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THE INFLUENCE OF MICROLENSING ON TIME DELAY DETERMINATIONS IN DOUBLE-IMAGED QUASARS

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ABSTRACT

The lag associated with the main peak of the cross-correlation function of the two light curves arriving from a double-imaged quasar is usually identified with the time delay between the components. However, short-timescale microlensing events can independently modify the light curve of each component, and when strong microlensing is present, the features of the cross-correlation function depend on both amplitude and shape of the microlensing events. This fact prevents a direct interpretation of the lag associated with the main peak as the true time delay.

We present a new analysis of the light curves cross-correlation function including short-timescale microlensing. We discuss its application to the 1995/1996 optical photometry of Q0957+561, and determine the trend of a possible microlensing event taking place from JD 2,450,150 to 2,450,200.

Subject headings: gravitational lensing — quasars: individual (0957+561)

1. INTRODUCTION

One of the main motivations for the study of extragalactic gravitational lenses is the possibility of determining the Hubble constant from the time delay between the light curves of the multiple images from a lensed quasar (Refsdal 1964a, 1964b). In the simplest case (a double-imaged QSO with components A and B and negligible microlensing fluctuations in the two images), the intrinsic fluctuations (caused by source variability) in the light curve of image A will be observed at a later time in the light curve of B. The time delay, then, can be inferred by comparing the light curves of A and B. This is usually done by computing the time lag associated with the main peak of the cross-correlation function of both light curves. However, in several cases, when the light curve of the A component is shifted by the time delay, it disagrees with the light curve of B. This fact affects the main hypothesis of the procedure (that the lag is obtained by comparing two functions of identical shape) and calls in question the identification of the time delay with the lag inferred from the main peak of the cross-correlation function (see, e.g., Schild 1996).

The discrepancy between the two signals is generally ascribed to microlensing events, a phenomenon caused by individual objects in the lensing galaxy that has been detected in some multiple imaged QSOs (see, e.g., Irwin et al. 1989; Schild & Smith 1991). The typical timescale of a microlensing event depends on the crossing time $t_{\rm E} = r_{\rm E}/v$, where $r_{\rm E}$ is the Einstein radius of the individual object (microlens) and v is the transverse velocity of the system. In the case of Q0957+561, $t_{\rm E} = 30$ yr for a star with $M = 1$ $M_\odot$. As $r_{\rm E}$ grows as the square root of the microlens mass, the observed events with a few months duration could be related to *rogue planets* (Schild 1996), although a very recent alternative explanation is based on stellar-mass microlenses and "spots" moving at the orbital velocity of the accretion disk in the source (Gould & Miralda-Escudé 1997).

In this paper we discuss the effect of short-timescale events (with a duration less than the sampling time of each image) on the determination of the time delay from the A-B cross-correlation function of a double-imaged quasar (§ 2). In § 3 we apply the preceding results to the case of Q0957+561 and analyze the cross-correlation functions obtained by using recent optical photometric data. The main conclusions and some remarks are presented in § 4.

2. THE CROSS-CORRELATION FUNCTION IN THE PRESENCE OF MICROLENSING

Let $\Delta\tau_{BA}$ be the time delay associated with image B, relative to image A, of a double-imaged quasar. In this case, the following relationship between the light curves (magnitudes) is verified:

$$B(t) = A(t - \Delta\tau_{BA}) + \ell + m(t) , \quad (1)$$

where ℓ is a constant and $m(t)$ accounts for the microlensing events. The classical correlation function is defined as

$$\mathrm{CF}_{XY}(\tau) = \frac{1}{\sigma_X \sigma_Y} \langle [X(t) - \langle X \rangle][Y(t+\tau) - \langle Y \rangle] \rangle , \quad (2)$$

with $\langle Z \rangle$ being the mean value of the function Z and σ_Z its standard deviation $\{\sigma_Z = \langle [Z(t) - \langle Z \rangle]^2 \rangle^{1/2}\}$. Therefore, the A-B cross-correlation function will be

$$\mathrm{CF}_{AB}(\tau) = \frac{\sigma_A}{\sigma_B} \left[\mathrm{CF}_{AA}(\tau - \Delta\tau_{BA}) + \mathrm{CF}_{Am}(\tau) \frac{\sigma_m}{\sigma_A} \right] . \quad (3)$$

