Three Lick 3 m plates taken by one of us (H. S.) in 1975 also clearly show the QSO. In all of these plates the relative brightness of the QSO, in comparison with other faint stellar objects in the field, is roughly the same as in our recent images. Direct quantitative comparisons between different plates are not very useful, since the brightness of the QSO relative to nearby stars greatly depends on the emulsion and filters used. Nonetheless, we can state with some confidence that the brightness of Q2203+29 has not varied strongly over the past 15 yr. This makes scenarios involving gravitational microlensing by individual stars, associated either with 3C 441 or the $z = 0.2$ galaxy, seem unlikely. Lensing directly due to the potential of the $z = 0.2$ galaxy might brighten the QSO somewhat. Following the formalism of Gott and Gunn (1974), we have estimated the expected amount of gravitational amplification, assuming the halo of the lensing galaxy to have a mass distribution $M(<r) \propto r$. The r_S magnitude of the galaxy is 18.3; we apply a K-correction of 0.12 appropriate to a Sb spiral at $z = 0.2$ from Coleman, Wu, and Weedman (1980) and use a canonical Sb color $(B-R) = 1.32$ to estimate a corrected photographic magnitude $m_{\text{pg}} \approx 19.5$. Using this, the luminosity distance to the galaxy determined from its redshift, and our mass model for the halo, we may calculate a mass for the galaxy using the Tully-Fisher relation (Tully and Fisher 1977): $M(<r) \approx 8.4 \times 10^{10} h^{-1.6}$ (r/10 kpc) $M_\odot$ (at 7″ from the QSO), nearly independent of the value of q_0. The lensing amplification is then derivable from Gott and Gunn's equations (1) and (5); we compute a brightening of 4% if $H_0 = 100$ km s^{-1} Mpc^{-1} and 30% if $H_0 = 50$ km s^{-1} Mpc^{-1}, again only weakly dependent on q_0. It should be noted that these values are rather strongly dependent on our mass estimate, particularly for small values of H_0.

From our direct images we have determined the offset to Q2203+29 from star B of Riley, Longair, and Gunn (1980) and from star C of Longair and Gunn (1975). With these, and the pixel size of $0''.731$, we derive the following (1950) position for the QSO:

$$\alpha = 22^{\text{h}}03^{\text{m}}47^{\text{s}}.03 \pm 0^{\text{s}}.07 \; ; \quad \delta = +29°15'23''.9 \pm 1'' .$$

c) Radio Images

Radio frequency observations of 3C 441 were made with the VLA (Thompson *et al.* 1980) on 1987 July 19; the array was in its most extended (A) configuration. The source was observed twice, for a total integration time of 2400 s. The observed wavelength was 20 cm, while the bandwidth used was 50 MHz. The pointing center was close to the parent galaxy of 3C 441. Further details of the radio (and optical) observations of 3C 441 will be given in P. J. McCarthy *et al.* (in preparation).

CLEANed maps of 3C 441 and the area around Q2203+29 were made to search for faint radio emission associated with the QSO. No emission was seen at the location of the QSO, at a level of 0.9 mJy (3 σ upper limit). At 51″ from the pointing center, any point source at the QSO's position would have been observed with ~50% loss of peak intensity due to bandwidth smearing. Thus, the effective upper limit to such radio emission would be ~1.8 mJy. Corrections due to primary beam attenuation are negligible.

III. DISCUSSION

As stated above, the QSO was discovered serendipitously during long-slit observations of an unrelated object. This is the first serendipitously discovered QSO of *any* redshift during 5 yr of long-slit CCD spectroscopy of faint radio sources at Kitt Peak and Lick Observatories by Spinrad and collaborators. A total of 268 long-slit spectra with exposures greater than 1800 s (most were $\gtrsim$3000 s) have been obtained at high galactic latitudes between 1983 and the present. These observations typically result in continuum detections down to $R \approx 22$ with a signal-to-noise ratio of ~2–3. Our ability to recognize a QSO (or any other emission-line object) is, of course, more strongly dependent on the line strength than on the continuum magni-

