**BVRI PHOTOMETRY OF QSO 0957+561A, B: OBSERVATIONS, NEW REDUCTION METHOD, AND TIME DELAY**

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**ABSTRACT**

CCD observations of the gravitational lens system Q0957+561A, B in the BVRI bands are presented in this paper. The observations, taken with the 82 cm IAC-80 telescope at Teide Observatory, Spain, were made from the beginning of 1996 February to 1998 July, as part of an ongoing lens-monitoring program. Accurate photometry was obtained by simultaneously fitting a stellar two-dimensional profile on each component by means of DAOPHOT software. This alternative method is equal to and even improves on the results obtained with previous techniques. The final data set is characterized by its high degree of homogeneity, since it was obtained using the same telescope and instrumentation during a period of almost 3 yr. The resulting delay, obtained with a new method, the $\delta^4$ test, is of $425 \pm 4$ days, slightly higher than the value previously accepted (417 days), but concordant with the results obtained by other researchers.

Subject headings: galaxies: photometry — gravitational lensing — quasars: individual (Q0957+561)

1. INTRODUCTION

Since the discovery of the first gravitational lens, the twin QSO 0957+561 (Walsh, Carswell, & Weymann 1979), the system has been subject to the most rigorous attempts to measure the time delay between its components. The especially propitious configuration of QSO 0957+561, two images separated by 6.1 of a quasar ($z = 1.41$) lensed by a galaxy ($z = 0.36$) placed at the center of a cluster of galaxies, make it suitable for photometric monitoring. Although the time delay controversy has recently been solved, establishing a value for the time delay of $\sim 420$ days (Oscoz et al. 1997; Kundic et al. 1997; Pelt et al. 1998b), an ongoing monitoring of the QSO components and comparison between the light curves may yield important results, both for the study of the physical properties of quasars (Peterson 1993; Gould & Miralda-Escude 1997) and for the detection of possible microlensing events (Gott 1981; Pelt et al. 1998a). Moreover, although it will not lead to substantial changes in the value of the Hubble constant, a secure statement of the time delay is crucial for microlensing studies.

The main requirement for obtaining useful information from the light curves of the two components is a high level of photometric accuracy. However, QSO 0957+561 is a very complicated system, for two main reasons: (1) the proximity of the pointlike QSO components, and (2) the extended light distribution of the underlying lensing galaxy. Moreover, the whole scenario presents an additional complication due to the large amount of data available to reduce and analyze (Vanderriest et al. 1989; Press, Rybicki, & Hewitt 1992; Schild & Thomson 1995), making automatic photometry codes mandatory. Up to now, the only automated solution presented was developed by Colley & Schild (1999), who used Hubble Space Telescope (HST) data to subtract the lens galaxy and estimate the level of cross talk between the QSO components by selecting reference stars.

In this paper, an alternative solution to this problem is presented: PSF fitting by means of DAOPHOT software. To check the feasibility of this new technique, it was applied to a sample of simulated data. The data set presented here is the result of 3 yr of monitoring, from 1996 February to 1998 July, a program that included 220 sessions of observation in the R band, 62 in the B band, 72 in the $V$ band, and 68 in the $I$ band. The data acquisition and reduction processes are explained in detail in §§ 2 and 3, respectively. The software environment used for the different reduction and analysis processes was IRAF (Image Reduction and Analysis Facility), so any task or package referred to elsewhere is included in the IRAF environment. Section 4 is devoted to presenting the observed light curves, and in § 5 we discuss the time delay obtained from these data. Finally, a brief summary of the results is given in § 6.

2. DATA ACQUISITION

Lens monitoring was performed in three consecutive seasons, 1996 February to June, 1996 October to 1997 July, and 1997 October to 1998 July (hereafter the 1996, 1997, and 1998 seasons, respectively), using the CCD camera of the 82 cm IAC-80 telescope at the Instituto de Astrofisica de Canarias' Teide Observatory (Tenerife, Canary Islands, Spain). A Thomson 1024 × 1024 chip was used, offering a field of nearly 7.5. Standard BVRI broadband filters were used for the observations, corresponding fairly closely to the Landolt system (Landolt 1992). The IAC Time Allocation Committee awarded time for two kinds of observing runs: routine observation nights (hereafter RON nights), in which we could make use of 1200 s per night, and normal

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observation runs (hereafter NON nights), in which the telescope was available during the whole night for our project. The observational procedure was as follows:

RON nights.—On dark nights, one image of 1200 s was taken; otherwise (moon nights) several short exposures, each of 300–400 s, were performed and then recentered on selected field stars, and averaged to give the total exposure. The position of each individual field star was measured using the IMEXAMINE task, and images were combined using the IMCOMBINE task.

NON nights.—Under photometric conditions, BVRI photometry of QSO 0957+561 was performed. Landolt standard fields (Landolt 1992) were observed to provide the photometric calibration. When the nights were not of photometric quality, several exposures of 1200 s each were performed in every filter to obtain a final deep exposure by averaging them.

