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Observations of the new gravitational lens system UM 673 = Q 0142–100 *

J. Surdej [1,], P. Magain [2], J.-P. Swings [1], U. Borgeest [3], T. J.-L. Courvoisier [4,***], R. Kayser [3], K. I. Kellermann [5], H. Kühr [6], and S. Refsdal [3]**

[1] Institut d'Astrophysique, Université de Liège, Avenue de Cointe 5, B-4200 Cointe-Ougrée, Belgium
[2] European Southern Observatory, Casilla 19001 Santiago 19, Chile
[3] Hamburger Sternwarte, Gojenbergsweg 112, D-2050 Hamburg 80, Federal Republic of Germany
[4] ST-ECF, European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-8046 Garching bei München, Federal Republic of Germany
[5] National Radio Astronomy Observatory, Edgemont Road, Charlottesville, VA 22903-2475, USA
[6] Max-Planck-Institut für Astronomie, Königstuhl, D-6900 Heidelberg 1, Federal Republic of Germany

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Summary. In order to better understand the effects of gravitational lensing on the observed quasar luminosity function, on the source counts of extragalactic objects, etc., we have recently initiated a high resolution direct imaging survey of a selected sample of Highly Luminous Quasars (HLQs). The observations are being carried out with the 2.2 m telescope at ESO, and with the VLA at the NRAO, New Mexico.

Following a first observing run at ESO, we have reported the discovery of a new gravitational lens system for the HLQ UM 673 = Q 0142-100. Additional observations supporting this interpretation are discussed here. We confirm that UM 673 is resolved into two quasi-stellar images $A\,(m_V = 17.0)$ and $B\,(m_V = 19.1)$ separated by 2″22 and having essentially the same redshift ($z_e = 2.719$ with $z_e(A) - z_e(B) = -0.0002 \pm 0.0008$). Their emission (Ly$\alpha$, N v, Si iv, C iv, etc.) as well as absorption (including a high ionization system at $z_a = 2.3564$) line spectra also appear to be quite identical. Further evidence for the presence of a lensing galaxy ($m_R = 19$, $z_g = 0.49$) between the two QSO images is given by the detection of faint absorption lines due to Ca ii *H* and *K*, and possibly Na i D1 and D2, at a redshift $z = 0.493$ in the spectrum of UM 673 B.

Application of gravitational optometry to this system is given in the present article: a value of $M_0 = 2.4\ 10^{11}\ M_\odot$ is derived for the mass of the lensing galaxy located between UM 673 A and B and a most likely estimate of $\Delta t = 7$ weeks is found for the expected delay between the arrival times of a similar variability event in the two lensed images of the quasar ($H_0 = 75$ km s^{-1} Mpc^{-1}, $q_0 = 0$).

A VLA observation of UM 673 has been obtained at 6 cm in the hybrid C/D-array configuration. This radio map indicates the presence of a faint elongated structure which is possibly associated with the UM 673 gravitational lens system.

Key words: cosmology – gravitational lenses – quasars: highly luminous – quasars: UM 673 = Q 0142-100 – spectroscopy: quasar

1. Introduction

Following the suggestion (e.g. Zwicky, 1937a, b) that gravitationally lensed distant objects should be discovered, Refsdal (1964a), Liebes (1964) and others have worked out the first detailed theories of gravitational light deflection. Refsdal (1964b) also suggested the interesting possibility of using "gravitational optometry" in order to measure the value of cosmological parameters (H_0, q_0) as well as to probe the absolute mass of the deflector(s). It was however not until March 1979 that the first case of a gravitational lens system was identified (Walsh et al., 1979) and there are now up to seven additional candidates of multiply imaged distant quasars (Weymann et al., 1980; Weedman et al., 1982; Lawrence et al., 1984; Djorgovski and Spinrad, 1983; Huchra et al., 1985; Hewitt et al., 1985, 1987). Let us however remark that no lensing object has yet been identified for more than half of the proposed cases. It is also likely that a first example of a giant radio galaxy – 3C 324 – gravitationally lensed by an intervening body has recently been discovered (see Le Fèvre et al., 1987). For the particular case of Q 0957+561 A and B, a very convincing physical model has been proposed by Young et al. (1980, 1981): the observed images are produced through the gravitational lensing of a single distant quasar ($z_q = 1.41$) by a giant elliptical galaxy and its associated cluster ($z_L = 0.36$). Using the difference in light travel time between the individual images of Q 0957+561, Borgeest and Refsdal (1984) and Falco et al. (1985) have derived an upper limit on H_0. *It is clear that a statistical evaluation of the occurrence of the gravitational lens effects within a well defined sample of quasars is of prime importance to better understand the QSO luminosity function and possibly the QSO phenomenon itself, to further test cosmology and to improve our knowledge on the hidden content of the Universe.*

The answer to the question "what fraction of QSOs are multiple due to gravitational lensing?" is very closely related to

Send offprint requests to: J. Surdej

* Based on observations collected at the European Southern Observatory, La Silla, Chile and at the National Radio Astronomy Observatory, Socorro, New Mexico

** Also, Chercheur Qualifié au Fonds National de la Recherche Scientifique (Belgium)

*** Affiliated to the Astrophysics Division of the Space Science Department of ESA that to the question "what is the mass distribution at different scales in the Universe?" If we consider for instance scales typical of galaxies and clusters, we know that the answer to the first question is highly dependent on the central velocity dispersions adopted for the bright elliptical galaxies and on the maximum surface densities in large galaxy clusters (Turner et al., 1984). More generally, any prediction made for the expected number of multiply lensed quasars is very much dependent on the adopted model (Barnothy and Barnothy, 1968; Tyson, 1981; Peacock, 1982; Turner et al., 1984; Hinshaw and Krauss, 1987). Once more, we naturally conclude that an observational approach is required to further constrain our understanding of the gravitational lens effects.

In the following, we adopt such a view and consider that the apparently ($m_V < 17.5$) and intrinsically ($M_V < -29.0$) luminous quasars (hereafter HLQs) constitute very promising candidates to search for the presence of gravitationally lensed images at arcsec and sub-arcsec angular scales. Indeed:

i) HLQs form a particularly high flux limited sample of QSOs for which the probability of detecting multiply lensed images is higher than for a volume limited one (Turner et al., 1984).

ii) HLQs are the most likely objects for which we may assume that their intrinsic brightness is partially due to gravitational lensing.

iii) The large cosmological distances suggested by the higher redshift values observed for the HLQs imply a high probability for gravitational lenses to be located along their line-of-sights. This is also suggested by the presence of rich absorption systems at redshifts $z_a < z_q$ recorded in the optical spectrum of most HLQs.

iv) We suspect that the paucity of known multiply lensed QSO images with angular separations in the range $\lesssim 2''$–$3''$ is mainly caused by strong observational biases. High resolution imaging of the HLQs with the Hubble Space Telescope, the Very Large Array and ground based optical telescopes under very good seeing conditions ought to bring important clues on the occurrence of lensing effects by galaxies or any other class of unknown massive objects.

Our first systematic search for gravitational lenses with the 2.2 m and 3.6 m telescopes at ESO has led to the discovery of UM 673 = Q 0142-100 = PHL 3703 ($z_e = 2.72$, $m_V = 17.0$; see MacAlpine and Feldman, 1982; Berger and Fringant, 1985; Véron-Cetty and Véron, 1987 [1]) as a new case of multiply lensed QSO images. A brief observational description of this system has been reported in Surdej et al. (1988, Paper I). Further details concerning the acquisition and reduction of those data as well as additional observations and plausible models for this new gravitational lens system are given in the present work. The technique used for searching multiply lensed quasars among the HLQs is presented in Sect. 2. Spectroscopic and photometric observations of UM 673 are described in Sects. 3 and 4. Application of gravitational optometry to this new lens system is then proposed in Sect. 5. Radio observations of UM 673 are finally discussed in Sect. 6.