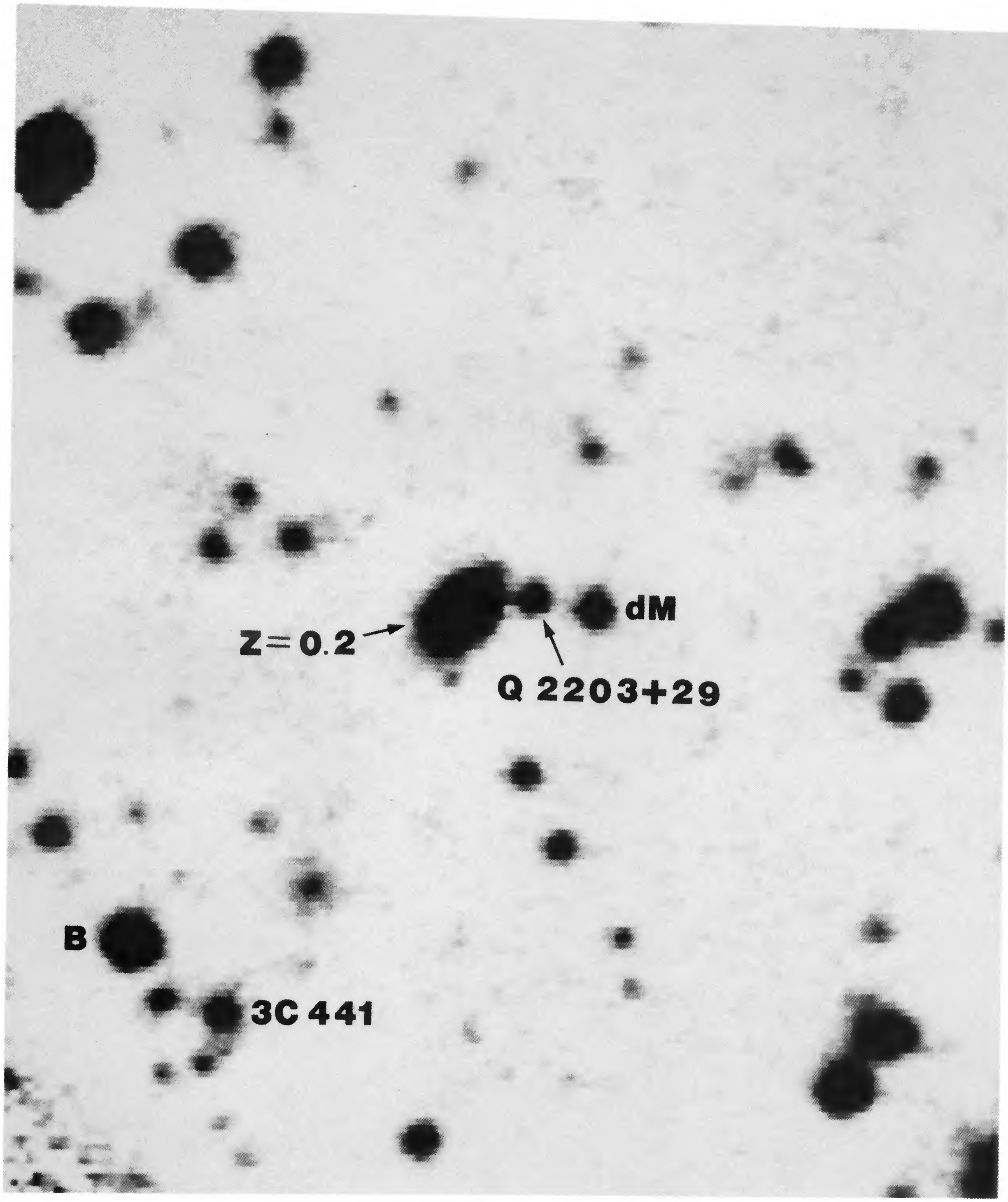

FIG. 4.—A stack of four r_S broad-band CCD images of the field containing Q2203+29. The image is 88″ × 88″, and the pixel size is 0″.731. Star B from Riley, Longair, and Gunn (1980) is marked, as are 3C 441, the $z = 0.2$ spiral galaxy, and the foreground dM star. The derived position of the QSO is $\alpha(1950) = 22^h03^m47^s.03 \pm 0^s.07$, $\delta(1950) = +29°15'23''.9 \pm 1''$. The total integration time was 1200 s.

tude. The average slit size was 2″ × 3′. Thus, we have randomly sampled ~0.012 square degrees of the sky. A breakdown of the observations in terms of instruments and gratings/grisms employed is given in McCarthy and Dickinson (1988). Based on the recent unbiased luminosity function of QSOs by Koo and Kron (1988), we would expect to find one QSO during these observations, as indeed we did. The fact that the single QSO we have found is at the extreme end of the redshift distribution is baffling.

There is, of course, some bias in the ease of recognition at QSO redshifts $\gtrsim 2$, since Lyα and C IV λ1549 then become observable from the ground. The APM multicolor survey of Warren *et al.* (1987*b*) resulted in the discovery of three QSOs with $z > 4$ in 30 square degrees surveyed to $R = 20.0$. From this we conclude that the probability of finding a $z > 4$ QSO in 0.012 square degrees of randomly selected sky (to $R \approx 22$) is a few times 10^{-3}, assuming that the surface density of $z > 4$ QSOs does not increase strongly from $R = 20$ to $R = 22$.

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