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UM 425: A NEW GRAVITATIONAL LENS CANDIDATE[1]

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ABSTRACT

We report the discovery of a probable new gravitational lens, associated with the quasar UM 425 = QSO 1120+019. This object was specifically selected in an optical imaging survey for gravitational lenses because of its relatively high redshift and apparently high luminosity. Multicolor (*BVR*) images were obtained with a charge-coupled device (CCD) at the Cerro Tololo Interamerican Observatory (CTIO) 60 inch (1.5 m) telescope in 1987 March, showing three close companions around the bright image of the quasar. The follow-up spectroscopy in marginal weather conditions, with the Mount Palomar 200 inch (5 m) and Las Campanas 100 inch (2.5 m) telescopes (in 1988 March and April), suggested that the brightest companion has the same emission lines as the quasar. Additional spectra and additional imaging were obtained with the European Southern Observatory (ESO) 3.6 m telescope at La Silla, in 1988 May. UM 425 and its brightest companion (which we denote as components A and B) have similar *BVR* colors. Spectra of both objects, in the range 3600–8000 Å, with resolution of about 7 Å pixel^{-1}, show the same emission lines, i.e., C IV 1549, C III] 1909, and Mg II 2799, with the same redshift $z = 1.465 \pm 0.005$. The spectra are also similar in shape and in some details, including, possibly some associated absorption in the Mg II 2799 and C IV 1549 lines. The velocity difference between the two brightest components from the cross-correlation technique is $\Delta V_{\rm A-B} = 200 \pm 100$ km s^{-1} and is consistent with zero. Subtracting a scaled spectrum of the brighter component (A) from that of the brightest companion (B), leaves a residual which may be interpreted as the spectrum of a lensing galaxy at $z \simeq 0.6$. Whereas we cannot exclude the possibility that we are seeing a pair of physically distinct AGNs, the overall data are in favor of the gravitational lens hypothesis.

Subject headings: gravitational lenses — quasars

I. INTRODUCTION

Gravitational lensing is now one of the most active fields of research in extragalactic astronomy. There are numerous theoretical investigations, but the observations of good gravitational lens candidates are still rare. Comprehensive recent reviews are given, e.g., by Burke (1986), Narayan (1986), Canizares (1987), and Blandford and Kochanek (1987).

We are conducting an optical imaging survey for lensed quasars (Djorgovski and Meylan 1989*a*, *b*), which has so far produced one probable binary quasar, PSK 1145−071 (Djorgovski *et al.* 1987), and several lens candidates. We report here initial results on a probable gravitational lens system, the quasar UM 425 = QSO 1120+019 (MacAlpine and Williams 1981). The preliminary report was given by Meylan and Djorgovski (1989) and Djorgovski and Meylan (1989*b*). The object was selected as a potential lens candidate on the basis of two criteria: a large apparent optical luminosity ($M_V \leq -28$), and a relatively large redshift ($z > 1$). These simple criteria, chosen to reflect possible gravitational magnification bias (apparent luminosity) and to provide a large intercept length (redshift), increase the *a priori* probability that a quasar selected from a magnitude-limited sample is lensed. A similar survey is being conducted independently by Surdej *et al.* (1988). The efficiency of our lens candidate selection criteria is demonstrated by the present case, by the two cases published by the Liège group (Surdej *et al.* 1987; Magain *et al.* 1988), and by a few other lens candidates from our survey which are still awaiting confirmation. We will describe our survey (over 250 quasars so far), and discuss UM 425 in greater detail in future papers.

II. OBSERVATIONS AND RESULTS

Our first CCD imaging observations of UM 425 were obtained with the CTIO 1.5 m telescope, on the night UT 1987 March 2, using a Texas Instruments 800 × 800 CCD in a 2-by-2 binning mode. The effective pixel size was 0″.552. The conditions were photometric with a seeing FWHM ≃ 1″.7. Exposures of 600 s in *V* and 500 s in *R* were obtained, with an additional 100 s *B* exposure on UT 1987 March 5. The images were processed using standard techniques. Figure 1 (Plate L1) shows the digital stack of the *V* and *R* frames: three close faint companions (labeled B, C, and D, in decreasing luminosity) encircle the bright image of the quasar (A). Our preliminary photometry indicated that the companions B and C have similar or identical colors to the brightest image, A. There is a large number of $V \sim 22$ mag galaxies in the field, suggesting a rich foreground ($z \sim 0.6$?) cluster. Thus, the initial optical imaging data were suggestive of gravitational lensing.