2. Ground-based optical search for multiply lensed QSO images

During three nights (1986 November 9–12) of good seeing conditions (FWHM $\lesssim 1\farcs2$) at La Silla, a CCD camera (RCA SID 501 EX chip, 320 × 512 pixels of 30 μm) at the Cassegrain focus of the 2.2 m telescope was used to perform high resolution direct imaging of selected HLQs. We succeeded in observing a total of 15 HLQs through narrow band filters chosen to isolate one of their bright redshifted emission lines (Ly α or occasionally C III]) as well as a nearby portion of their continuum. The comparison of two such calibrated CCD frames provides an efficient means of selecting QSOs and/or QSO images located at the same redshift (cf. Djorgovski et al., 1985). This is illustrated in Fig. 1 for the particular case of the HLQ UM 673. The CCD frames 1a and 1b have been obtained through the ESO interference filters No. 114 (λ/FWHM = 4531/110 Å, exp.: 12 min) and No. 482 (λ/FWHM = 5075/370 Å, exp.: 7 min), respectively. Since the two resolved images A and B seen in Fig. 1 are characterized by a same excess of radiation at the location of the redshifted Ly α emission line, we naturally conclude that UM 673 A and UM 673 B, located $2\farcs22$ apart on the sky, constitute good candidates for multiply lensed QSO images or twin QSOs.

3. Spectroscopic observations of UM 673 A and B

Low dispersion spectroscopic observations of UM 673 A and B were obtained at the beginning of December 1986 using the ESO faint object spectrograph and camera (EFOSC; Dekker and D'Odorico, 1985) at the $f/8$ Cassegrain focus of the ESO 3.6 m telescope. The spectra were recorded on an RCA "double density" CCD detector (RCA SID 503 chip, 640 × 1024 pixels of 15 μm) and the spectrograph was rotated so that UM 673 A and B could be both placed in the long slit ($1\farcs5$ width) and thus observed simultaneously. Details on the equipment, configuration, etc., used to collect the different sets of spectroscopic data are summarized in Table 1. Reduction and analysis of these data have been performed with the Image Handling And Processing system (IHAP) of ESO at La Silla (Chile) and at IAL Space (Liège). The reduction of the spectra consisted of flat-fielding to remove pixel-to-pixel gain variations in the detector, sky subtraction, a careful sum to combine the object signal in several adjacent spatial increments (while correcting for contamination of the spectrum of one object by light from the other one) and linearization of the wavelength scale using comparison spectra. Because most of the present observations have been carried out during part of the time officially allocated to other observing programs (see the acknowledgements), we were just able to obtain one B300 grism spectrum of the standard star L870-2 (Oke, 1974). Consequently, it was only possible to calibrate the B300 spectra of UM 673 A and B in relative flux. A comparison between the B300 and B150 spectra has however allowed us to subsequently calibrate in relative flux the B150 spectra in the $\lambda\lambda$3800–5577 Å spectral range.

A description and illustration of the B300 low dispersion spectra of UM 673 A and B were given in Paper I. We have illustrated in Fig. 2 the B150 spectra; these are characterized by a spectral resolution approximately twice as good. These data allow us to confirm that the two objects are physically very similar and that they constitute a good new case of gravitationally lensed images of a single distant quasar. In the remainder of this section, we shall present further arguments supporting this interpretation.

First of all, we have listed in Table 2 the central wavelength and equivalent width of all emission lines identified in the B150, B300 and R300 EFOSC spectra of UM 673 A and B. Assigning an equal weight to all emission lines definitely present in the QSO image spectra, we have derived the mean emission redshifts $z_e(A) = 2.719 \pm 0.009$ and $z_e(B) = 2.719 \pm 0.011$ for UM 673 A

[1] A more accurate optical position of the unresolved quasar as seen on a blue POSS print has been measured to be: R.A. = $1^h42^m47\fs88 \pm 0\fs07$ and Dec. = $-10°00'16\farcs4 \pm 1\farcs0$ for the 1950.0 equinox

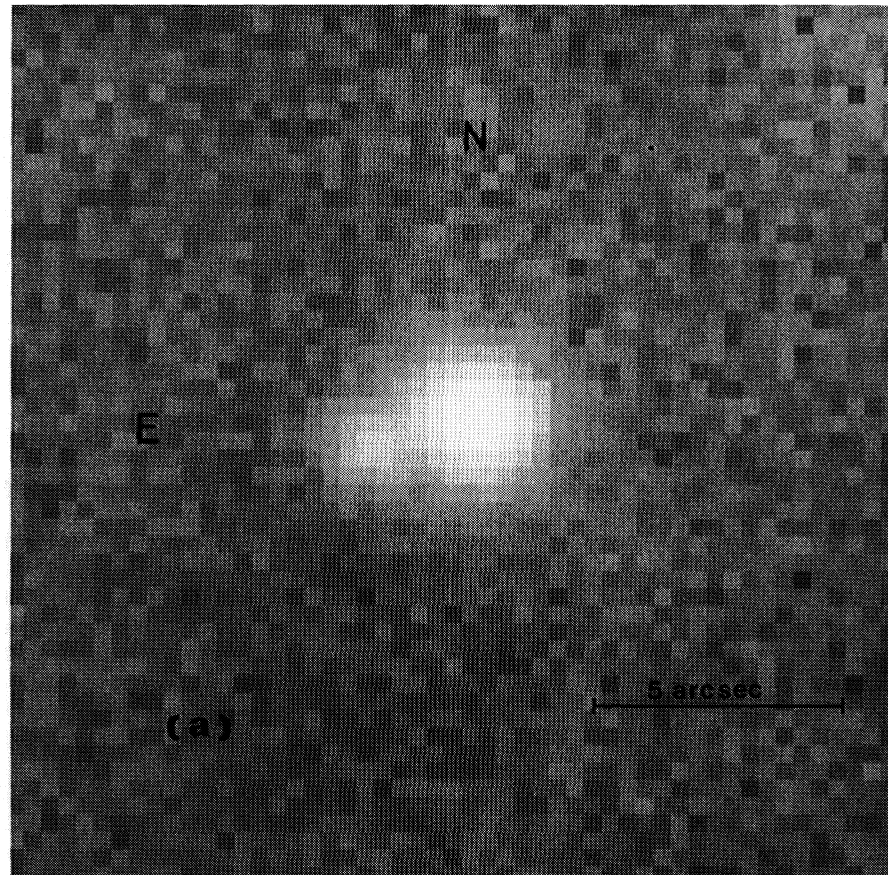

Fig. 1a. The central region of a CCD frame of UM 673 obtained through the ESO interference filter No. 114 at the Cassegrain focus of the 2.2 m telescope at La Silla. This narrow band filter was selected because it isolates the bright redshifted ($z_q = 2.719$) Lyα emission line observed in the spectrum of UM 673