The final data set is composed of 15 B, 14 V, 44 R, and 19 I brightness measurements in the 1996 season; 13 B, 25 V, 72 R, and 18 I data points in the 1997 season; and 34 B, 33 V, 104 R, and 31 I data points in the 1998 season. High-quality photometry in BVRI was obtained on 30 nights during 1997 and 1998. Mean results for two reference stars (H and D, see Fig. 1) and the QSO components are given in Table 1. It is important to mention that QSO B-component

![Image of QSO 0957+561 field](image)

**Fig. 1.**—QSO 0957+561 $R$ field obtained as a combination of all the individual images for the three seasons. The total equivalent exposure time is 51.46 hr, and the calibrated limiting $R$ magnitude 25. The label shows the QSO components (A and B) and five field stars (F, G, H, D, and E).

| Object | $V$       | $B-V$       | $V-R$       | $R-I$       |
|--------|-----------|-------------|-------------|-------------|
| D ...... | 15.601 ± 0.009 | 0.76 ± 0.02 | 0.437 ± 0.008 | 0.371 ± 0.007 |
| H ...... | 15.139 ± 0.008 | 0.92 ± 0.01 | 0.520 ± 0.007 | 0.451 ± 0.006 |
| QSO A ... | 17.55 ± 0.06  | 0.19 ± 0.18 | 0.35 ± 0.06  | 0.27 ± 0.06  |
| QSO B ... | 17.46 ± 0.06  | 0.17 ± 0.18 | 0.28 ± 0.06  | 0.27 ± 0.06  |

* See Figure 1.
3. DATA REDUCTION PROCESS

A remarkable characteristic of the photometric data presented here is their high degree of homogeneity; they were obtained using the same telescope and instrumentation over the entire monitoring campaign. Therefore, the reduction process can be the same for all the frames. In a first step, the data were reduced using the CCDRED package. The overscan was subtracted from the images, which were then flat-fielded using very high signal-to-noise ratio master flats, each taken from the mean of 10 sky flat exposures made shortly before the beginning of the observations. These basic CCD reductions (bias, flat-field) are crucial when the noise must be kept as low as possible. However, to attempt the observation of quasar brightness fluctuations of \( \sim 0.01 \) mag (in order to detect short-timescale microlensing events), a high level of photometric accuracy is needed. To this end, it is crucial to separate every source of error, adopting specific solutions for each of them. There are two main sources of error in CCD photometry of the QSO 0957 + 561 system:

1. **Extinction errors**: It is known that the main part of the variability of the observed target magnitude is explained in terms of atmospheric extinction and air-mass variability. Extinction errors are complicated by color terms when broad multiband photometry is dealt with.

2. **Aperture photometry errors**: Due to the special configuration of QSO 0957 + 561 system, there are some specific aperture photometry errors to take into account. As demonstrated in Colley & Schild (1999), these errors are driven by seeing variations, and can be separated into two categories. (1) Influence of the lens galaxy: since the core of the giant elliptical lens galaxy of \( R = 18.3 \) is only separated by 1” from the B image, most of the galaxy’s light lies inside the image B aperture, but outside the image A aperture. This effect could introduce errors of the order of 1%–2% in the final measured fluxes from images A and B (see Colley & Schild 1999). (2) Overlapping of images: the separation between the two images is 6.1”, so when poor seeing conditions prevail, there is an important effect of cross-contamination of light between the two quasar images.

As explained above, the amount of archived data is so large (more that a thousand 1k \( \times \) 1k CCD images) that an automated photometry code is necessary. For extinction errors, the best and most traditional method to work with is to measure differential photometry with several field stars close to the lens components (Kjeldsen & Frandsen 1992).

However, the solution for aperture photometry errors presents a higher level of difficulty. The only automated solution offered to date is explained in Colley & Schild (1999). These authors used HST data (Bernstein et al. 1997) of the lens galaxy for subtraction and reference stars to estimate the level of cross talk between the images. After these corrections, they found that photometry is reliable to about 5.5 mmag (0.55%) over three consecutive nights of real data. In this paper, an alternative solution to the problem is proposed: PSF fitting using DAOPHOT software. A new, completely automatic IRAF task, PHO2COM, has been developed. Using a sample of simulated data, it is demonstrated that the proposed scheme can reach high-precision photometry; 0.5% for the B component and 0.2% for the A component. The following two sections are devoted to explaining each of the adopted solutions to eliminate CCD photometry errors.