Because of the promising character of these images, radio snapshots were kindly taken by Dr. R. Perley with the Very

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[1] Based on observations collected at the European Southern Observatory, Cerro Tololo Interamerican Observatory, Las Campanas Observatory, and Palomar Observatory.

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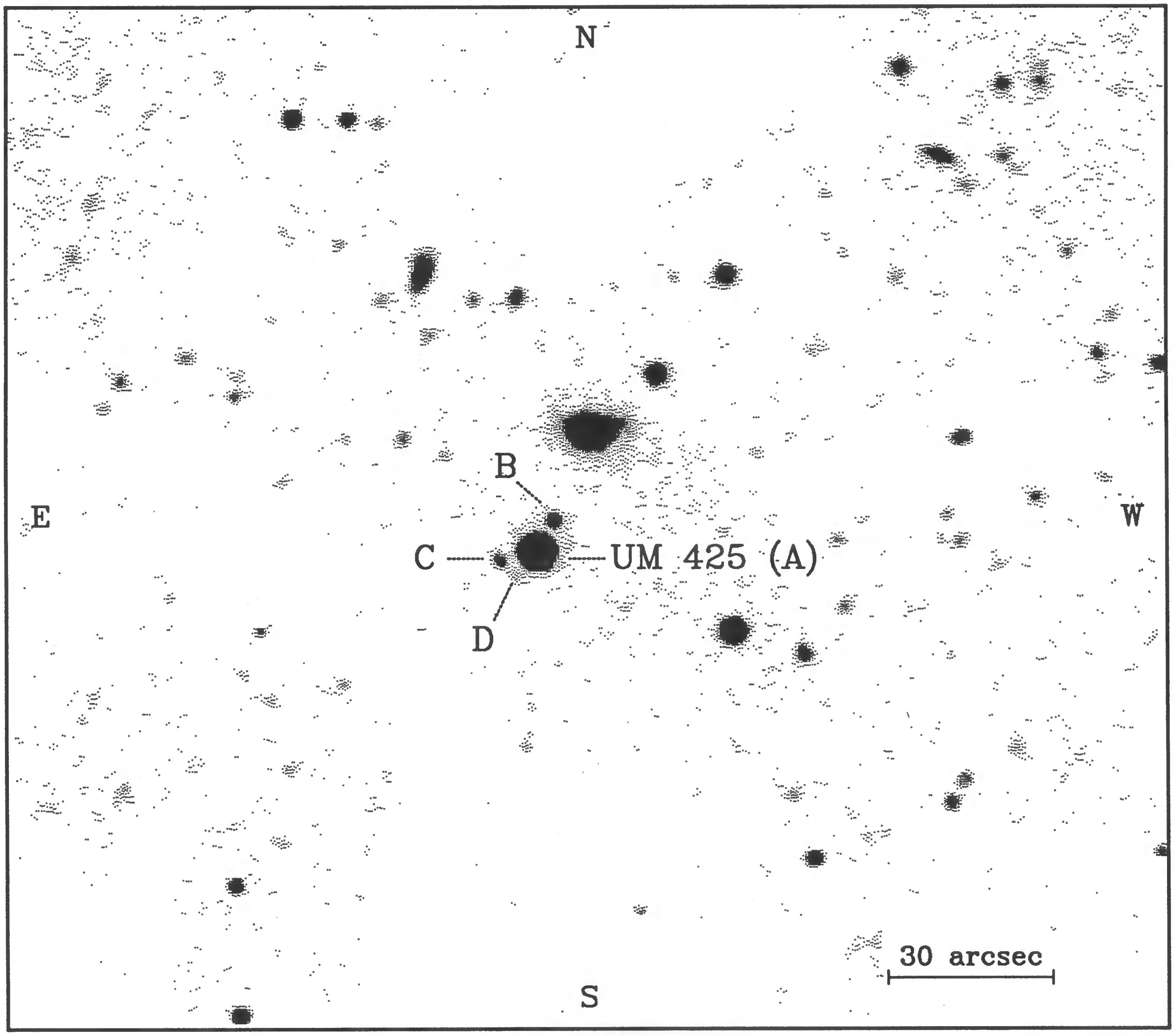

