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A NEW WIDE-SEPARATION GRAVITATIONAL LENS CANDIDATE[1]

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ABSTRACT

We present observational evidence for the existence of a new wide-separation (5″.14), high-redshift ($z = 2.076$), gravitationally lensed quasar Q1429−008. The discovery of the system represents the first bona fide gravitationally lensed quasar to be detected in the automated optical survey described by Webster *et al.* The Q1429−008 system comprises two components, *R*-band magnitudes $m_R = 17.7$ and 20.8. The spectra of the two components are very similar although small systematic differences in the emission-line strengths are probably present. The velocity difference between the two spectra, derived from cross-correlation techniques, is $\Delta V = 260 \pm 300$ km s^{-1}. The observational data are consistent with a deflector of cluster mass and dimensions, at a redshift $z \sim 1.5$, but such an observer-deflector-source geometry is unlikely *a priori*. If the deflector is at the "most likely" redshift, $z \sim 0.6$, then the lower limit to the deflector mass-to-light ratio is extremely high.

Subject headings: gravitational lenses — quasars

I. INTRODUCTION

We are undertaking an optical survey for gravitationally lensed quasars of what is the largest and most complete sample of bright quasars selected without any reference to their morphological appearance. The Large Bright Quasar Survey (LBQS) which provides the basis for the gravitational lens survey comprises 1000 quasars, redshifts, $0.2 < z < 3.3$, magnitudes, $16.0 < m_{B_J} < 18.8$, with a surface density of ~ 2 per square degree. The probability of inclusion of a quasar in the sample is known precisely as a function of the apparent magnitude, redshift, and quasar spectral energy distribution. A more detailed description of the LBQS can be found in Foltz *et al.* (1987, 1989).

The techniques employed in the search for gravitational lenses are described in Webster, Hewett, and Irwin (1988) with additional refinements to the search procedures noted in Webster *et al.* (1988). All images with quasar-like spectra irrespective of their morphological appearance are included in the LBQS. Consequently, close quasar-galaxy projections (Webster *et al.* 1988) and multiply imaged quasars can be detected. The Webster *et al.* survey contrasts with the majority of optical searches for gravitationally lensed quasars which employ heterogeneous quasar samples. Surveys involving imaging studies of the very brightest quasars, where the amplification bias should be most apparent, have begun to produce a number of positive detections (e.g., Surdej *et al.* 1987). However, it is difficult to interpret the results of these surveys statistically, and hence to derive parameters such as the space density of the lensing population.

In this *Letter*, we describe observations of the first bona fide gravitational lens candidate from the Webster *et al.* survey—Q1429−008.

II. OBSERVATIONAL RESULTS

The primary image of Q1429−008 was identified as a redshift $z = 2.076$ quasar at the Multiple Mirror Telescope (MMT) on the night of 1988 March 14. An MMT spectrum of the secondary image, which is clearly visible on the UK Schmidt Telescope B_J survey plate, was obtained on the night of 1988 March 18, with further data being acquired on 1988 May 10. Figure 1 shows the spectra of both primary (480 s) and secondary (4200 s) components. The spectra were obtained using the MMT spectrograph coupled to an intensified photon-counting Reticon detector, giving a spectral coverage of $3200 \lesssim \lambda \lesssim 7400$ Å and a resolution of ~ 6 Å. Exposures of He-Ar, Ne, and Hg-Cd emission-line sources were obtained before and after the exposures. The resulting wavelength calibrations have systematic shifts of <2 Å—deduced from the wavelengths of night-sky lines—and rms residuals of ~ 2 Å—from fits to the emission-line comparison spectra. Sensitivity variations with high spatial frequencies were removed through suitably normalized exposures of a quartz-halogen incandescent (flat-field) source. Observations of standard stars were obtained to allow relative flux calibrations of the objects to a precision of $\sim 15\%$, although absolute spectrophotometry was not attempted.

The primary spectrum is that of a "classical" strong-lined quasar with Lyman-α/N V (1216–1240 Å), Si IV–O IV (1400 Å), C IV (1549 Å), and C III] (1909 Å) visible. The rest-frame equivalent widths of the features are 112 ± 20 Å, 12 ± 3 Å, 35 ± 6 Å, and 29 ± 7 Å, respectively. The redshift of the primary, taken from the C IV emission-line centroid, is $z = 2.076 \pm 0.002$. A cross-correlation of the primary and secondary spectra ($3600 \le \lambda \le 5500$ Å) gives a velocity shift of $+260 \pm 300$ km s^{-1}, for the velocity of the secondary relative to the primary; thus the redshifts are identical within the limitations imposed by noise. The cross-correlation was carried out using the SCROSS routine in the STARLINK FIGARO spectral reduction package. A bin size of 250 km s^{-1} was employed,

