1993A&A...280..360G

Astron. Astrophys. 280, 360–364 (1993)

ASTRONOMY
AND
ASTROPHYSICS

Near-infrared and optical imaging of Q 2345+007: the largest gravitationally lensed QSO system?

Gopal-Krishna[1,2,3], **M. Yates**[4], **Paul J. Wiita**[5,3], **A. Smette**[2,6], **A. Pati**[7], **and B. Altieri**[2,8]

[1] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, Maryland 21218,USA
[2] European Southern Observatory, Casilla 19001, Santiago 19, Chile
[3] National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, Poona University Campus, Post Bag No. 3, Pune 411007, India (permanent address)
[4] Max-Planck-Institut für Astronomie, Königstuhl, D-69117 Heidelberg, Germany
[5] Department of Physics & Astronomy, Georgia State University, Atlanta, Georgia 30303-3083, USA (permanent address)
[6] Institut d'Astrophysique de Liège, 5 Avenue de Cointe, B-4000 Liège, Belgium (permanent address)
[7] Indian Institute of Astrophysics, Bangalore 560034, India
[8] ESTEC, Postbus 299, NL-2200 Noordwijk, The Netherlands (current address)

Received February 2, accepted May 7, 1993

Abstract. We have taken *K*, *R*, *V*, and *B* band images of Q 2345+007, which has been claimed to be the gravitationally lensed quasar with the widest separation between the two images ($\approx 7''$), although the lens remains to be identified. The *K* band image extends the observations to longer wavelengths, and in conjunction with the published data and our new results at shorter wavelengths show that the colors of the two components do not differ markedly over the wavelength range 0.4–2.2 μm, though it is possible that the weaker component is slightly redder. From a comparison of our *V* and *B* band images with published images we find that the intensities of both components have declined substantially over the past decade. This opens up the possibility of testing the lensing hypothesis by measuring a temporal offset between the light curves of the two components.

Key words: galaxies: active – gravitational lensing – quasars: general – quasars: individual: 2345+007

1. Introduction

The quasar 2345+007 ($z = 2.15$), which consists of two unequally bright images $\sim 7''$ apart, has been claimed to be the most widely separated lensed quasar, with the lensing material most likely located at $z \approx 1.49$ (Weedman et al. 1982; Foltz et al. 1984; Sol et al. 1984; Subramanian & Chitre 1984; Tyson et al. 1986; Nieto et al. 1988; Duncan 1991). Tyson et al. (1986) have taken very deep images in the *I* band and found 5 galaxies with a mean apparent magnitude of 23.9 ± 0.3 within $0\overset{\prime}{.}5$ of the QSO(s), which is consistent with their being part of a cluster at $z \approx 1.5$; however, there is no evidence for a cluster near this redshift which is rich enough to account for such a wide image splitting. Also, a single galaxy at $z = 1.5$ capable of producing a $7''$ separation would require an unreasonably high mass ($\sim 1.2\ 10^{13}\ M_\odot$); such an object with normal M/L should have been easily seen, leading to the suggestion that the lens is predominantly composed of dark matter (Tyson et al. 1986; Narasimha & Chitre 1989). Still, the claim for lensing has been fraught with controversy (see also Shaver et al. 1987), in view of the following observations related to the two images (Bahcall et al. 1986; Steidel & Sargent 1990; Weir & Djorgovski 1991): (i) a marginally significant difference in their emission line spectra; (ii) the absence of any obvious lensing material, even though (iii) the large image separation would require an extremely massive cluster lens ($\approx 5\ 10^{13}\ M_\odot$).

In the UV, Nieto et al. (1988) found a splitting of the weaker (B) image on the scale of $0\overset{\prime\prime}{.}4$, roughly along the line to component A. According to them, this is probably caused by the lensing action of a $\sim 5\ 10^{10}\ M_\odot$ galaxy, which makes a negligible contribution to the observed UV brightness of component B; such a galaxy would probably belong to the same cluster which is presumed to yield the splitting into the two main images (for the relevant theory see, e.g., Narayan et al. 1984). In contrast, while Weir & Djorgovski (1991) also find B to be elongated by a similar amount in their *g* and *r* images, the direction of elongation seems to be approximately perpendicular to the line A–B,

---

Send offprint requests to: P.J. Wiita (Atlanta address)

Table 1. Observing log

Date	Color	Telescope	CCD	Array size	Pixel size (″)	Exposure (min)	Seeing (″)
1989.86	*K*	UKIRT[a]	InSb	62 × 58	0.62	39	1.1
1991.96	*R*	NTT[b]	THX 31156	1024 × 1024	0.44	2	1.3
1992.73	*V*	ESO 3.6 m[c]	TEK 512	512 × 512	0.62	10	2.4
1992.88	*B*	ESO 3.6 m[c]	TEK 512	512 × 512	0.62	10	1.4

[a] UK Infrared Telescope, Mauna Kea
[b] ESO New Technology Telescope (3.6 m), La Silla
[c] La Silla

and they propose that the somewhat redder color of B compared to A may be due to an intervening galaxy.