3.1. **PSF Photometry: The PHO2COM IRAF Task**

It is well known that PSF fitting is the most precise method for carrying out photometry of faint and/or crowded field stars, whereas aperture photometry is better for brighter, isolated stars. In order to benefit from these facts, the PHO2COM task, written in the IRAF command language, combines aperture photometry (APPHOT package) and PSF fitting (DAOPHOT package) as explained below. Before applying the PHO2COM task, it was necessary to select an image as a reference image and recenter all the frames, using accurate centroid determination from field stars, to the reference frame. The PHO2COM photometry has two main iterations:

*Iteration 1.*—Accurate sky background determination. A precise determination of the sky background is extremely important for accurate photometry. There are mainly two different ways to find the sky background: global-sky or local-sky determination. While in the local-sky method the sky value is calculated from pixels around objects, in the global-sky determination the sky is described by a simple, slowly changing function of the position in the field, e.g., a plane. This last method is the most precise, but uncrowded fields are necessary in order to prevent sky-level changes from field stars. This is the case of the twin QSO field, where most pixels see a background-sky value unperturbed by stars, so the global-sky option was used for sky determination. The main steps of current iteration are:

1. Reference stars and QSO components were removed from the frame using PSF fittings (ALLSTAR DAOPHOT task). This was done, as explained above, to prevent perturbations from these objects in the sky determination.

2. The sky level was determined by means of a smooth surface fitting (IMSURF task) to the frame. The resulting image of iteration 1 is a sky-subtracted frame.

*Iteration 2.*—Object photometry. As discussed above, the PHO2COM tasks uses aperture photometry for reference stars and PSF fitting for twin QSO components. Following Stetson (1987), the PSF is defined from a small sample of isolated stars (G, H, E, and D stars in our case). The PSF fit has two components: an analytic and an empirical. For the two-dimensional analytic function, the user can select between an elliptical Gaussian, an elliptical Moffat function, an elliptical Lorentzian, and a Penny function consisting of an elliptical Gaussian core and Lorentzian wings. These functions were applied to each frame, selecting the one that yields the smaller scatter in the fit. For the PSF empirical component, a linear variation with position in the image proved to give the best results. The main steps in iteration 2 are:

1. Applying aperture photometry with a variable aperture of radius \( 2 \times \text{FWHM} \) (the FWHM was measured from reference stars), the reference star fluxes are extracted. It is important to remember that the frames resulting from iteration 1 are sky-subtracted, and therefore the sky background value is forced to zero in the aperture intensity extractions.

2. PSF fit photometry, with a variable aperture of radius FWHM, is applied to all the objects.

3. Aperture corrections are computed from the previous data to compare the QSO component fluxes with reference
stars (aperture correction will transform data with radius FWHM to radius $2 \times$ FWHM) and standard stars (aperture correction will transform data with radius FWHM to photometric standard star radius, normally $4 \times$ FWHM).

A sample of simulated astronomical data was chosen in order to test the performance of the PHO2COM task. Simulations were made with the ARTDATA package. Each simulated frame included the lens galaxy, the A and B quasar components, and the D and H reference stars (see Table 1 for photometric data). The lens galaxy was created with a de Vaucouleurs (elliptical) light distribution, $I(r) = \exp \{-7.67[(r/R_e)^{1/4} - 1]\}$, with $R_e = 4'5$, taking into account published HST data (Bernstein et al. 1997) and ground-based photometry (Schild & Weekes 1984; Bernstein, Tyson, & Kochanek 1993). The accurate position of each object was also defined using HST astrometry. Finally, 200 simulated images were created with the MKOBJECTS task. The only free parameter (see Table 2) was the atmospheric seeing, which was simulated with values between 0'9 and 2'7 (see Figs. 2 and 3). Effects of pixellation and noise were included (for more details see the MKNOISE task). Noise effects were considered by adding a Gaussian and Poisson noise to the images, which have a constant background (for each filter a mean sky value is deduced from real data). This kind of ideal photometry is not, of course, a full noise description. In any case, the main error sources (lens galaxy light contamination and cross talk between components) were included in the simulated images, so the final estimated errors should be considered first-order ones, where high-order corrections (faint neighboring stars or galaxies, basic CCD reductions, etc.; see Gilliland et al. 1991) are neglected. Aperture (with a fixed radius of 3") and PHO2COM photometry was applied to the simulated images. Differential light curves are plotted in Figures 2 and 3. Correlations with seeing variations are clear. Although the seeing profile is the same for the two reference stars and the QSO 0957 + 561 components, fixed-aperture photometry has final mean errors of $\approx 1.5\%$ and $\approx 2.2\%$ for the A and B components, respectively.

PSF fitting photometry improves aperture photometry magnitudes, but subtraction of the lens galaxy is still not perfect, and some of its light is present in the final B-component magnitude; therefore, the final QSO B-component magnitudes are overestimated. To correct the B-component magnitudes from underlying galaxy light, linear relations between seeing and magnitude errors were calculated by means of simulated data. Figures 4 and 5 show plots of magnitude errors for the A and B components versus seeing for $BVRI$ filters. After correcting data for these errors, final errors of $\approx 0.2\%$ and $\approx 0.5\%$ were obtained for the A and B simulated components, respectively. Two main conclusions can be deduced: (1) as explained above, the B component presents higher errors than A, due to its proximity to the lens galaxy; and (2) because the lens galaxy is extremely red (Schild & Weekes

| Parameter | Value |
|-----------|-------|
| Poisson background (ADU) | 400, 650, 1650, 1500 (B, V, R, I) |
| PSF profile | Moffat |
| Seeing radius/scale (pixels) | variable (see Figs. 2 and 3) |
| Moffat parameter $\beta$ | 2.5 |
| Moffat axial ratio (minor/major) | 1 |
| Gain (electrons per ADU) | 2 |
| Readout noise (electrons) | 5.4 |

FIG. 2.—$R$ light curves for the A component obtained from a simulated data sample. See text for details.