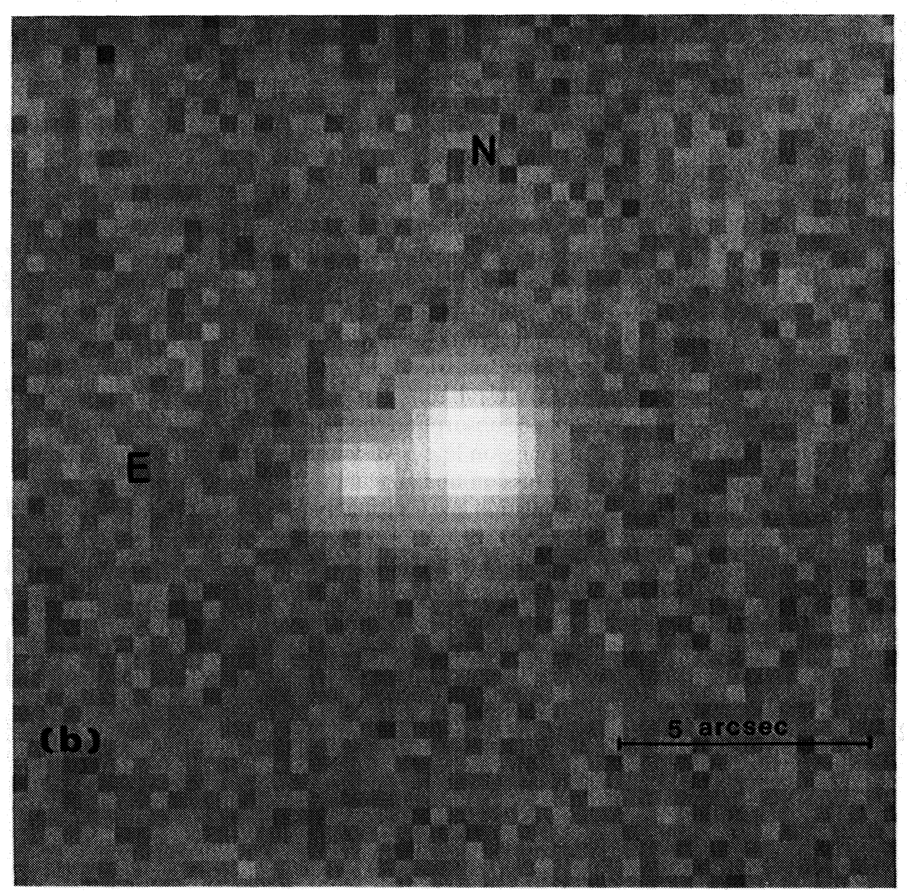

Fig. 1b. This CCD frame was similarly taken through the ESO interference filter No. 482 which samples the QSO continuum in a spectral region void of any conspicuous emission or absorption line feature. The absence of significant differences between these two frames suggests that UM 673 A and B, located 2.″22 apart on the sky, constitute a good new case of gravitationally lensed QSO images or of twin quasars

Table 1. Journal of the spectroscopic observations of UM 673

Spectrum	B300	B150	R300
Observation date	3/12/1986	8/12/1986	8/12/1986
Grism[a]	Blue 300	Blue 150	Red 300
Dispersion (Å/mm)	230	120	270
Wavelength range (Å)	3800–7067	3660–5577	5700–10048
Resolution (FWHM in Å)	13	7.5	14.5
Exposure time (min)	20	30	40

[a] See ESO Operating Manual No. 4 (1985)

Table 2. Central wavelength (Å) and equivalent width (Å) of the emission lines present in the B150, B300, and R300 spectra of UM 673 A and B. No attempt was made to correct the observed equivalent width of the C IV and C III] emission-lines for contamination by the light of the lensing galaxy

Line identification	UM 673 A		UM 673 B		Remarks
Ly β	?		?		
1025.7					
O VI	3850.4±	1.0	3845.2±	2.0 $	
1034.8	7.5	1.1	8.4	2.2 #	
N II	4016.6!	1.1	4017.9!	1.5	1
1085	7.2	0.6	5.7	1.5	
Ly α	4529.5	0.7	4529.5	0.7	2
1215.7	246.7	17.7	240.4	18.7	
N V	4598.5	2.1	4594.9	2.2	2
1240.8					
O I	4862.8:	10.8	4853.0:	21.0	3
1304.4	9.0	1.0	12.8	2.3	
C II	4985.7:	6.2	4987.5:	7.4	3
1334.5	5.7	1.3	7.0	1.8	
Si IV/O IV]	5206.3	7.0	5199.1:	15.0	3,4
1401.6*	17.9	2.8	17.6	6.3	
C IV	5752.3	3.3	5761.1	2.7	5
1549.5	74.6	5.1	75.2	5.6	
He II	6082.0	14.8	I.D.		6
1640.4					
O III	6192.7	4.6	I.D.		6
1664	5.9	0.9			
N III	?		?		7
1750					
Al III	6954.6!	2.3	I.D.		8
1857					
C III]	7108.2	0.9	I.D.		9
1910.1 &	83.3	3.1	78.2:	4.2	

Explanation of symbols:

? Possibly present but not measurable due to the high noise background.

$ These error estimates represent r.m.s. values as derived from three independent measurements of the line centers. Although we have, for most emission components, fitted the observed profile with a gaussian in order to derive the line center, these error estimates should just be considered as internal deviations of our measurements.

Because the equivalent width of an emission line is very much dependent on the accurate setting of the continuum level, the values reported in this table are somewhat subjective. The error estimates merely represent internal scatter among three independent measurements.

! Not taken into account in the determination of the emission line redshift.

: Somewhat uncertain value.

* See Wills and Netzer (1979) for the adopted rest wavelength of this blend.

I.D. Ill-defined because of the low signal-to-noise ratio.

& See Wills (1980) and Ferland (1981) for the adopted rest wavelength of the C III] line transition.

Remarks to Table 2:

1 Tentative identification.

2 The central wavelength of Ly α refers to that of the narrow emission peak. The reported equivalent width is that derived for the Ly α + N V blend. It is also possible that Si II λ1264 contributes to this emission blend.

3 Very noisy emission line feature.

4 The Si IV/O IV] emission line is centrally cut by the C IV resonance absorption lines at $z = 2.3564$ (see Table 4).

5 This emission line is very asymmetrical.

6 This emission line appears to be very broad.

7 This emission line is probably detected in the R300 spectrum of UM 673 A.

8 It seems that the Al III λ1857 emission line is present in both QSO image spectra but strongly absorbed on its blue wing by an atmospheric line at λ6876 Å.

9 The reported equivalent width refers to the Al III + C III] blend, also affected by the strong atmospheric absorption at λ6876 Å.