The possibility of a dark matter lens, and the interest in constraining the dimensions of the Lyman alpha forest clouds (Foltz et al. 1984; Duncan 1991; Smette et al. 1992), imply that it is important to examine the reality of the lensing hypothesis in this extreme case. The reported marginal difference between the optical colors of the two images as well as the possible temporal variability of their relative intensities (Weir & Djorgovski 1991) both have obvious relevance for the lensing hypothesis. We report imaging observations in the *K*, *R*, *V*, and *B* bands made using large telescopes at Mauna Kea and La Silla between 1989 and 1992, and compare them with the previously published data.

2. Observations and results

Table 1 summarizes the epochs, filters, telescopes and CCDs used, exposure times, and seeing conditions for all of our observations.

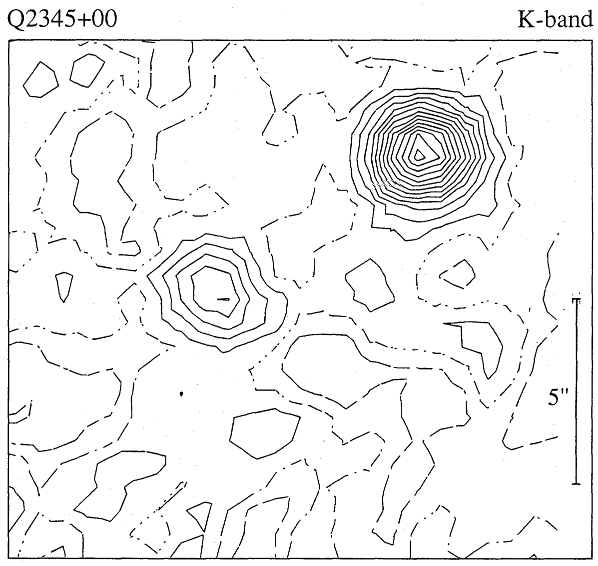

Fig. 1. Contour map of the *K* band image of Q 2345+007, using a constant contour interval and an arbitrary flux density scale. North is up and East to the right

2.1. *Near-infrared observations*

The *K* band (2.2 μm) imaging was carried out with the IRCAM (McLean et al. 1986) on the 3.8 m UKIRT on Mauna Kea in November 1989. The contour map shown in Fig. 1 was derived from 13 scans of 3 minutes each. All these data were reduced using the MIDAS software at ESO. Three mosaic sequences, each consisting of 5 or 6 exposures of 3 minutes, generated by successively offsetting the field center by 3″ were analyzed. Two of the frames in mosaic 1, and one in mosaic 3, had to be rejected, as bad pixels fell within 2 pixels of either object A or B. For every mosaic sequence, the sky was obtained by normalizing the individual dark-subtracted 3 minute frames and then taking a median of the normalized frames; for each frame the sky subtracted was generated by using the remaining frames of the same mosaic. The sky-subtracted frames of a given mosaic were flat-fielded and aligned using the peak of the stronger component A; thus three integrated mosaic pictures were produced. For each mosaic, the fluxes of components A and B were found, using a circular aperture of 5 pixels radius, subtracting the background level estimated by averaging the counts within the same aperture to the N, E, S, and W of the two components. The individual mosaics were then normalized to the flux of component A. Finally, the three normalized mosaics were aligned on A and added; this amounted to a total integration time of 39 minutes.

Neither of the two components appears significantly resolved at this long wavelength. The separation between their centroids is $6\overset{\prime\prime}{.}75 \pm 0\overset{\prime\prime}{.}15$, and their magnitude difference is found to be 1.11 ± 0.17.