FIG. 3.—$R$ light curves for the B component obtained from a simulated data sample. See text for details.

FIG. 4.—Magnitude errors vs. seeing for the A component, obtained from a simulated data sample by applying PSF fitting photometry by means of the PHO2COM IRAF task.
1984), QSO B-component magnitude errors are larger in the red colors. Real data were also corrected for underlying galaxy light using the linear correlations of Figures 4 and 5.

3.2. Differential Photometry

The basic technique of differential photometry is very simple, and consists of determining the difference, in terms of magnitude, of the A and B images to selected field stars. The B component presents higher errors than A, due to its proximity to the lens galaxy.

The transformation equations used to obtain the standard magnitudes are

\[ b = B + B_0 + B_1(B - V) + B_2 X, \]
\[ v = V + V_0 + V_1(B - V) + V_2 X, \]
\[ r = R + R_0 + R_1(V - R) + R_2 X, \]
\[ i = I + I_0 + I_1(R - I) + I_2 X, \]

where \( BVRI \) are the standard magnitudes, \( bvr \) are the instrumental magnitudes (i.e., \( r = -2.5 \log [F_r] \), where \( F_r \) is the object flux through a predefined aperture), \( X \) is the air mass, and \( (B_0, V_0, R_0, I_0), (B_1, V_1, R_1, I_1), \) and \( (B_2, V_2, R_2, I_2) \) are the zero-point constants, the color term coefficients, and the extinction coefficients, respectively, determined from observations of standard stars. For a given object, the main source of magnitude variability can be explained in terms of atmospheric extinction and air-mass variability. The usual way to remove this error is to use a comparison star observed at the same time under the same conditions (this is one of the main advantages of CCD observations). Under this assumption, the differential magnitude, for instance \( I \), is then found as

\[ r_o - r_s = (R_o - R_s) + R_1[(V - R)_o - (V - R)_s], \]

where subscripts \( o \) and \( s \) indicate the object and comparison star, respectively. The term \( R_1[(V - R)_o - (V - R)_s] \) is very important and is null only if the color term of the system is equal to zero, \( R_1 = 0 \), or the target object and the companion star have similar colors, \( (V - R)_o = (V - R)_s \). In \( BVRI \) photometry, color terms are not zero, and to decrease errors it is necessary to have similar spectra for the object and the comparison star. In this case, it is possible to approximate \( R_o = R_s + (r_o - r_s) \).

Figure 1 shows the field of QSO 0957 + 561 in the R band obtained as a combination of all the individual images taken during the three seasons. The total equivalent exposure time is 51.46 hr, and the limiting R magnitude 25. The set of potential comparison stars, F, G, H, E, and D, were examined differentially in sets of four versus one star. This allowed us to establish the stability of each comparison star. After careful analysis, only two stars (D and H) were selected as reference stars for differential photometry. Photometric errors were calculated using the statistical error analysis developed by Howell, Mitchell, & Warnock (1988), which uses the rms of the differential photometry of comparison stars (H and D in our case) to deduce the photometric errors of QSO components A and B. In initial rms calculations the derived values are higher than expected, so equation (2) was considered, which, for selected reference stars, can be written as

\[ r_H - r_D = (R_H - R_D) + R_1 \text{ col } VR_{H-D}, \]

where \( \text{col } VR_{H-D} = (V - R)_H - (V - R)_D \), which, taking into account the data in Table 1, is equal to 0.08. The color terms \( B_1, V_1, R_1, \) and \( I_1 \) are not normally expected to change during the course of a night, since they are due to the mismatch between the instrumental bandpasses and the standard Johnson \( BVRI \) bandpasses. However, instrumental bandpasses are derived as the convolution of the mirror reflectivities, the filter transmissions, and the chip response, so significant changes are indeed expected in the course of a season. Under this assumption, equation (3) can be formulated as

\[ r_H - r_D = (R_H - R_D) + f(H) \text{ col } VR_{H-D}, \]

where \( f(H) \) is a smooth function of Julian day that fits the possible time changes of the color term \( R_1 \). This equation is demonstrated in Figure 6, where we plotted the color term \( R_1 \) derived from Landolt standard stars and the same term derived from equation (4) using observational data from reference stars H and D. The curve is a parabolic fitting to reference star data that has large error bars (≈0.1) due to error propagation. If it is assumed that the parabolic fitting represents real data without noise, it is clear that the
smooth variations in the differential light curves of reference stars H and D are mainly due to changes in color terms. To correct $R$ data of color term variations (the process is equivalent for the other filters), the following steps were taken: (1) from the differential light curve of reference stars, the $f_R(JD)$ function was calculated by means of a parabolic fitting; (2) for reference star data, the term $col$ was $f_R(JD)$ directly subtracted from observational data, giving the differential magnitude values $R_A - R_D$; and (3) for QSO data it was necessary to assume mean constant values for $col$ and $col_{VR}$ as $col_{VR} = (V - R)_A - (V - R)_D = -0.09$ and $col_{VR} = (V - R)_H - (V - R)_D = -0.16$, and the final corrected $R$ magnitudes are

$$R_A = R_D + (r_A - r_D) + f_R(JD) \cdot col_{VR}$$

$$R_B = R_D + (r_B - r_D) + f_R(JD) \cdot col_{VR}$$

(5, 6)