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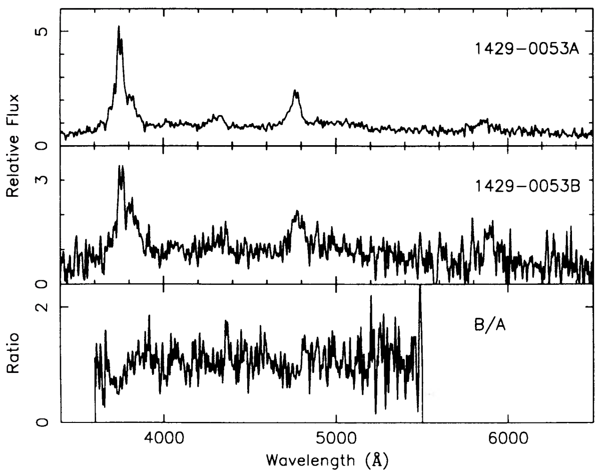

FIG. 1.—Blue spectra of the A and B components of Q1429−008. Relative flux per unit wavelength is plotted against wavelength in angstroms. Each pixel is 2.5 Å, and the spectra have been smoothed using a Gaussian filter with a dispersion of 1 pixel: *top*, spectrum of component A; *middle*, spectrum of component B; *bottom*, division of spectrum B by spectrum A for a restricted wavelength range where the signal-to-noise ratio is adequate.

and the result is not sensitive to the exact wavelength range used but extending the long-wavelength limit beyond 5500 Å, where the signal-to-noise ratio of the spectra drops considerably, produces a much noisier cross-correlation—in practice, the cross-correlation is dominated by the Lyman-α, S IV, and C IV emission lines. The secondary spectrum is extremely similar to that of the primary, both in overall shape and in the appearance and strength of the emission lines. The result of the division of the secondary spectrum by that of the primary is also shown in Figure 1. Small but probably significant differences between the spectra are evident in the wavelength ranges corresponding to the location of the Lyman-α/N V and C IV emission features. These differences could be due to (*a*) different line to continuum ratios in the two spectra, (*b*) actual line profile differences between the two spectra, or (*c*) a combination of both effects. A red spectrum of the primary was obtained with the Faint Object Spectrograph at the William Herschel Telescope on the night of 1988 April 15. In addition to strong Mg II emission from the quasar, two intervening Mg II absorption systems with redshifts $z = 1.55$ and $z = 1.62$ are clearly visible.

Direct imaging of Q1429−008 was undertaken with the Canada-France-Hawaii Telescope (CFHT) on the night of 1988 May 22. Three 360 s exposures using the double-density 640 × 1024 pixel RCA2 chip and an *R* filter were obtained. The RCA2 pixel size is 15 μm giving 0".206 per pixel at the prime focus of the CFHT; the seeing was ∼0".9 FWHM. Calibration frames of a comparison field in M92 (Christian *et al.* 1987) were also obtained. Standard reduction procedures were applied and the reduced frames were co-added to produce a master frame—Figure 2 (Plate L10). Magnitudes in the Cousins *R* system of $m_R = 17.74 \pm 0.05$ and $m_R = 20.77 \pm 0.10$ for the primary and secondary respectively were derived using routines in DAOPHOT (Stetson 1987). The equinox 1950.0 position of the primary is $14^h29^m54^s.5$, $-00°53'04''$. The separation of the two images is 5".14 ± 0".10 and the position angle of the secondary image is 306° ± 5° measured north through east.

No additional images are visible between the primary and secondary images to an *R* magnitude $m_R \sim 24.5$. The image closest to the quasars is an $m_R \sim 23$ nonstellar image north-west of the secondary—image "g" in Figure 2. A number of additional faint stellar and nonstellar images are evident at larger distances, but there is no evidence of a significant excess of galaxies. In addition, a VLA image of the field was taken at 2 cm on 1988 May 8; Q1429−008 was not detected to a flux limit of 0.3 mJy.

III. GRAVITATIONAL LENSING MODEL

Two quasar images with similar spectra and relatively small angular and line-of-sight separations might be either a binary quasar (Djorgovski *et al.* 1987) or multiple images of a single quasar. Determination of the character of Q1429−008, which is radio-quiet, relies on either the detection of additional quasar images, detection of the lensing mass, measurement of a time delay between the two images, or establishing there is a significant velocity difference between the two images. None of these data are available, and both explanations are possible; however, for the remainder of the *Letter* we consider the identification of Q1429−008 as a gravitational lens.

If the mass distribution of the lensing object is not singular on the scale of the source, then an odd number of images of the source are created (Burke 1981). For smooth isothermal mass distributions it is possible to determine the relative probabilities of various image configurations. If the surface mass distribution in the lens is nearly circular, then three-image geometries are most probable, whereas an elliptical surface mass distribution will more probably result in five-image geometries (Blandford and Kochanek 1987).