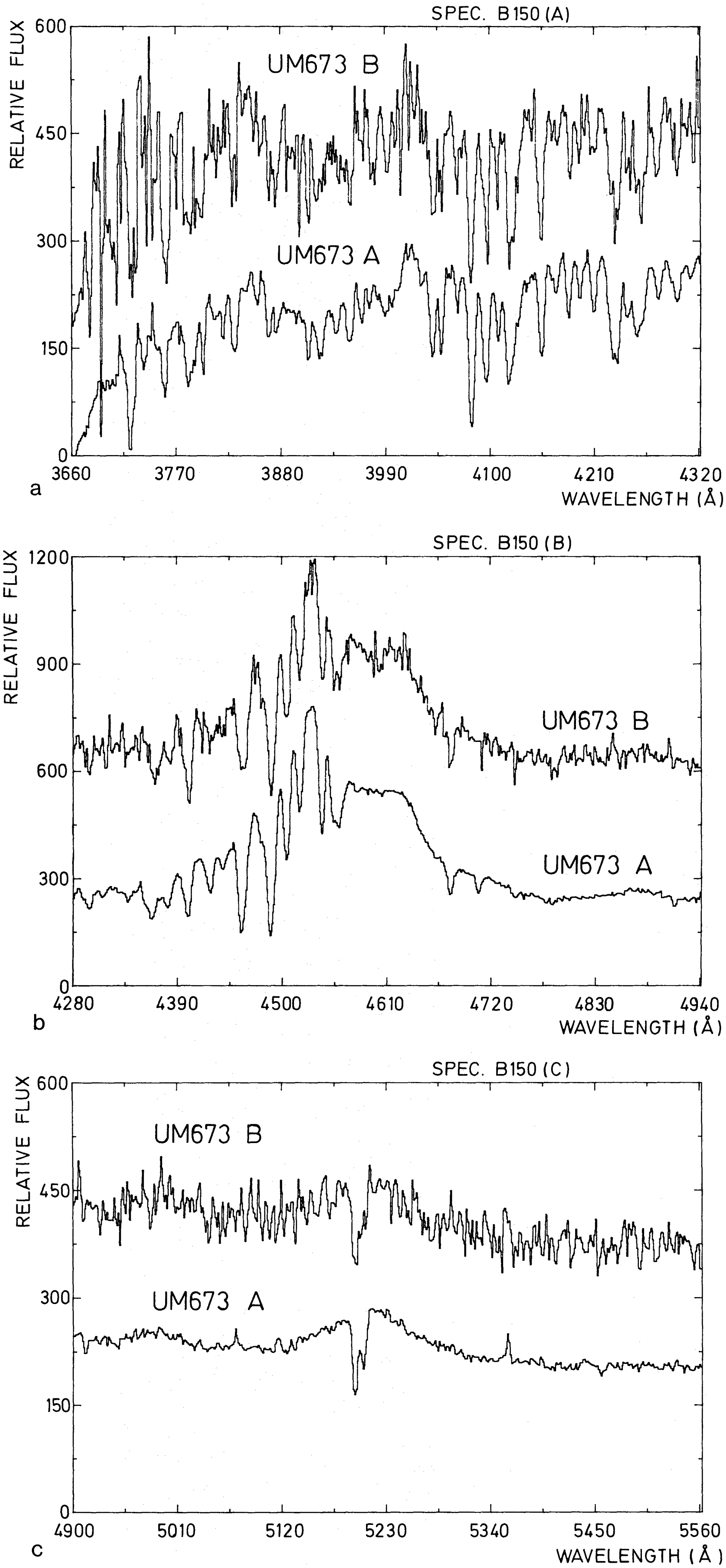

Fig. 2a–c. The B150 low dispersion spectra of UM 673 A and B observed on 1986 December 8 with EFOSC at the f/8 Cassegrain focus of the ESO 3.6 m telescope (see Table 1). The ordinates of the UM 673 B spectrum have been multiplied by a constant factor equal to 8.9 and offset in ordinate by 200 units (**a** and **c**) and 400 units (**b**). Note that the ordinate scale is not the same in **b–c**, and that the flux calibration is uncertain below 3800 Å

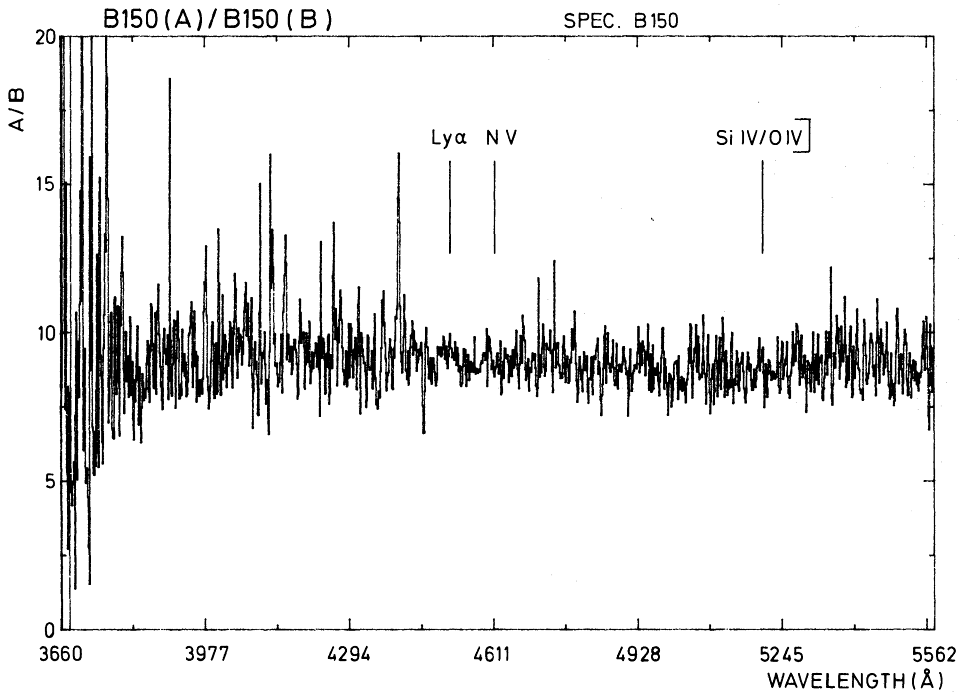

Fig. 3. Result of dividing the B150(A) by the B150(B) EFOSC spectrum of UM 673 (see Table 1). The expected positions of the strongest emission lines present at a redshift $z_e = 2.719$ in the spectrum of UM673 A and B are indicated

and B, respectively. Furthermore, a cross-correlation between the B150 spectra leads to a difference $\Delta z = -0.0002 \pm 0.0008$ between the redshifts of UM 673 A and B, corresponding to a Doppler shift $\Delta v = -14 \pm 63\,\mathrm{km\,s^{-1}}$. We have also illustrated in Fig. 3 the net result of dividing the B150(A) by the B150(B) spectrum. As one can notice, there is no trace left from the presence of strong emission lines. Let us further remark that the several outstanding noise peaks which are seen in the division of the two spectra shortward of Lyα can be readily interpreted as arising from the much lower signal-to-noise ratio characterizing the weaker spectrum of UM 673 B at locations of deep and narrow absorption lines (see below). These new observational results thus support the interpretation that UM 673 A and B are two gravitationally lensed images of a single distant quasar.

The B300 and R300 grism spectra of UM 673 A and B also appear to be quite similar except for the fact that the spectrum of UM 673 B shows a small but clear excess of continuum radiation at wavelengths $\lambda > 5800$ Å. As discussed in Paper I, this apparent reddening of UM 673 B can be accounted for by light contamination from a superimposed object, i.e. the lensing galaxy at a redshift $z_L = 0.49 \pm 0.01$. This identification is strongly supported by the detection of two faint absorption lines at λ5872.3 and λ5923.9 Å, in the better exposed R300 spectrum of UM673B, consistent with the Ca II H and K lines at a redshift $z_L = 0.493 \pm 0.001$ (see Fig. 4a). The equivalent widths of these lines are measured to be 1.2 ± 0.1 Å and 1.3 ± 0.1 Å, respectively. There is also good evidence that the Na I D1, D2 resonance lines are present in absorption at λ8797.0 Å in the R300(B) spectrum, unfortunately very near the impact of a cosmic ray particle (see Fig. 4b)!

Whereas more than 50 narrow absorption lines seem to be present in the blue spectra of UM673 A and B, most of these appear to be unresolved or blended, ill-defined and very often severely underexposed. The low spectral resolution and signal-to-noise ratio of the present data prevent us from studying in detail the location, spatial extent and physical characteristics of the clouds in which they arise. Such a work will be reported elsewhere on the basis of intermediate resolution spectra still to be reduced and/or to be obtained. Nevertheless, we report in Table 3 the central wavelength and equivalent width of the most conspicuous absorption lines detected in the B150 and B300 EFOSC spectra of UM 673 A and B. A preliminary analysis of these data allows us to state that:

i) the average velocity difference between the absorption lines listed in Table 3 amounts to $v(\mathrm{A}) - v(\mathrm{B}) = -15 \pm 46\,\mathrm{km\,s^{-1}}$,

ii) within the observational and measurement uncertainties, we find that the equivalent widths of these absorption lines measured in the two QSO image spectra compare very well.

Furthermore, we have identified a high ionization absorption line system at $z_a(\mathrm{A}) = 2.3565 \pm 0.0006$, $z_a(\mathrm{B}) = 2.3562 \pm 0.0004$; a suspected Lyman absorption system at $z_a(\mathrm{A}) = 2.7360 \pm 0.0002$, $z_a(\mathrm{B}) = 2.7366$ and another possible absorption line system at $z_a(\mathrm{A}) = 1.8987 \pm 0.0001$, $z_a(\mathrm{B}) = 1.8988 \pm 0.0005$ (see the details in Table 4). As usual, most of the absorption lines located shortwards of Lyα remain unidentified.