For the current system, the red spectra of the D reference star and those of the QSO components are similar, so the derived color term correction values are rather small, $\approx 0.5\%$ for the $R$ and $I$ filters. On the other hand, the QSO 0957 + 561 is bluer than the D star, and in this case color term errors become as high as $\approx 2\%$ and $\approx 5\%$ for $V$ and $B$

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colors, respectively. The final mean errors for reference stars and A- and B-component light curves are presented in Table 3.

4. $BVRI$ light curves

The results of our monitoring program are shown in Figures 7, 8, 9, and 10. In these figures we show the light curves and error bars for components A (filled circles) and B (squares) of QSO 0957 + 561 in the $R, B, V,$ and $I$ bands, where the data for the B component are shifted by 425 days (for the time delay estimate in this paper, see § 5). Final magnitudes were calculated using the PHO2COM task and finally corrected for (1) the influence of the lens galaxy (see § 3.1) and (2) color-term variations (see § 3.2). Note the similar behavior of the curves for both components (especially in Fig. 7, corresponding to the $R$ band).

The robustness of the proposed photometry method can be assessed by comparing the magnitudes of the QSO 0957 + 561 A and B components deduced from monitoring light curves (averaged values) and Landolt standard star calibrations (see Table 1). The calculated values are presented in Table 4. The global agreement between the two sets of magnitude values is clear.

The photometric data presented in Table 1 also needs discussion. In principle, the colors of QSO A and QSO B,
averaged over the monitoring campaign, should be essentially the same if sight-line-dependent extinction is ignored. A slight reddening is present in component A, although the significance of this excess, $E(V-R) = 0.07 \pm 0.08$, is questionable. In order to verify the significance of the previous result, in Figure 11 we have plotted the $V-R$ color difference between components A and B, with B shifted by 425 days, so that the emission time is the same for both components over the monitoring campaign, averaged every 20 days. The “blueing” of component A is now clear, and we can try to understand its origin:

1. A lens galaxy absorption effect would have produced a redder, and not a bluer, $V-R$ color for image B.
2. The most likely explanation, proposed by Michalitsianos et al. (1997), is that the ray paths of lensed com-

Fig. 8.—Same as Fig. 7, for B filter

Fig. 9.—Same as Fig. 7, for V filter
ponents intercept different regions of a galactic disk associated with the host galaxy of the source that is viewed pole-on and situated in the quasar rest frame.

A preliminary analysis of the data obtained in the $R$ filter has yielded an important result: component B is brighter than component A. The $R$ data have been averaged every 10 and 20 days, and then the B-component light curve has been shifted by 425 days. The average difference between components A and B is $m_B - m_A = -0.06$ mag for both the 10 and 20 day averages. Moreover, the averaged B/A magnification ratio is 1.06, varying between 1 and 1.12, in perfect agreement with the results described in Press & Rybicki (1998), indicating a prolongation of the long-timescale microlensing event during 1997 and 1998. At any rate, an exhaustive analysis of the long-timescale microlensing in the whole data set is being conducted and will be presented in a future paper. This study will also include a comparison between the short-timescale microlensing during an epoch of calmness (1996/1997 seasons) and the rapid microlensing at a relatively active (but nonviolent) epoch (the 1997/1998 seasons). The consequences for the population of dark matter objects in the lensing galaxy and quasar properties will be also discussed and put into perspective.

5. TIME DELAY

Today, the historical controversy regarding the value of the time delay of QSO 0957+561A, B is almost solved. After 20 yr of monitoring, recent data establish this value at around 420 days. There is, however, a small controversy between two values, $\Delta t_{BA} = 417$ days (Kundic et al. 1997; Pelt et al. 1998b) and $\Delta t_{BA} = 424$ days (Pelt et al. 1996; Oscoz et al. 1997; Pijpers 1997; Goicoechea et al. 1999). The difference (one week) is irrelevant in the Hubble constant calculations, but it may be crucial in order to detect microlensing events.