2.2. *Optical observations*

Since the object has been imaged frequently in various optical bands over the past decade we attempted to check

Table 2. Magnitude difference and separations for Q 2345+007 A & B

Reference	Epoch	Band	Δm	Separation (″)
Weedman et al. (1982)	1951.91	B	≈1.5	7.3±0.1
Sol et al. (1984)	1981.92	U	1.45±0.06	
		B	1.43±0.06	
		V	1.43±0.05	7.13±0.05
	1981.98	r	1.54±0.13	
	1982.57	r	1.44±0.15	
	1982.90	r	1.41±0.13	
Nieto et al. (1988)	1984.79	U'	1.76±0.05	7.03±0.08
Tyson et al. (1986)	1984, 1985	J_{ccd}	1.44	
		R	1.39	
		I	1.33	
Steidel & Sargent (1990)	1989.62	m_{spect}	1.43±0.01	
Weir & Djorgovski (1991)	1989.65	B	1.30±0.14	
		g	1.31±0.07	
		r	1.24±0.06	
		i	1.08±0.06	
	1989.67	r	1.28±0.04	
	1989.69	g	1.32±0.03	
		r	1.27±0.04	
		i	1.19±0.04	
This work	1989.86	K	1.11±0.17	6.75±0.15
	1991.96	R	1.25±0.09	7.05±0.11
	1992.73	V	1.13±0.12	7.20±0.05
	1992.88	B	1.30±0.06	7.30±0.05

the claim of variability of the intensity ratio of the two components (Nieto et al. 1988; Weir & Djorgovski 1991). To utilize the V and B band photometric magnitudes that are available for several stars within a few arc minutes of the QSO (Sol et al. 1984) we have employed wide-field CCD chips for these optical observations. We have also been able to measure the separation between the two components at several wavelengths, and the results are summarized in Table 2. Other entries in Table 2 are taken from the references cited therein. The original measurements of the separation and estimated magnitude difference were determined from Palomar Sky Survey plates by Weedman et al. (1982). We made an independent measurement of the separation, using the Palomar prints, which agrees with that of Weedman et al.

The reduction of the R band data was carried out in the standard fashion employing the MIDAS software, by subtracting a zero-exposure frame and flat-fielding using the median averaged twilight sky frames. The quoted relative magnitude was derived using a circular aperture with 5 pixel radii and is found to be 1.25±0.09, practically identical to two independent measurements made two years earlier in the r band (Table 2) but probably smaller than measurements of roughly a decade ago (see Sect. 3).

The V and B band images were reduced using the IRAF software. Again, quoted magnitudes are based upon circular apertures with radii of 5 pixels. Using larger apertures would have picked up negligible additional flux from a given component but would have introduced increasing contamination from the other component, particularly for the weaker B component in the V image, which was taken in poor seeing. The positions of the individual components were defined as the centroids of emission and the separations and their errors were measured both in terms of the pixel units and relative to the separations between a web of several brighter stars seen around the QSO(s) on the CCD frames. (Both estimates were in excellent agreement.) The blue image of 2345+007 is shown in Fig. 2. By using the photometry presented in Sol et al. (1984) for the brightest stars registered on both their and our CCD frames (star numbers 2 and 3 in their Fig. 1) we obtained flux calibrated values for the apparent magnitudes of the components in B and V. In this way we found $m_B(\text{A}) = 19.47 \pm 0.06$, $m_B(\text{B}) = 20.77 \pm 0.08$, $m_B(\text{A+B}) = 19.18 \pm 0.04$, $m_V(\text{A}) = 19.37 \pm 0.08$, $m_V(\text{B}) = 20.47 \pm 0.10$ and $m_V(\text{A+B}) = 19.03 \pm 0.06$.

The deep images taken in I and R bands by Tyson et al. (1986) show a faint feature centered about 3″ to the NW of

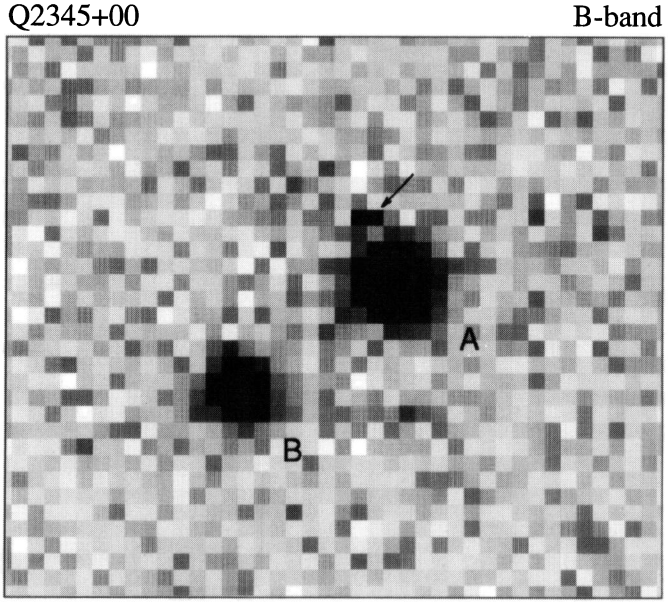

Fig. 2. *B* band image Q 2345+007. North is up and East to the right. The faint object indicated by an arrow is most probably real, as discussed in the text

component A, which they presumed to be one of the several galaxies seen in the vicinity of the QSO; it is roughly 4 magnitudes fainter than A in the *I* band. This feature seems to be present also in our *B* band image (shown with an arrow in Fig. 2), and here too, we find it to be approximately 4 magnitudes fainter than component A. Thus the color of this object seems to be similar to that of the QSO. However, since the present detection of this feature is at the $\sim 4\sigma$ level, its reality and colors need to be affirmed by deeper observations before it could be regarded as a candidate for the third lensed image.