FIG. 1.—Central part of an image of the quasar UM 425 (digital stack of V and R frames) obtained with a charge-coupled device (CCD) and the Cerro Tololo Interamerican Observatory (CTIO) 1.5 m telescope, on UT 1987 March 2. The high-luminosity quasar is resolved into at least four images. Two quasi-stellar images, the main component A and its brightest companion B, separated by 6".5, have $V = 16.2$ mag and $V = 20.8$ mag, respectively. The C component ($V = 21.8$ mag) and the even fainter D component are similar to the numerous nonstellar objects in the field, suggestive of a rich foreground ($z \simeq 0.6$?) cluster of galaxies.

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Large Array (VLA) in 1987 September. The system was not detected at 20 cm and 6 cm, with the 2 σ limits of 0.35 mJy per beam and 0.23 mJy per beam, respectively.

The follow-up spectroscopy, in marginal weather conditions, with the Mount Palomar 200 inch telescope, on the night UT 1988 March 8, and with the Las Campanas 100 inch telescope, on the night UT 1988 April 7, indicated inconclusively possible similar emission lines in spectra of components A and B, and possibly also C.

The conclusive observations were obtained with the ESO Faint Object and Spectrograph Camera (EFOSC) at the ESO 3.6 m telescope, on the three nights UT 1988 May 15, 16, and 17, using a RCA 640 × 1024 CCD (ESO No. 11). In the 2-by-2 binned mode, the effective pixel size was $0''.675$. The weather conditions were nonphotometric with a mean value of the seeing FWHM $\simeq 1''.4$. Several direct imaging exposures were obtained, with 60 s integration with the B filter (ESO No. 552), 45 s with the V (ESO No. 553), and 30 s in the R (ESO No. 554). The data were processed and added using standard techniques. These good-seeing images suggest that the component C is somewhat diffuse (nonstellar) in appearance.

The separation between the quasar image A and its brightest companion B is

$$\Delta\alpha_{\rm A-B} = +3''.1 \pm 0''.1\ , \quad \Delta\delta_{\rm A-B} = -5''.7 \pm 0''.1\ ,$$

which corresponds to a separation of $6''.5$ in the direction PA = −29°. The separation between the images A and C is

$$\Delta\alpha_{\rm A-C} = -6''.6 \pm 0''.1\ , \quad \Delta\delta_{\rm A-C} = +1''.8 \pm 0''.1\ ,$$

which corresponds to a separation of $6''.8$ in the direction PA = +105°.

The spectrophotometric magnitudes of the QSO (A), 16.5 B mag, 16.2 V mag, and 15.7 R mag, are uncertain by a couple of tenths of a magnitude, because of the poorly determined zero point, which also plagues our direct imaging. The spectrophotometric colors are much better determined, since the zero-point uncertainties cancel: we obtain $(B-V)_{\rm A} = 0.33$, and $(V-R)_{\rm A} = 0.49$, with the uncertainty of a couple of percent. However, differences between magnitudes in a given bandpass can be accurately determined from our direct imaging. We obtained a relative photometry of the components A, B, and C by using the point-spread function fitting program for stellar photometry DAOPHOT (Stetson 1987) (its PEAK and NSTAR routines). For the components A and B, we obtain

$$\Delta B_{\rm A-B} = -4.68 \pm 0.15\ , \quad \Delta V_{\rm A-B} = -4.61 \pm 0.08\ ,$$
$$\Delta R_{\rm A-B} = -4.42 \pm 0.12\ ,$$