One of the "classical" ways of obtaining the time delay between components A and B of QSO 0957+561 is the computation of the A-B cross-correlation (see Oscoz et al. 1997, and references therein). In the standard procedure, the maximum of the CCF (cross-correlation function) is identified with the time delay. However, the delay peak generally has an irregular shape, and this fact causes a bias in the measurement of the time delay between the two components of the system. In this way, two different data sets could lead to two different estimates of the time delay that are in appreciable disagreement. This problem was considered by some authors in the past. Lehár et al. (1992) made a parabolic fit around the maximum of the cross-correlation function, whereas Haarsma et al. (1997) used a cubic polynomial fit to the delay peak. Lehár et al. (1992) suggested that the delay peak of the cross-correlation func-
tion should be closely traced by the central peak (around \( \tau = 0 \)) of the autocorrelation function. Moreover, other features of the cross-correlation function around lags \( \tau_1, \tau_2, \ldots \), will be closely reproduced in the autocorrelation function around lags \( \tau_1 - \Delta t_{BA}, \tau_2 - \Delta t_{BA}, \ldots \).

In this paper we make use of the similarity between the discrete autocorrelation function (DAC) of the light curve of one of the components (B, for example) and the A-B discrete cross-correlation function (DCC) to improve the estimation of the time delay. The same origin of the A and B curves should, in general, have the same features of the cross-correlation function around lags \( \tau_1, \tau_2, \ldots \), will be closely reproduced in the autocorrelation function around lags \( \tau_1 - \Delta t_{BA}, \tau_2 - \Delta t_{BA}, \ldots \), respectively.

Prior to computing the time delay from real data, the \( \delta^2 \) test was applied to some simulated data sets to verify its reliability when dealing with discrete and irregularly sampled data sets. Several sets of artificial photometric data with similar magnitudes, error bars, and time distribution to that of the observations collected at Teide Observatory were created. In this section we will use the same terminology as used with the real data; that is, the \( \delta^2 \) test of the auto- and cross-correlation functions enables the time delay to be determined by comparing two discrete series, DCC and DAC, which should, in general, have the same shape.

### 5.1. Simulated Data

Prior to computing the time delay from real data, the \( \delta^2 \) test was applied to some simulated data sets to verify its reliability when dealing with discrete and irregularly sampled data sets. Several sets of artificial photometric data with similar magnitudes, error bars, and time distribution to that of the observations collected at Teide Observatory were created. In this section we will use the same terminology as used with the real data; that is, the \( \delta^2 \) test of the auto- and cross-correlation functions enables the time delay to be determined by comparing two discrete series, DCC and DAC, which should, in general, have the same shape.

A program was developed to generate sets of dates, \( x_i \), between 1800 and 2000 (JD), approximately, with a pseudo-random separation taken from a uniform distribution between 0 and 5 days, obtained with the G05CAF NAG function. The time data were then alternately separated in two different subsets, corresponding to A- and B-component light curves. A first value of the magnitude was obtained from the B component; and \( (3) \) similar to case 1, from a normal Gaussian distribution with zero mean and standard deviation \( \sigma_y \), were calculated with the G05DDF NAG function, allowing them to adopt positive or negative values. Finally, the magnitude was generated from the equation \( y_i = F(x_i) + d_i = y_i + d_i \), with an error bar of \( \sigma_y \). The A component was forced to be brighter by adding 0.1 to the magnitudes of the B component (although this situation is not realistic, it may be illustrative); moreover, 420 days were subtracted from the JD of the A data set to simulate the existence of a time delay. The result was two pseudorandom sampled functions with pseudorandom noise, a true delay of 420 days, and a B component 0.1 mag fainter than component A. The first two selected functions were:

- **F1**: \( y = 17.17 + 0.5 \exp(-0.5f) \sin f \), where \( f = \frac{(x - 1800)}{20} \)
- **F2**: \( y = 17.2 + 0.1 \sin f \sin 4f \), where \( f = \frac{x}{40} \)

An additional function, consistent with the actual variability of QSO 0957+561, was created. The raw observational data, with none of the modifications explained in this paper, were selected from the 1997–1998 seasons. The light curves were then fitted by the function

- **F3**: \( y = 17.07 - 0.16 \exp(f) \), where \( f = \frac{-{(x - 15.8 - m)}^2}{2(10 + s)^2} \)

where \( m \) is the mean of the JD in the selected range and \( s \) is its standard deviation. The resulting simulated data show a lower variability than that obtained from F1 and F2.

To calculate the DAC and the DCC functions, the procedure described in Edelson & Krolik (1988; see also Oscoz et al. 1997) was followed. For two discrete data trains, \( a_i \) and \( b_j \), the formula corresponding to the DCC is

\[
DCC(\tau) = \frac{1}{M} \frac{(a_i - \bar{a})(b_j - \bar{b})}{\sqrt{(\sigma_a^2 - \bar{a}^2)(\sigma_b^2 - \bar{b}^2)}}
\]

averaging over the \( M \) pairs for which \( \tau - \alpha \leq \Delta t_{ij} < \tau + \alpha \), \( \alpha \) and \( \varepsilon_\alpha \) being the bin semi-size and the measurement error associated with the data set, \( k_i \), respectively. The expression for the DAC can be obtained in a straightforward manner from equation (11), while the expression for \( \delta^2 \) is given by equation (7). Finally, to calculate the uncertainty in the estimation of the time delay, a Monte Carlo algorithm with 1000 iterations was applied to the simulations (see Efron & Tibshirani 1986).