3. Conclusions

We have obtained the first *K* band images of Q 2345+007, which together with our new measurements in the *R*, *V*, and *B* bands are consistent with the two components differing in apparent magnitude by about 1.2 ± 0.1 over the wavelength range 0.4 to 2.2 μm, though the possibility of the fainter component being slightly redder is allowed by the data in Table 2. There is also a hint of the separation between the two components at *K*-band being slightly smaller than at the shorter wavelengths (Table 2). This could conceivably arise from a contribution to the fainter image B from a redder object (presumably a galaxy) projected close to B (see, Nieto et al. 1988; Tyson et al. 1986). It is plausible that this putative galaxy contributes to the lensing, and is mainly responsible for the apparent fine splitting of the image of component B (Nieto et al. 1988; Weir & Djorgovski 1991). The expected elongation of component B in this scenario could have easily remained undetected due to the limited sensitivity of our *K* band observations.

An important new result of these measurements is the evidence for intensity variations of the objects A and B in the blue and visual bands. This follows from a comparison of our measurements with the photometric data reported by Sol et al. (1986) based on their observations of December 1981. We find that over the intervening 11 years, A and B have faded by about 0.6 and 0.4 magnitudes in the blue, and by approximately 0.55 and 0.2 magnitudes in the visual, respectively. The fact that component B shows less variation than does A, particularly at the longer wavelength, is again consistent with the possibility of component B being significantly contaminated by a galaxy. The lack of absolute photometric data in *R* and our relatively short exposure in that band preclude a proper investigation of the temporal variability at this longer wavelength. We do find the magnitude difference between A and B in *R* to be very similar to that found by Weir & Djorgovski in 1989 *r* band measurements, and likely to have changed from the 1981 and 1982 *r* band measurements of Sol et al.; but the large error bars on those old data prevent us from claiming to have detected clear changes here.

While the detection of substantial flux variability of the two components clearly complicates the use of their measured colors for testing the lensing hypothesis, a more definite test of the hypothesis should now be possible by measuring any temporal offset between the light curves of the two components. Long-term photometric monitoring of this system would thus be very worthwhile.

Acknowledgements. We are very grateful to J. Melnick for help with the ESO observations. We also thank M. Giavalisco, J. Noble, S. M. Chitre, D. Narasimha, and S. Nair for assistance and discussions. The referee, C. Vanderriest, made useful suggestions for improving the presentation. G. K. is grateful to ESO for a Senior Visiting Fellowship at La Silla. This work has been supported in part by NSF grant AST9102106, Smithsonian Institution Grant FR 10263600, and the Chancellor's Initiative Fund at Georgia State University.

References

Bahcall J. N., Bahcall N. A., Schneider D. P., 1986, Nat 323, 515
Duncan R. C., 1991, ApJ 375, L41
Foltz C. B., Weymann R. J., Roser H. J., Chaffee F. H., 1984, ApJ 281, L1
McLean I. S., Chuter T. C., McCaughrean M. J., Rayner J. T., 1986, in: Crawford D. L., (ed.) Instrumentation in Astronomy VI, SPIE 627, 430
Narasimha D., Chitre S. M., 1989, AJ 97, 327
Narayan R., Blandford R. D., Nityananda R., 1984, Nat 310, 112

Nieto J. L., Roques S., Liebaria A., Vanderriest Ch., Lelièvre G., di Serego Alighieri S., Macchetto F. D., Perryman M. A. C., 1988, ApJ 325, 644

Shaver P. A., Wampler E. J., Christiani S., 1987, Nat 327, 40

Smette A., Surdej J., Shaver P. A., Foltz C. B., Weymann R. J., Williams R. E., Magain P., 1992, ApJ 389, 39

Sol H., Vanderriest C., Lelièvre G., Pedersen H., Schneider J., 1984, A&A 132, 105

Steidel C. C., Sargent W. L. W., 1990, AJ 99, 1693

Subramanian K., Chitre S. M., 1984, ApJ 284, 1

Tyson J. A., Seitzer P., Weymann R. J., Foltz C., 1986, AJ 91, 1274

Weedman D., Weymann R. J., Green R. F., Heckman J. M., 1982, ApJ 255, L5

Weir N., Djorgovski S., 1991, AJ 101, 66