giving 21.2 B mag, 20.8 V mag, and 20.1 R mag for the component B. Using the spectrophotometric colors of the image A as the zero-point, we derive $(B-V)_{\rm B} = 0.40$, and $(V-R)_{\rm B} = 0.68$. The colors of the component B derived from our spectrophotometry are $(B-V)_{\rm B} = 0.36$, and $(V-R)_{\rm B} = 0.67$, uncertain by a few percent, and thus in an excellent agreement. For the components A and C, the differences in magnitudes are

$$\Delta B_{\rm A-C} = -6.05 \pm 0.25\ , \quad \Delta V_{\rm A-C} = -5.56 \pm 0.15\ ,$$
$$\Delta R_{\rm A-C} = -5.77 \pm 0.15\ .$$

giving 22.5 B mag, 21.8 V mag, and 21.5 R mag, with $(B-V)_{\rm C} = 0.8$, and $(V-R)_{\rm C} = 0.3$. These colors have uncertainties of about 0.3 mag.

The component D, possibly nonstellar in appearance, is too faint and too close to the bright image A to obtain any reliable measurements, or even to estimate how much brighter it is than our magnitude limits. Nevertheless, it is clearly detected in all of our CCD images, both at ESO and CTIO. Field stars do not show ghost images or reflections which could correspond to this object, and we conclude that it is real. It is about $4''$–$5''$ away in the direction PA $\simeq$ +150°.

Given the measurement errors, these results are consistent with constant colors of the three components, but with two hints: (1) B may be slightly redder than A, perhaps by the presence of an underlying (lensing?) galaxy; (2) C may be redder than A in $(B-V)$, but bluer in $(V-R)$, and in view of its apparently nonstellar appearance, it could be (as well as the component D) a member of a faint foreground cluster of galaxies.

During the same three nights of 1988 May, the spectra of the components A and B were obtained with the B300 and R300 grisms of EFOSC. The final usable range in wavelength runs from 3600 to 8000 Å, with a resolution of ~7 Å pixel^{-1}. The data confirmed immediately that both objects A and B have quasar spectra, with the same emission lines at apparently the same redshift. The resulting spectra for components A and B are displayed in Figure 2. These two spectra are the result of seven exposures of 1800 s in each of the B300 and R300 grisms, giving a total of 14 exposures, or 7 hr of integration. The usual strong emission lines are present in both spectra, i.e., C IV 1549, C III] 1909, and Mg II 2799. The spectra are very similar in the overall shape, except that the spectrum of B is slightly redder (see below).

The equivalent widths of the emission lines are comparable, and probably equal within the error-bars: W_λ(C III] 1909) = 63 ± 1 Å, for the component A, and 69 ± 7 Å, for the component B; W_λ(Mg II 2799) = 74 ± 3 Å, for the component A, and 71 ± 9 Å, for the component B (imperfect removal of the atmospheric absorption is responsible for the larger errors in this line). The rest-frame velocity widths (FWHM) of the C III] 1909 are 6800 ± 200 km s^{-1} (component A), and 8000 ± 1300 km s^{-1} (component B). There may be some associated absorption present in both objects. There is an asymmetry or an absorption in the blue wing of the Mg II 2799 line, but it is confused by the atmospheric B band, which we can remove only partly. The blue wing of the C IV 1549 line also appears self-absorbed, but our signal at that wavelength is insufficient to say more about it.

The determination of the redshifts of both objects is complicated by the presence of possible associated absorption features. Consequently, the redshift of the quasar (A) has been obtained by using only the C III] line, the only "clean" emission line in our spectra: $z_{\rm A,1909} = 1.465 \pm 0.005$. From the C IV line, we obtain $z_{\rm A,1549} = 1.469$, and from the Mg II line, $z_{\rm A,2799} = 1.476$. If $z = 1.465$ is considered as the best value of the redshift, the peak of the C IV line should be at 3818 Å instead of 3824 Å, and the peak of the Mg II line should be at 6900 Å instead of 6938 Å, possibly reflecting the presence of an associated absorption in the two permitted lines.