The three simulated clean data sets are shown in Figure 12. Open circles correspond to the A component, while squares correspond to the B component shifted by 420 days and with an offset in magnitude. As can be seen, the two first sets of simulated data (Figs. 12a and 12b) could represent violent epochs in the source quasar, with episodes in which the variability is as much as 0.2–0.3 mag in only 20–30 days. The last set (Fig. 12c) represents an epoch with less variability than the observational one reported in Figure 7. The \( \delta^2 \) test was applied to each clean data set in three different cases: (1) DAC obtained from the A component; (2) DAC obtained from the B component; and (3) similar to case 1,
but this time with a large gap in the light curve B (32 days for F1, 30 days for F2, and 30 days for F3). The resulting values for the time delay and the corresponding error (1σ) in days (see Table 5) clearly indicate that the $\delta^2$ test offers good estimates in all the simulations, even considering the large error bar generated for each point, the existence of “periodic” trends, and the presence of some gaps in some light curves. From Table 5, one can see that the maximum difference between the real and the central value of the derived time delay is 4 days (for a relatively inactive source), and the 1σ intervals always include the true delay. An example of the performance of the $\delta^2$ test has been plotted in Figure 13. The DAC (open circles) for the A component shifted by 420 days versus the DCC (squares) for F2 appear in the upper panel. There is a very good correspondence between the two curves. Possible values of the time delay ($\theta$) versus the associated values, $\delta^2(\theta)$, normalized by its minimum value, have also been represented in the lower panel.

**TABLE 5**

RESULTS OF THE APPLICATION OF A MONTE CARLO ALGORITHM WITH THE $\delta^2$ TEST TO THE SIX SIMULATED CLEAN DATA SETS

| Function | Time Delay | Comments                 |
|----------|------------|--------------------------|
| F1 ........ | 422 ± 2    | DAC with A data          |
|          | 422 ± 2    | DAC with B data          |
|          | 420 ± 3    | gap in B                 |
| F2 ........ | 420 ± 1    | DAC with A data          |
|          | 419 ± 1    | DAC with B data          |
|          | 420 ± 1    | gap in B                 |
| F3 ........ | 420 ± 6    | DAC with A data          |
|          | 420 ± 7    | DAC with B data          |
|          | 416 ± 7    | gap in B                 |

**FIG. 12.**—Simulated clean data sets obtained from three different functions (see text). Circles correspond to the A component; filled squares represent the B component shifted by 420 days and with an offset in magnitude.

**FIG. 13.**—Top: DAC (open circles, shifted by 420 days) vs. DCC (squares) for F2. Bottom: Results of the $\delta^2$ test (divided by its minimum value) offer the expected delay, i.e., 420 days.
5.2. Real Data

The success of the calculation of the time delay from simulated data, as shown in § 5.1, made it reasonable to apply the $\delta^2$ test to real data. The observations, collected at Teide Observatory, covered three consecutive seasons (1996, 1997, and 1998), with 220 different points in the R band. Some points are affected by strong systematic effects and show a strong and simultaneous variation in both components. Once these points were discarded, their total number was reduced to 197. Taking into account the presence of two main gaps in the data, JD 2450242 to 2450347 and JD 2450637 to 2450729, roughly corresponding to the summer months, two different data sets (free from large gaps and edges) can be selected: DS I, corresponding to the 1996–1997 seasons, with 28 points for the A component and 27 points for the B component; and DS II, corresponding to the 1997–1998 seasons, with 44 points for the A component and 86 points for the B component. Both DS I and DS II have been represented in Figure 14, where the B-component light curves have been shifted by 420 days and $+0.06$ mag. As can be seen, DS I corresponds to an epoch of significant calmness in the activity of the quasar, which, together with the relatively small number of points, made it problematical for time-delay calculations. This fact was stated after some tests. In contrast, DS II (the 1997 and 1998 seasons) shows some level of activity (although not as strong as in A 1995/B 1996), and moreover contains an appreciable number of points. Neither is there any clear evidence for any microlensing event, a fundamental requirement for selecting a clean data set. Therefore, DS II was finally used to perform time-delay calculations, i.e., DS II is our clean data set.