4. Direct imaging of the UM 673 gravitational lens system

Direct imaging of UM673 has also been performed at the beginning of December 1986 using EFOSC (cf. Sect. 3) and a set of Bessel V and R filters. These data were reduced with the MIDAS application programs available at ESO (La Silla) following a standard procedure which consists of cleaning, flat fielding and dark subtraction. We have also obtained V and R exposures of a reference field near NGC 300 (Graham, 1981) in order to calibrate the fluxes.

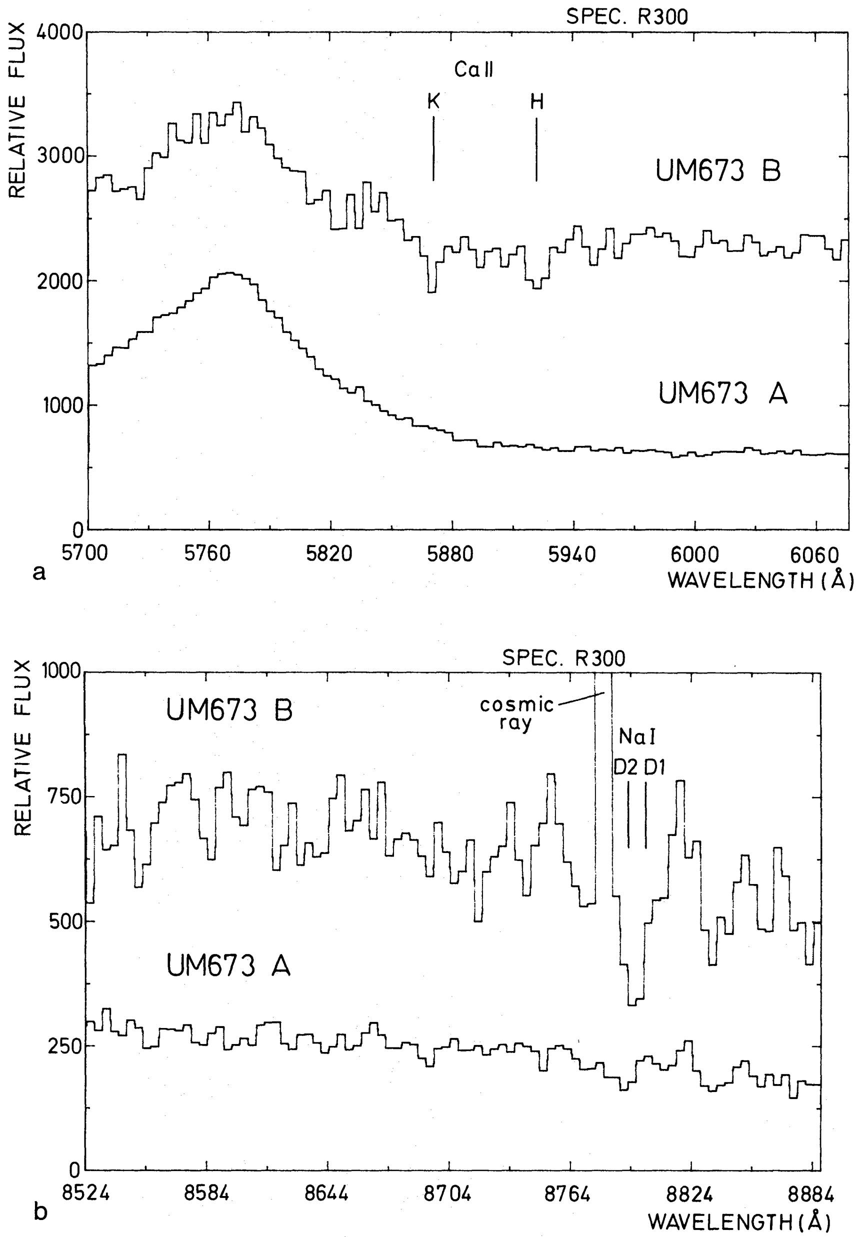

Fig. 4a and b. Selected portions of the red EFOSC spectra R 300 (see Table 1). The spectrum of UM 673 B in **a** clearly displays the presence of faint absorptions due to the Ca II H and K lines at a redshift $z = 0.493$. Similarly, one can notice in the UM 673 B spectrum of **b** a broad absorption feature at the expected position of the Na I D1, D2 resonance lines at $z = 0.493$. We identify these absorption lines as being due to the contamination of the spectrum of UM 673 B by that from the lensing galaxy at $z_g = 0.493$. These spectra were not calibrated in flux

Reduction of a short V exposure frame taken on 1986 December 8 (exp. = 15 s, seeing = 1″) gives $m_V(\mathrm{A}) = 17.0 \pm 0.2$ and $m_V(\mathrm{B}) = 19.1 \pm 0.2$ for the magnitudes of UM 673 A and B, respectively. The angular separation between the two lensed QSO images was measured to be $2''.22 \pm 0''.03$ in the position angle $106^\circ.3 \pm 0^\circ.5$.

A careful processing of an R CCD frame exposed during 2 min on a good seeing night ($\simeq 1''$ on 1986 December 6) allowed us to detect the image of the suspected lensing galaxy (see Sect. 3). This result obtained after subtraction of the two QSO images from the original frame is described and illustrated in Fig. 1 of Paper I. We have represented in Fig. 5 the same result in a digital form. The different smoothed contour levels shown in that figure delineate the approximate shape of the lensing galaxy. As already indicated in Paper I, the center of the galaxy is found to be located very near ($< 0''.2$) the line joining the two QSO images, at $0''.8 \pm 0''.2$ from the position of UM 673 B. After correction for the seeing effects, we estimate the size (FWHM) of the lensing galaxy to be $3''.2$ and $1''.8$ along the E–W and N–S directions, respectively. The integrated magnitude of this galaxy is measured to be approximately $m_R = 19$, a value which is quite consistent with that predicted for an elliptical galaxy at a redshift $z_g = 0.5$ (see Coleman et al., 1980). We have also measured the R magnitude of UM 673 A and B: $m_R(\mathrm{A}) = 16.9 \pm 0.2$ and $m_R(\mathrm{B}) = 19.1 \pm 0.2$.

5. The mass of the lensing galaxy and the travel time difference between the two light paths from UM 673

We give hereafter a detailed description of the method used to estimate the mass M_0 of the lensing galaxy and the expected delay Δt between the travel times of the two lensed QSO images (cf. the values quoted in Paper I).

Table 3. Central wavelength (Å) and equivalent width (Å) of the most conspicuous narrow absorption lines detected in the blue spectra of UM 673 A and B

UM 673 A	UM 673 B
4040.0 ± 0.1 $	4041.1 ± 0.1
2.8 0.1 #	2.9 0.1
4080.9 0.1	4080.6 0.2
6.5 0.1	6.0 0.2
4095.8 0.2	4097.0 0.2
5.2 0.2	4.3 0.2
4154.4 0.2	4153.8 0.2
3.2 0.2	3.8 0.2
4400.6 0.1	4401.2 0.1
3.4 0.2	5.3 0.2
4457.7 0.2	4458.2 0.4
7.1 0.2	6.9 0.2
4487.8 0.2	4488.1 0.2
8.6 0.2	8.5 0.2
4504.4 0.1	4504.2 0.1
3.0 0.2	3.5 0.2
4518.5 0.1	4517.8 0.1
2.1 0.2	2.6 0.2
4541.9 0.1	4542.5 0.2
2.0 0.2	1.8 0.2
4677.7 0.2	4677.3 0.2
1.4 0.2	2.1 0.2

Note: The remarks $ and # quoted in Table 2 equally apply to the case of absorption lines measured here

Since we do not have yet enough information on the mass distribution and orientation of the lensing galaxy, or on its immediate surroundings (presence of a galaxy cluster, etc.), it is premature at this stage to attempt a precise modelling of the UM 673 gravitational lens system. Therefore, we shall first discuss the possible image properties of this new system on the basis of topological arguments. We shall then make use of a simple model to estimate M_0 and Δt.