We looked for a possible difference in redshift between the two spectra (A and B), using the cross-correlation technique (Djorgovski and Spinrad 1984; Huchra 1986). The different measurements were done by varying the limits of the wavelength range used (from ~4000 to ~7100 Å), containing different emission lines, and using different binning in wavelength. For example, for the essentially whole wavelength range, 4000–7100 Å, we obtain the mean difference $\Delta z_{\rm A-B} = (1.3 \pm 0.7)$

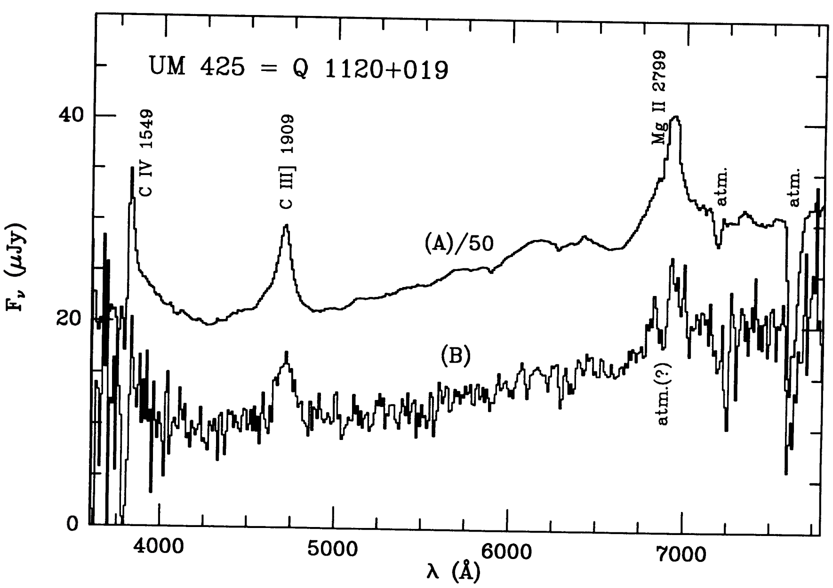

FIG. 2.—Spectra of the quasar UM 425 (A and B), obtained with the Faint Object and Spectrograph Camera (EFOSC) at the European Southern Observatory (ESO) 3.6 m telescope, on the three nights UT 1988 May 15, 16, and 17. Because of the large difference in luminosity between the two components, the spectrum of A is divided by a factor of 50 for display purposes. The spectra are similar in shape and show the same emission lines (C IV 1549, C III] 1909, and Mg II 2799) at the same redshift. There may be some associated absorption present in the Mg II 2799 line (confused by the atmospheric B band), and probably also in the C IV 1549 line of both objects.

$\times 10^{-3}$, corresponding to the rest-frame velocity difference $\Delta v^{\rm rf}_{\rm A-B} = 160 \pm 90$ km s^{-1}; for the wavelength range 3900–6000 Å, excluding the Mg II line, we obtain the mean difference $\Delta z_{\rm A-B} = (1.9 \pm 1.0) \times 10^{-3}$, corresponding to the rest-frame velocity difference $\Delta v^{\rm rf}_{\rm A-B} = 240 \pm 130$ km s^{-1}; and for the wavelength range 4300 – 5100 Å, dominated by the C III] line, we obtain the mean difference $\Delta z_{\rm A-B} = (1.4 \pm 0.9) \times 10^{-3}$, corresponding to the rest-frame velocity difference $\Delta v^{\rm rf}_{\rm A-B} = 170 \pm 110$ km s^{-1}. As a grand average, we adopt $\Delta v^{\rm rf}_{\rm A-B} = 200 \pm 100$ km s^{-1}. A cruder measurement can be obtained from the centering of the peak of the C III] 1909 line: we obtain $\Delta z_{\rm A-B} = (2.3 \pm 2.0) \times 10^{-3}$, corresponding to the rest-frame velocity difference $\Delta v^{\rm rf}_{\rm A-B} = 280 \pm 250$ km s^{-1}, consistent with the cross-correlation measurements. These very preliminary measurements are then consistent with a zero velocity difference between the components A and B, at about 1.5 σ level. Additional data are needed in order to improve on this measurement.