The DAC and DCC functions were obtained with the same procedure as used in § 5.1, taking into account that the better monitoring of the B-component light curve as compared to that for the A light curve (see Fig. 14) made it more suitable for the DAC calculations. The application of the $\delta^2$ test to the DAC and DCC curves appears in Figure 15 (normalized as in § 5.1), where the minimum of the $\delta^2$ curve appears at 425 days, corresponding to the best delay. The uncertainty in our estimate of the time delay was obtained by using a Monte Carlo algorithm. A random-number generator added a variable to each point of DS II to simulate the effects of observational errors (see Efron & Tibshirany 1986), standard bootstrap samples being thereby obtained. The $\delta^2$ test was applied to the bootstrap samples to get the time delay in each case, repeating the process 10,000 times, a number large enough for the results to be treated statistically. The use of the Monte Carlo algorithm led to a final value of $425 \pm 4$ days ($1\sigma$). The uncertainty with the $\delta^2$ test is better than the uncertainties obtained with the same clean data set with other alternative methods, such as the dispersion spectra and the discrete cross-correlation tech-
niques (426 ± 12 and 428 ± 9 days, respectively; see Oscoz et al. 1997 and references therein). On the other hand, the $\delta^2$ test with the DAC obtained from the A light curve gives a time delay of 425 ± 5 days. Figure 16 shows the resulting DCC (filled squares) and DAC (for the A component, open circles) curves, where a bin semi-size of $\sigma = 20$ days was used. The DAC has been shifted by 417 (top) and 425 (bottom) days. The disagreement between the two curves is evident in the former case. Our study indicates that the time delay between components A and B of QSO 0957+561 must be in the interval 420–430 days, and is therefore slightly different from the "standard" typical value of 417 days.

6. CONCLUSIONS

CCD observations of the gravitational lens system QSO 0957+561A, B in the $BVRI$ bands are presented in this paper. The observations, taken with the 82 cm IAC-80 telescope at Teide Observatory, Spain, were made from the beginning of 1996 February to 1998 July, as part of an ongoing lens-monitoring program. An alternative method for obtaining accurate multiband CCD photometry of this object is presented. A new, completely automatic IRAF task, PHO2COM, has been developed. This code yields accurate photometry by simultaneously fitting a stellar two-dimensional profile to each QSO component by means of DAOPHOT software. Using a sample of simulated data, it is demonstrated that the proposed method can achieve high-precision photometry, 0.5% for the B component and 0.2% for the A component. In this paper we show that it is also necessary to correct $BVRI$ photometry for color-term variations during a season, and a possible procedure is presented. Although PSF fitting photometry improves aperture photometry errors, the subtraction of the lens galaxy is still not perfect, and some of its light is present in the final B-component magnitude; therefore, the final QSO B-component magnitudes are overestimated. To correct the B-component magnitudes from underlying galaxy light, linear relations between seeing and magnitude errors are deduced by means of simulated data. A remarkable characteristic of the final presented light curves is their high degree of homogeneity; they have been obtained using the same telescope and instrumentation during the 3 yr monitoring campaign.

A calculation of the time delay between the two components by using a clean data set has been performed. The resulting delay, obtained with a new test, the $\delta^2$ test, is 425 ± 4 days, slightly higher than the value previously accepted (417 days), but concordant with the results obtained by Pelt et al. (1996), Oscoz et al. (1997), Pijpers (1997), and Goicoechea et al. (1999).

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REFERENCES

Bernstein, G., Fischer, P., Tyson, J. A., & Rhee, G. 1997, ApJ, 483, L79
Bernstein, G., Tyson, J. A., & Kochanek, C. S. 1993, AJ, 105, 816
Colley, W. N., & Schild, R. E. 1999, Ap&SS, in press (preprint astro-ph/9801315)
Gott, J. R. 1981, ApJ, 243, 140
Gould, A., & Miralda-Escude, J. 1997, ApJ, 483, L13
Haarsma, D. B., Hewitt, J. N., Lehár, J., & Burke, B. F. 1997, ApJ, 479, 102
Howell, S. B., Mitchell, K. J., & Warnock, A., III. 1988, AJ, 95, 247
Kjeldsen, H., & Frandsen, S. 1992, PASP, 104, 413
Kundic, T., et al. 1997, ApJ, 482, 75
Landolt, A. U. 1992, AJ, 104, 340
Lehár, J., Hewitt, J. N., Roberts, D. H., & Burke, B. F. 1992, ApJ, 384, 453
Michalitsianos, A. G., et al. 1997, ApJ, 474, 598
Oscoz, A., Mediavilla, E., Goicoechea, L. J., Serra-Ricart, M., & Buitrago, J. 1997, ApJ, 479, L89
Pelt, J., Hjorth, J., Refsdal, S., Schild, R., & Stabell, R. 1998a, A&A, 337, 681
Pelt, J., Kayser, R., Refsdal, S., & Schramm, T. 1996, A&A, 305, 97
Pelt, J., Schild, R., Refsdal, S., & Stabell, R. 1998b, A&A, 316, 829
Peterson, B. M. 1993, PASP, 105, 247
Pijpers, F. P. 1997, MNRAS, 289, 933
Press, W. H., & Rybicki, G. B. 1998, ApJ, 507, 108
Press, W. H., Rybicki, G. B., & Hewitt, J. N. 1992, ApJ, 385, 404
Schild, R. E., & Thomson, D. J. 1995, AJ, 109, 1970
Schild, R. E., & Weckes, T. 1984, ApJ, 277, 481
Stetson, P. B. 1987, PASP, 99, 191
Vanderriest, C., Schneider, J., Herpe, G., Chevreton, M., Moles, M., & Wierick, F. 1989, A&A, 215, 1
Walsh, D., Carswell, R. F., & Weymann, R. J. 1979, Nature, 279, 381