5.1. Possible image properties of the UM 673 gravitational lens system

When fitting a deflector model to an observed gravitational lens system, some important information may be derived from the observed QSO image brightnesses. Since UM 673 belongs to the 20 known most luminous quasars, it may be assumed that the A image is highly amplified, whereas the brightness of B may more closely correspond to the intrinsic quasar luminosity. The amplification of A may be due to macro- and/or micro-lensing. In the first case, A will be a single, close double- or triple-image with an angular separation of typically some 0\.″1. A bright single or close triple image can only then be produced by a generic lens if the source is located near a cusp catastrophe (see Blandford and Narayan, 1986). We present in Fig. 6a a three-image situation produced by a galaxy with an elliptical symmetry, which is the

Table 4. Proposed identification of narrow absorption line systems in the spectra of UM 673 A and B

Line identification	Observed central wave-length (Å)	Observed equivalent width (Å)	Remarks (see below)
1. The high ionization absorption line system at $z_a = 2.3564$			1
a) UM 673 A			
C IV λ1550.8	5205.9 ± 0.1 $	4.4 ± 0.2 #	2
1548.2	5197.4 0.1		
Si IV 1402.8	4707.3 0.2	0.8 0.2	
1393.7	4677.7 0.2	2.1 0.3	
Lyα 1215.7	4080.9 0.1	6.6 0.2	
Si III 1206.5	4048.9 0.1	2.1 0.2	
b) UM 673 B			
C IV λ1550.8	–	4.7 0.5	2, 3
1548.2	–		
Si IV 1402.8	I.D.		
1393.7	4677.3 0.2	2.9 0.3	
Lyα 1215.7	4080.6 0.1	6.1 0.2	
Si III 1206.5	4049.1 0.1	1.8 0.2	
2. A suspected Lyα system at $z_a = 2.7362$			
a) UM 673 A			
Lyα λ1215.7	4541.9 0.1	2.1 0.2	
Lyβ 1025.7	3831.9 0.1	2.4 0.3	
b) UM 673 B			
Lyα λ1215.7	4542.5 0.2	1.8 0.2	
Lyβ 1025.7	I.D.		
3. A possible absorption line system at $z_a = 1.8987$			
a) UM 673 A			
C IV λ1548.2	4487.8 0.2	8.1 0.2	4
Si IV 1402.8	4066.2 0.2	0.6 0.2	
1393.7	4040.0 0.2	3.1 0.1	
Si II 1526.7	4424.1 0.2	2.1 0.2	
C II 1334.5	3868.2 0.1	1.6 0.2	
b) UM 673 B			
C IV λ1548.2	4488.1 0.2	8.0 0.2	4
Si IV 1402.8	4065.9 0.4	I.D.	
1393.7	4041.1 0.2	3.3 0.2	
Si II 1526.7	I.D.		
C II 1334.5	3867.8 0.1	I.D.	

Note: The remarks $, # and I.D. have the same meaning as in Table 2 but for the case of narrow absorption lines

Remarks to Table 4:

1 We suspect that narrow absorption lines due to Si II λ1260.4, N V $\lambda\lambda$1238.8, 1242.8 and N I λ1134.7 are also present in this system. Better quality data are needed to confirm these possible identifications

2 The observed equivalent width refers to the blend of the two resonance lines

3 The two C IV resonance lines are blended and it is therefore not possible to measure the individual central wavelengths

4 The expected position of the C IV λ1550.8 absorption line coincides with the location of an abrupt rise in the underlying continuum (see Fig. 2)

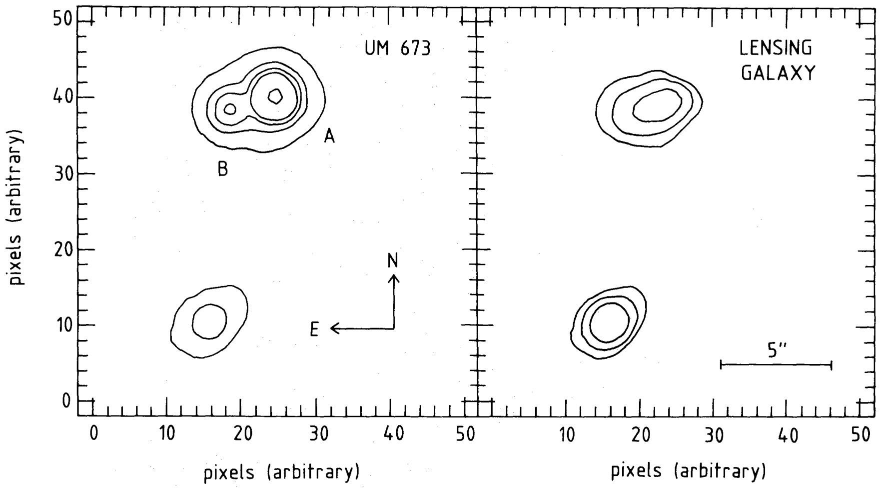

Fig. 5. Contour maps of the UM 673 field. The left panel shows the two quasar images 2″.22 apart, as seen on a CCD exposure with *R* filter. The right panel shows the same field after the two QSO images have been removed using a double gaussian model. The residual contours indicate the presence of a 19th magnitude galaxy. The light center of this galaxy is close to the line connecting the two QSO images, at 0″.8 from image B. A further galaxy can be seen ≃11″ S and ≃3″ E from UM 673 A

most realistic generic lens model that can be adopted as long as no better observational data are available. Image A is highly amplified, image B has "ordinary" brightness and image C is too faint to be detected. It should be noted that image A changes into a close triple-image if the quasar is placed on the other side of the inner caustic (Fig. 6b). Bright double images will be produced if the source is located near a fold catastrophe (Fig. 6c). These models lead to a QSO image configuration that is compatible with the observed one. In the third case, however, the galaxy is near image A. This property is valid in general and does not depend on parameters of the elliptical galaxy (Bourassa and Kantowski, 1975; Blandford and Narayan, 1986). For this reason, the first two models fit better the observations and, thus, we expect image A to be single or triple. Assuming, for instance, that image A is multiple, with at least two of its components being equally bright, we can use the present observations to set an upper limit of approximately 0″.3 on their separation. Finally, the extreme case for which the small, but extended, optical source of the quasar lies exactly on a caustic can be ruled out since this would require that the A/B flux ratio be much larger than is observed.

High amplification by micro-lensing in one image does not seem very likely because the observed emission line to continuum flux ratio should then be appreciably different in the two QSO images (Kayser et al., 1986). This is of course in contradiction with the spectroscopic observations presented in Sect. 3.

To summarize, we note that it is possible to fit qualitatively the observations by assuming a lens model with elliptical symmetry and with the quasar near a cusp of the inner caustic produced by the lens. This possibility should however be tested by further observations.

5.2. *Estimation of the mass of the lensing galaxy*

Contrary to the above discussion on possible image properties of UM 673 A and B where the use of generic lens models was required, the lensing galaxy being described by an elliptical distribution of matter (see Blandford and Narayan, 1986), our estimation of the mass of the lensing galaxy essentially relies on the observed redshifts and positions of the QSO images, and of the deflector. Generity is not demanded here and this allows us to adopt more simple models for which an analytical treatment is possible.