III. DISCUSSION

The spectroscopic measurements described above (redshifts, line parameters, etc.) show marginal differences between the spectra of the components A and B, and are consistent with the hypothesis that the spectra are essentially identical, and with no velocity offset. If the two objects were physically distinct quasars, their luminosities would be different by a factor of ~100, and one would expect to see some difference in the equivalent widths of the emission lines on account of the Baldwin effect, perhaps as much as a factor of 2 (cf. Kinney 1987, and refereces therein). Yet, the equivalent widths do not differ more than 10%–20% (we are indebted to Dr. Bohdan Paczyński for pointing this out).

The spectra of A and B are also very similar in shape. The result of the division of the two spectra (B/A) is fairly constant in the blue part (3600–6400 Å), and a slight but significant increase in the red part (6400–8000 Å), which is equivalent to the slight difference in color, noted above. It is possible to consider the apparent reddening of the component B as a contribution from a foreground galaxy, which could be a part of the gravitational lens itself. We divided the spectrum of the component A by 100 (very close to the flux ratio from the division), and subtracted it from the spectrum of the component B. The resulting spectrum, shown in Figure 3, is suggestive of an early-type galaxy spectrum at a redshift $z \sim 0.6$, if the continuum rise is attributed to the 4000 Å break (see Surdej *et al.* 1987, or Turner *et al.* 1988, for similar investigations). The

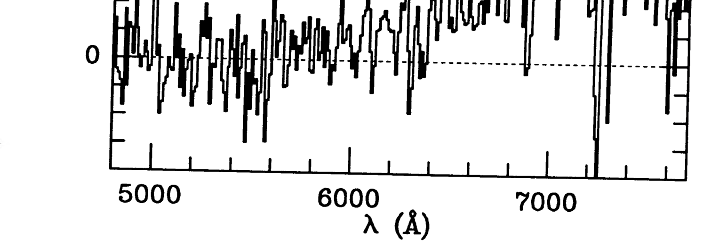

FIG. 3.—Residual spectrum obtaind after dividing the spectrum of the component A by 100 and subtracting it from the spectrum of the component B. Each original spectrum corresponds to 3.5 hr of integration time in each grism. The residual spectrum difference is reminiscent of an early-type galaxy spectrum at a redshift $z \sim 0.6$, if the continuum rise at ~6400 Å is attributed to the 4000 Å break.

rough R magnitude of this component is $\sim 23 \pm 0.5$ (about 7 mag fainter than A and 2 mag fainter than B), comparable to what is expected of a luminous elliptical galaxy at $z \simeq 0.6$ (Guiderdoni and Rocca-Volmerange 1987). The large number of other faint galaxies in the field is also consistent with the presence of a rich foreground cluster at that redshift. Finally, it is possible that the companion D (and perhaps even C) are other members of this hypothetical lensing cluster along the line of sight to UM 425. The brighter ($V \simeq 17.8$) galaxy just NW from UM 425 is at $z = 0.1265$, and probably unrelated to the system.

A generic feature of gravitational lensing is that the magnification ratio is inversely proportional to the components separation. In the case of UM 425, we see a relatively large image separation ($6\farcs5$) and a large difference in brightness (almost a factor of a 100). Furthermore, the lensing galaxy is expected to be closer to the fainter image (B) than to the brighter image (A), and we may have a spectroscopic evidence for just such a situation. However, the lensing potential is probably fairly complicated, and we postpone any modeling of the system to a future, more comprehensive paper.

The very similar spectra and colors, the presence of a possible lensing galaxy and/or a cluster, and the luminosity and redshift bias used to select the object in the first place all argue in favor of the gravitational lens hypothesis. It is regrettable that the system is not detected in the radio, since the comparison of the optical and radio images can be used as a powerful test for lens candidates (Djorgovski *et al.* 1987). Further data are needed in order to tighten the measurements presented here, check the lensing hypothesis, and establish the nature of the components C and D.

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