By using the definition of σ_B together with equation (1), the standard deviations σ_A and σ_B are related by

$$\sigma_B^2 = \sigma_A^2 + \sigma_m^2 + 2\mathrm{CF}_{Am}(\Delta\tau_{BA})\sigma_A \sigma_m , \quad (4)$$

and, from equations (3) and (4),

$$\mathrm{CF}_{AB}(\tau) = \left[\mathrm{CF}_{AA}(\tau - \Delta\tau_{BA}) + \mathrm{CF}_{Am}(\tau) \frac{\sigma_m}{\sigma_A} \right] \times \left[1 + 2\mathrm{CF}_{Am}(\Delta\tau_{BA}) \frac{\sigma_m}{\sigma_A} + \frac{\sigma_m^2}{\sigma_A^2} \right]^{-1/2} . \quad (5)$$

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In the absence of microlensing, equation (5) is reduced to the standard result $CF_{AB}(\tau) = CF_{AA}(\tau - \Delta\tau_{BA})$. That is to say, the cross-correlation at τ should be equal to the autocorrelation (for A) at $\tau - \Delta\tau_{BA}$. This relationship leads to $CF_{AB}(\Delta\tau_{BA}) = CF_{AA}(0) = 1$. In this case ($m = 0$), we expect a main peak at $\tau = \Delta\tau_{BA}$ (of amplitude equal to 1) and, maybe, secondary peaks at different time lags (depending on the complex shape of the light curve A). However, from equation (5), assuming the presence of strong microlensing ($\sigma_m/\sigma_A \approx 1$) with $|CF_{Am}(\Delta\tau_{BA})| \ll 1$, one obtains a reduced delay peak of amplitude $CF_{AB}(\Delta\tau_{BA}) \approx (1 + \sigma_m^2/\sigma_A^2)^{-1/2}$. In this case, it is not evident that the relationship $\max[CF_{AB}] = CF_{AB}(\Delta\tau_{BA})$, where $\max\,[CF_{AB}]$ is the maximum value of the A-B cross-correlation function is applicable. If we restrict our attention to a case in which $CF_{AA}(\tau_0 - \Delta\tau_{BA})$ and $CF_{Am}(\tau_0)$ are relatively large (and positive), then (see eq. [5]) $CF_{AB}(\tau_0) > CF_{AB}(\Delta\tau_{BA})$. As a consequence, a conspiracy of nature could lead us to an incorrect determination of the time delay (taking the time lag τ_0 as the delay) and to detect false microlensing events (by comparing the light curve A shifted by τ_0 and the light curve B).

In practice, the analysis of the A and B images are carried out during a finite monitoring time. So the quantities ℓ and $m(t)$ that appear in equation (1) must be considered as a general magnitude offset (which denotes an effective amplification ratio caused by lensing, microlensing on long timescales, a calibration of image B in disagreement with the calibration of A, etc.) and a microlensing variability on (short) timescales smaller than the monitoring time, respectively.

3. APPLICATION TO THE CASE OF QSO 0957+561

After 10 years of controversy on the time delay of the double quasar Q0957+561, recent studies confirm the "short" delay of 400–440 days. The dispersion spectra method, applied to the optical brightness history of Q0957+561 (see Schild & Thomson 1995), leads to a time delay close to 420 days (Pelt et al. 1996). Radio light curves also show that the time delay is less than 500 days (in the range 398–461 days, with 430 days on average), in contrast with previous work based on the 1979/1990 monitoring program (Haarsma et al. 1997). Moreover, the 1995/1996 optical monitoring campaigns of Q0957+561 have been crucial in deriving the time delay in this gravitational mirage. On the one hand, the image A exhibited a significant variability from 1994 December to 1995 May (Kundić et al. 1995); on the other, the system has been analyzed by (at least) three different groups: Smithsonian (Whipple Observatory 1.2 m telescope), IAC (Teide Observatory 0.8 m telescope), and Princeton (Apache Point Observatory 3.5 m telescope). From the A95(Princeton), B96(Princeton), and B96(IAC) light curves, a time delay of about 420 days is derived, which is robust against variations in the method of analysis, optical filter, and telescope (Oscoz et al. 1996, 1997; Kundić et al. 1997).

Very recently, Rudy Schild provided us with the A95(Smithsonian) and B96(Smithsonian) R-band light curves. The A95 data set contains observations from 1994 December to 1995 May, in agreement with the monitoring time by Kundić et al. (1995), whereas the B96 data set contains CCD photometry of the B-image from 1996 February to 1996 June, in agreement with the campaign carried out by Oscoz et al. (1996). By means of these light curves, the reliability of the time delay deduced from the above quoted comparisons (Princeton-Princeton and Princeton-IAC) can be discussed. In particular, we are going to analyze the A95(Smithsonian)-B96(IAC) and A95(Smithsonian)-B96(Smithsonian) cross-correlation functions. By using this method we obtain the discrete correlation functions (Edelson & Krolik 1988), instead of interpolating in the temporal domain.