Only two images are observed; for Q1429−008 to have a five-image geometry, either three images have magnitudes $m_R > 24.5$, or image A is triple and the quasar is located very close to a cusp in the caustic line in the source plane. Both these configurations have low probabilities for a lens with a smooth mass distribution.

For the more probable three-image geometry, the images are opposed or allied (in the terminology of Blandford and Kochanek). One can show that for an opposed configuration, the large brightness ratio of the images means the mass distribution must be more centrally concentrated than isothermal and the core radius small, ≲0".5. In an allied configuration, image A is double and the core radius is much larger; the central surface density of the lensing mass is likely to be close to critical, and an isothermal mass distribution is allowed.

Using the observed parameters of the Q1429−008 system, it is possible to determine the gross parameters of the lensing mass as a function of redshift (Webster 1985). If the mass distribution of the lens is approximately symmetric about the quasar images, then, by Birkoff's theorem, a point mass provides a good estimate of the mass in the circular cone defined by the images. Figure 3 shows (1) the lens mass, (2) the lens *R*-band mass-to-light ratio, and (3) the diameter of the enclosed cone, as a function of the lens redshift. Calculations have been made for three cosmological models: (*a*) $\Omega = 0$, (*b*) $\Omega = 1$ smooth mass distribution, and (*c*) $\Omega = 1$ clumpy mass distribution. The most likely redshift for a lensing mass for a quasar at $z \sim 2$ is indicated, as are the redshifts of the two Mg II absorption systems seen in the image A spectrum. The magnitude limit for the detection of galaxies in the CCD image is a function of redshift because of the $(1 + z)^4$ dependence of the surface brightness. Total magnitudes were calculated for objects with an area of >0.16 arcsec^2 above the detection threshold of ∼24.4 mag arcsec^{-2}. The faintest objects detected have *R* magnitudes of $m_R = 24.5$; however, for certain galaxy