In the absence of more accurate observational data on the exact position, excentricity and orientation of the lensing galaxy, we assume for the sake of simplicity that this object is axially symmetric with respect to the line-of-sight, with its centre located on the projected line joining the two QSO images. For this particular model, Borgeest and Refsdal (1984) have introduced a very useful two-parameter theory describing the formation of gravitationally lensed images.

In their model, κ is a measure of the central mass concentration ($0<\kappa<1$; the deflection law of a point mass being obtained for $\kappa=0$). M_0 is the mass of the galaxy included in a circle having a radius $\theta_t/2$ around its centre (θ_t being the angular separation between the QSO images seen on the opposite sides of the galaxy). In addition to the galaxy, we assume the existence of large scale matter distribution with constant surface density around the quasar images, which is described by the normalized density $\sigma\,(0<\sigma<1)$. For $\sigma=1$, this matter alone will focus the quasar radiation at the Earth. With the introduction of σ we can roughly take into account the action of a cluster surrounding the lensing galaxy or the action of any other large scale matter accumulation due to cosmological density fluctuations (Alcock and Anderson, 1985). A very extended massive halo of the galaxy would also be included in σ and would therefore not contribute to M_0. M_0 can now be expressed in terms of the observational data θ_A, θ_B, z_q and z_g, the model parameters κ, σ and the two cosmological quantities T and H_0 (see Borgeest and Refsdal, 1984; Kayser and Refsdal, 1983):

$$M_0=\frac{c^3\,z_q\,z_g\,T(1-\sigma)\,\theta_t^2}{16\,G(1+z_g)(z_q-z_g)\,H_0}\left\{\frac{1-\kappa}{1-v^2}+\kappa\right\}^{-1}, \tag{1}$$

where we have used the abbreviation $v=(\theta_A-\theta_B)/\theta_t$. As usual, c is the velocity of light, G the gravitational constant and H_0 the Hubble parameter. The cosmological factor T corrects for the error introduced by using Hubble's law at large redshifts.

For the case of the UM 673 gravitational lens system, we have $\theta_t=2''.22$, $z_q=2.719$ and $z_g=0.493$. For the assumed galaxy position with respect to the QSO images ($\theta_A=1''.4$ and $\theta_B=0''.8$), we obtain $v=0.28$. If θ_A roughly equals θ_B, as in the case discussed here, v^2 becomes small and the last factor in Eq. (1) is close to unity. For $v=0.28$, a 10% error in v will induce an error on M_0 of only about 2%. Therefore, an estimate of M_0 does not crucially depend on the exact measurement of the galaxy position or on κ, a

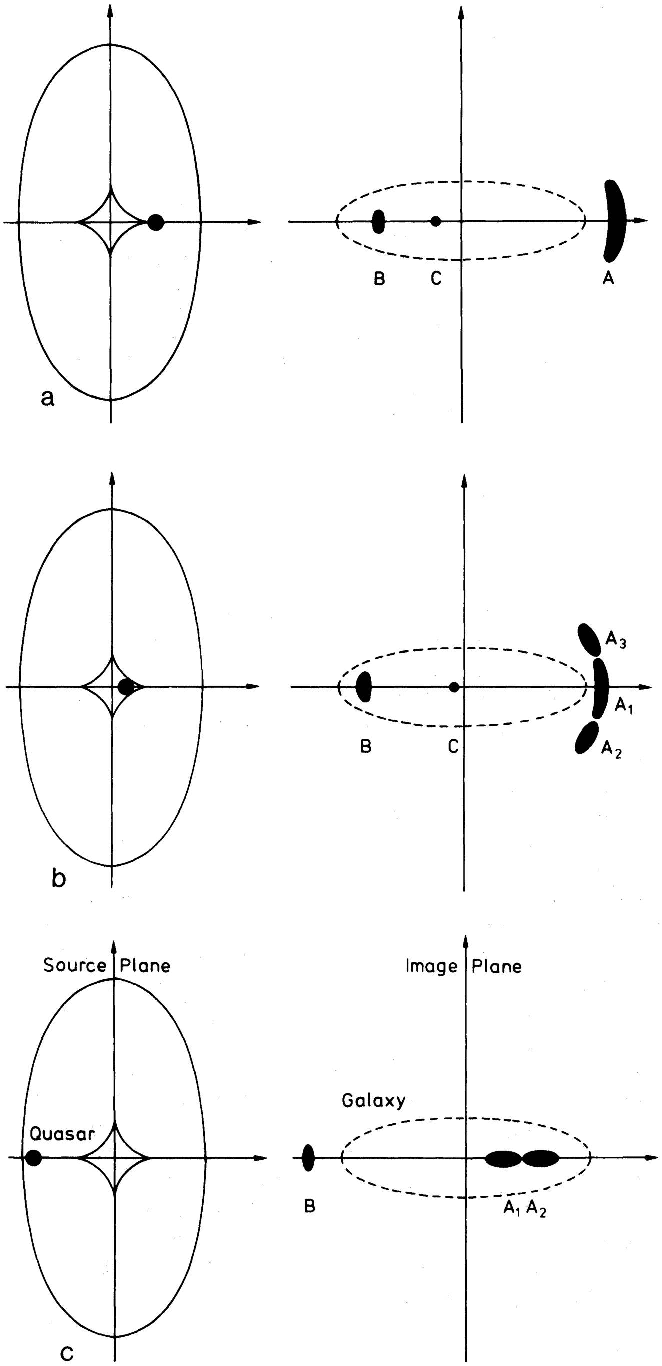

Fig. 6a–c. Gravitational imaging by an elliptical galaxy is shown for three different positions (**a–c**) of the quasar. On the left hand side of the figures, the location of the quasar relative to the caustics is indicated in the source plane. The right hand side illustrates the image configurations and the location of the lensing galaxy as seen by a distant observer. The image sizes are proportional to their brightnesses

decisive measure of the relative matter distribution in the galaxy. Inserting the observational data in Eq. (1), we thus obtain:

$$M_0 = 1.69\, T h_0^{-1} (1-\sigma)\, (1+0.085\,\kappa)\; 10^{11}\, M_\odot\,, \tag{2}$$

where h_0 is H_0 in units of 100 km s^{-1} Mpc^{-1}. T is of order unity; for $q_0 < 1$ (Friedmann Universe), one gets $0.85 < T < 1.28$ (Kayser and Refsdal, 1983). The main uncertainty on M_0 is due to h_0 and σ. Negative values of σ cannot be excluded in principle (Nityananda and Ostriker, 1984), but they would make the appearance of multiple lensed quasars unlikely, as discussed by Borgeest and Refsdal (1984). Therefore, for $\sigma > 0$ and $h_0 > 0.5$, we obtain an upper limit on M_0: $M_0 < 4\; 10^{11}\, M_\odot$. For $h_0 = 0.75$, we find that $M_0 = 2.4\; 10^{11}\, M_\odot$.

5.3. *The expected time delay* Δt

In order to estimate the delay Δt between the arrival times of one and the same variability event in the two lensed QSO images, we can use the simple proportionality relation existing between Δt and M_0, as discussed by Borgeest (1986). For the previously adopted deflection model (cf. Sect. 5.2), we find that

$$\Delta t = 16\, G\, M_0 (1-z_g)\; v\, (1-0.5\,\kappa)/c^3\,, \tag{3}$$

where the third- and higher-order terms in v have been neglected. Inserting the observational data, and making use of Eq. (2), we obtain for Δt:

$$\Delta t = 0.18\; T h_0^{-1} (1-\sigma)\, (1-0.42\,\kappa)\;\mathrm{yr}\,. \tag{4}$$

For the extreme case of a point mass lens ($\kappa = 0$) and for $h_0 > 0.5$ and $\sigma > 0$, we derive an upper limit to Δt: $\Delta t < 5$ months. Using $\kappa = 1$, $\sigma = 0$, $h_0 = 0.75$, and $T = 1$, we find that $\Delta t \simeq 7$ weeks. It should be noted that intrinsic luminosity variations of UM 673 are expected to be seen first in image A.