The Smithsonian-IAC and Smithsonian-Smithsonian discrete correlation functions (DCFs) appear in Figure 1. They are binned in 5 day intervals centered at different time lags (*circles*), while the noise levels (see the end of § II in Edelson & Krolik 1988) have been represented by solid lines. In the Smithsonian-IAC comparison (*top panel*), we can see a peak of typical amplitude close to 1, which is characterized by a "cloud" (maximum) centered at $\tau = 417$ days (one suspects that $\Delta\tau_{BA} = 417$ days; here, we only obtain typical or mean values—for comments on errors, see, e.g., Oscoz et al. 1997). This prominent feature is accompanied by some secondary peaks (of typical amplitude equal to 0.3) and two prominent regions of anticorrelation. The A-A autocorrelation function, shifted by 417 days, basically agrees with the cross-correlation function in the top panel (Fig. 1), and so there is no evidence in favor of an important microlensing event, and our suspicion is confirmed; i.e., $\Delta\tau_{BA} = 417$ days, in good agreement with previous work.

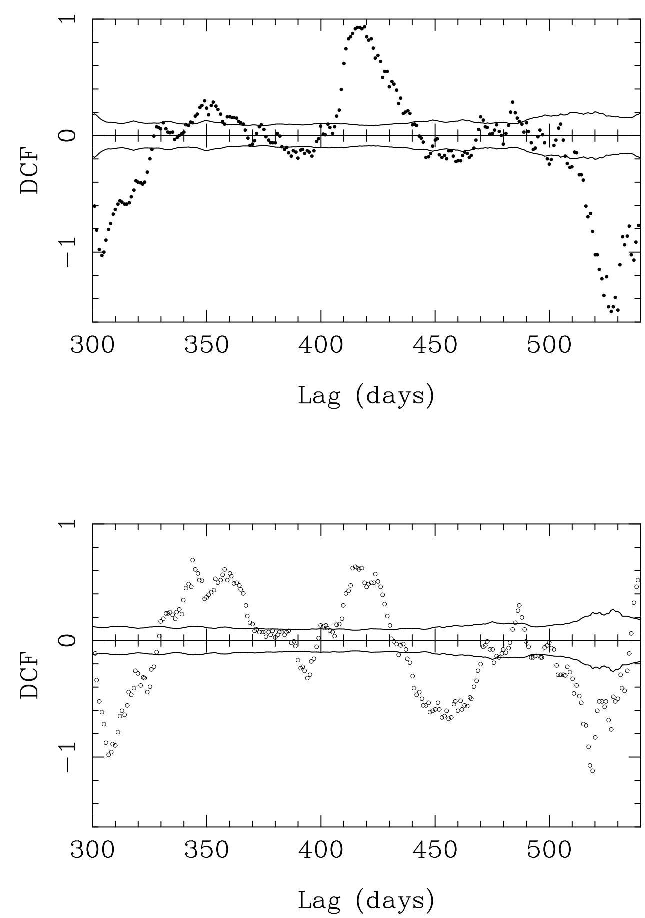

FIG. 1.—DCF of Q0957+561, evaluated every 1 day (using an interval with size of 5 days) in the region from 300 to 540 days. The noise levels are traced by solid lines. DCF(Smithsonian-IAC) appears in the top panel (*filled circles*), whereas DCF(Smithsonian-Smithsonian) appears in the bottom panel (*open circles*).

On the contrary, the Smithsonian-Smithsonian correlation function (Fig. 1, *bottom panel*) is peculiar. A main peak with amplitude of about 0.7 (corresponding to a time lag of 344 days) appears, and also there is a secondary peak at $\tau = 414$–418 days (with amplitude of about 0.6). Naively, one might think that $\Delta\tau_{BA} < 1$ yr (a very short delay). However, the results of the previous section, together with a private communication (1997) by Rudy Schild (who kindly advised us that the Smithsonian data show a microlensing event of 2 months' duration), suggest the need for a more rigorous analysis. In particular, we cannot directly rule out a time delay of about 420 days, e.g., 417 days. The presence of a strong microlensing could be responsible for such a low delay peak at $\tau = 414$–418 days.