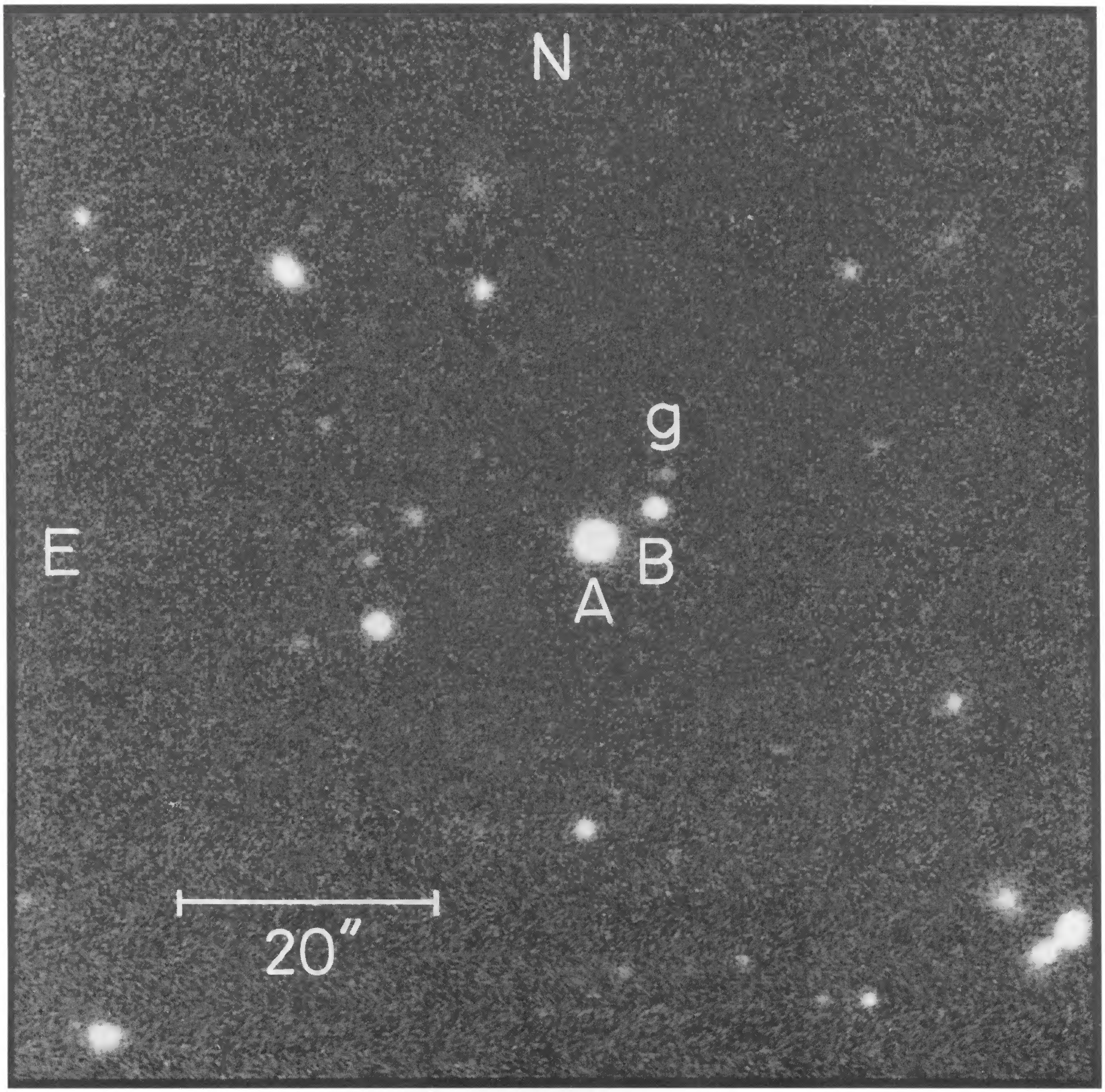

FIG. 2.—*R* band CCD frame of the field containing Q1429 − 008. North is up, and east to the left of the frame.

HEWETT *et al.* (*see* **346**, L62)

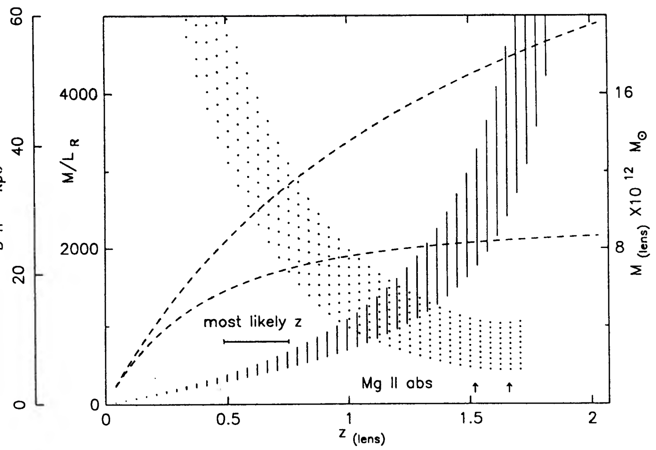

FIG. 3.—The deflector characteristics as a function of the redshift of the deflector; mass-to-light ratio in the R band (*dotted region*), the diameter between the two quasar images (bounded by the two dashed lines), and the point mass (*hatched region*) required to give the observed separation of the two quasar images. Also shown are the most likely redshift for the lensing mass and the redshifts of the two Mg II absorption systems seen in the spectrum of the primary image. The range in the parameters reflect the differences due to the three different cosmological models described in the text.

luminosity profiles and redshifts $z > 1$, objects as bright as $m_R \sim 23$ may remain undetected. The results shown in Figure 3 employ a nonevolving elliptical galaxy spectral energy distribution with a limiting magnitude of for detection of $m_R = 24$ and k-corrections derived from Pence (1976) and Bruzual and Spinrad (1980). For spiral spectral energy distributions, the k-corrections are smaller and the mass-to-light ratios higher. If galaxies were brighter in the past, then the universal value of mass-to-light decreases with increasing redshift. This evolution in luminosity offsets the effect of the k-correction and mass-to-light ratios are effectively higher.

IV. DISCUSSION

Q1429−008 is another wide-separation gravitational lens candidate similar to three previously published lens candidates: Q1120+019 (Meylan and Djorgovski 1989), Q1635+267 (Djorgovski and Spinrad 1984), and Q2345+007 (Weedman *et al.* 1982). In all four cases no potential luminous deflector has been detected, and quantitatively similar limits to the deflector mass and mass-to-light ratio, as a function of redshift, can be obtained. Galaxy clusters with mass and mass-to-light ratios consistent with those derived from virial arguments are capable of producing the observed image configurations, and they can remain "hidden" providing they are at high-$z \gtrsim 1.5$ redshifts. However, for isothermal masses with constant comoving space density, the probability that the deflector is located at redshift $> z$ is $P(z) = \int_{z_s}^{z} p\,dz / \int_0^{z_s} dz$, where p is the probability that a source at redshift z_s is lensed by a mass at redshift z (Turner, Ostriker, and Gott 1984). For the four wide-separation sources listed above the probabilities $P(z) \gtrsim 1.5$ are 0.22 (Q1120+019), 0.10 (Q1429−008), 0.08 (Q1635+267), and 0.12 (Q2345+007). If Q1429−008 is a gravitational lens, there is a low probability that, taken together with the other wide-separation lens candidates, all four are the result of lensing by high-redshift clusters. If these four candidates are representative, and the fraction of wide-separation candidate lenses without identified deflectors remains high, this suggests that relatively nearby objects with very large mass-to-light ratios may exist.

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