On the other hand, a measurement of Δt should allow a determination of the galaxy mass M_0 to be made independently of the values of h_0, T, and σ (see Eq. (3) and Borgeest, 1986).

The estimates of M_0 and Δt presented here are based on the assumptions of a symmetric lens galaxy and of a perfect alignment between the galaxy centre and the line joining the QSO images. Past experience in numerical modelling has shown that slight deviations from these assumptions have only a marginal influence on the results of such calculations. More accurate analytical and numerical computations will be made as soon as better observational data become available.

6. VLA radio observations of UM 673

We made a radio observation of UM 673 with the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO, Socorro, New Mexico) on 1987 January 25 using the C/D-array configuration. We observed for 30 min at 4.885 GHz (6 cm) with a bandwidth of 100 MHz in each of the two circular polarizations. The edited and calibrated visibility data were Fourier transformed and the resulting map was cleaned using the AIPS reduction package; the r.m.s. noise on the map is 0.05 mJy/beam. The radio image of UM 673 is shown in Fig. 7. As can be seen, a faint elongated radio structure is present near the position of UM 673. The radio flux densities of the individual knots forming this structure are in the range 0.1 to 0.25 mJy. Higher angular resolution observations will allow us to test the possible association between the faint detected radio structure and the lensed QSO images, or the deflecting galaxy.

7. Discussion

Direct imagery and spectroscopy of a new gravitational lens system for which it has been possible to derive important,

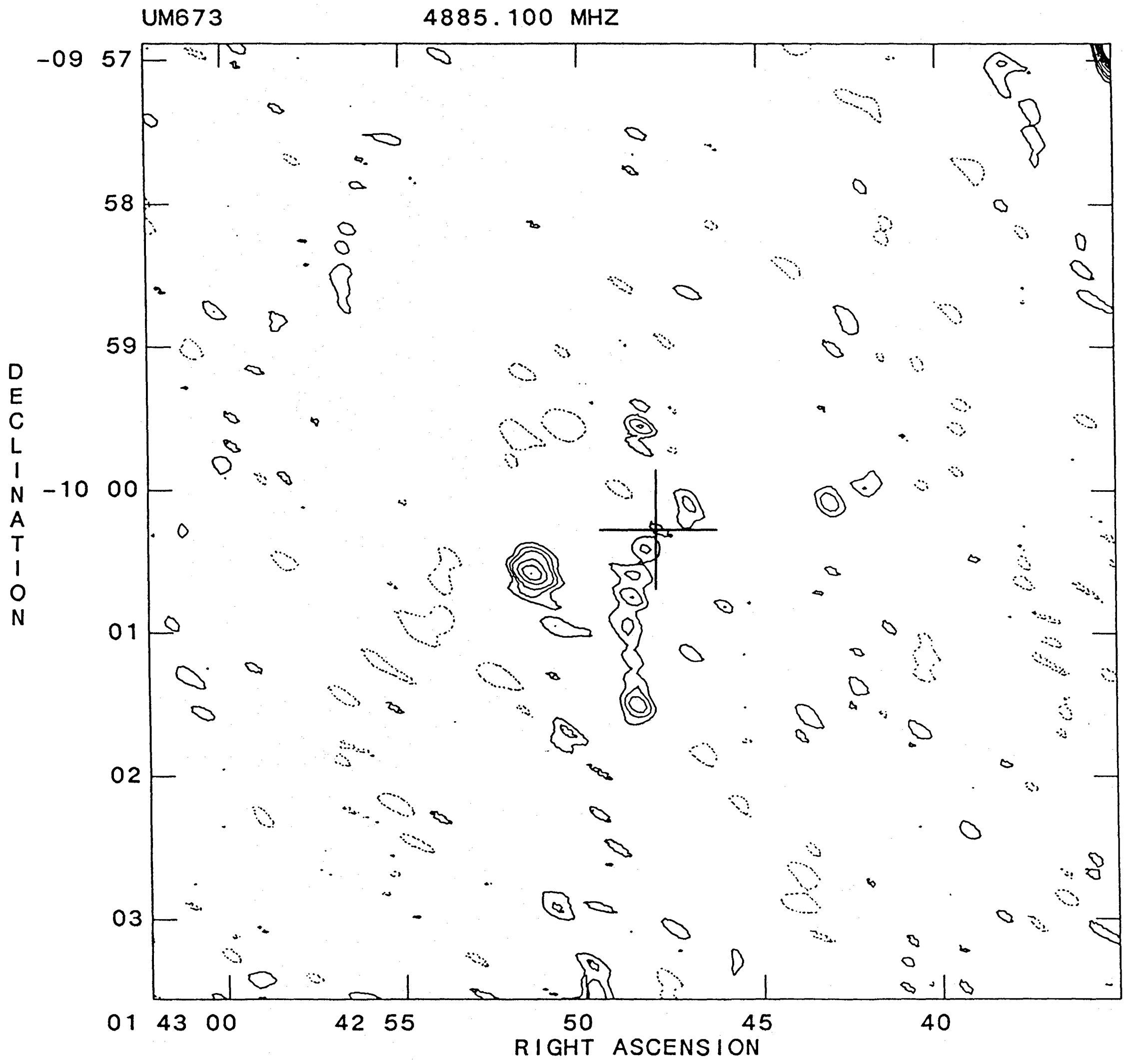

Fig. 7. 5 GHz VLA map of the field near the Highly Luminous Quasar UM673. The beams size is about 13″. The contour levels are at −0.10, 0.10, 0.15, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, and 0.90 mJy/beam. The optical position of UM673 is indicated by a cross

although still preliminary, physical parameters have been reported. We refer the reader to the abstract for a summary of the main results. We only discuss here the relevance of future observations of UM 673 in the context of a better understanding of this new gravitational lens system.

Since the theoretical estimate of the time delay Δt between the two lensed QSO images leads to a most likely value of 7 weeks, as well as to a firm upper limit of 5 months, it is important to start monitoring UM 673 A and B at least once a week. Such photometric data will help in setting interesting constraints on the physical model describing the deflector. Note that a time delay of the order of about 7 weeks looks quite ideal since it is sufficiently long to be observed at all (i.e. not too short with respect to the known QSO variability time scales) and small enough to be measured within a single observing season. In order to render easier and feasible a comparison between CCD photometric measurements acquired at different observatories, we suggest that potential observers take one CCD frame of the stars 12–14 located in the reference sequence near the galaxy NGC 300 (Graham, 1981), each time UM 673 is being monitored.

Very deep direct CCD imaging of the lensing galaxy, under optimal seeing conditions, is also essential in order to better determine its precise position, orientation, shape, etc. and to check for the possible presence of an associated galaxy cluster. Speckle interferometric imagery of UM 673 A should be carried out to look at the possible multiple structure that has been predicted for this image.

Since the spectroscopic observations reported in this work have low signal-to-noise ratio and spectral resolution, it will be most useful to obtain well exposed intermediate resolution spectra of UM 673 A and B, specially in the ultraviolet spectral range, to identify the numerous absorption lines located shortward of Ly α. These data should also contribute to the study of the location, size, degree of homogeneity, abundances, ionization, etc. of the absorbing clouds. Furthermore, special efforts should be made to measure the rotation curve or the velocity dispersion of the lensing galaxy.

We conclude that UM 673 appears to be one of the most highly luminous quasars not because of an intrinsic cause but due to the amplification of the image A by gravitational lensing. We intend to report soon about direct CCD imaging and high angular resolution VLA observations of further interesting HLQs. The statistical implications of this work with respect to the determination of the QSO luminosity function, etc. will also be discussed in a separate paper.

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