From the Smithsonian-Smithsonian comparison, is $\Delta\tau_{BA} = 417$ days reasonable? The answer is yes, and our reasoning is simple. Assuming that $\Delta\tau_{BA} = 417$ days, we use the A95(Smithsonian) light curve shifted by 417 days and the B96(Smithsonian) light curve to estimate a discrete microlensing curve binned in intervals of 5 days (around the dates in B96). Figure 2 illustrates the microlensing history (*open circles and solid line*) and the evolution of $A - \langle A \rangle$ (*dotted line*). The existence of a deep event from JD 2,450, 150 to 2,450,200 is apparent as well as different events on weekly scales. In addition, one finds that the fluctuations caused by the phenomenon ($m - \langle m \rangle$) are similar to the fluctuations in the QSO signal ($A - \langle A \rangle$); i.e., there is a strong microlensing with $\sigma_m/\sigma_A \approx 1.3$. Finally, in presence of this strong and weakly correlated ($|\mathrm{CF}_{Am}(\Delta\tau_{BA})| \ll 1$, see Fig. 2) microlensing, equation (5) leads to $\mathrm{CF}_{AB}(\Delta\tau_{BA}) \approx (1 + \sigma_m^2/\sigma_A^2)^{-1/2} \approx 0.6$, in excellent agreement with the height of the "cloud" at $\tau = 414$–418 days.

To complete the analysis of the 1995/1996 data we have also combined the A95(Princeton)-B96(Smithsonian) and A95(Smithsonian)-B96(Princeton) time series. The A95(Smithsonian)-B96(Princeton) cross-correlation function gives a peak close to one at a lag near 420 days. On the contrary, the shape of the A95(Princeton)-B96(Smithsonian) also turns out to be peculiar, showing a main peak with amplitude of about 0.7 at a lag of 372 days and a secondary double peak at $\tau = 414$–430 days. The global conclusion is that the comparisons [A95(Smithsonian)-B96(IAC); A95(Princeton)-B96(Princeton); A95(Smithsonian)-B96(Princeton); A95(Princeton)-B96(IAC)] suggest a time delay near 420 days, whereas the two comparisons involving the light curve B96 of Smithsonian [A95(Princeton)-B96(Smithsonian); A95(Smithsonian)-B96(Smithsonian)] lead to peculiar results. This fact seems to confirm the existence of a perturbation in the B96(Smithsonian) data, possibly caused by microlensing events (see Fig. 2). As we have shown, even the anomalous A95(Smithsonian)-B96(Smithsonian) cross-correlation function is not in disagreement with a true time delay of about 420 days.

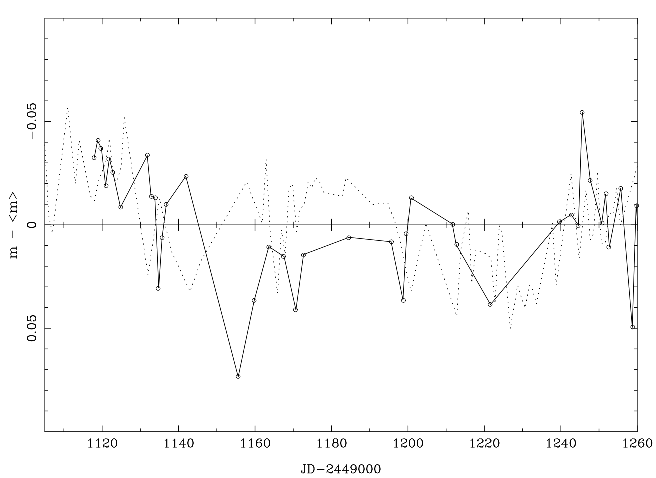

FIG. 2.—Discrete microlensing curve of 0957+561 (Smithsonian-Smithsonian, $\Delta\tau_{BA} = 417$ days) binned in intervals of 5 days (*open circles and solid line*), and evolution of $A - \langle A \rangle$ (*dotted line*). Note that both curves $m - \langle m \rangle$ and $A - \langle A \rangle$ are similar in amplitude.

4. CONCLUSIONS AND FINAL REMARKS

For a double-imaged quasar, in the absence of significant microlensing events on timescales smaller than the monitoring time of each image, the lag associated with the main peak of the cross-correlation function of the two light curves (A and B) gives a good estimate of the time delay (which can be improved by matching the shifted autocorrelation function with the cross-correlation function). However, as has been discussed in this paper, the presence of short-scale microlensing events in some of the curves can distort the cross-correlation shape and modify the expected (in absence of microlensing) amplitudes of the delay-peak (equal to one) and secondary peaks. That is why the lag associated with the main peak of the cross-correlation function cannot be directly interpreted as the time delay. However, if the true time delay can be obtained from complementary observations, the analysis developed in § 2 is useful for studying the light curve of a typical microlensing event and its frequency (number of events per year).

From recent optical data of the double quasar 0957+561, we have inferred a cross-correlation function of

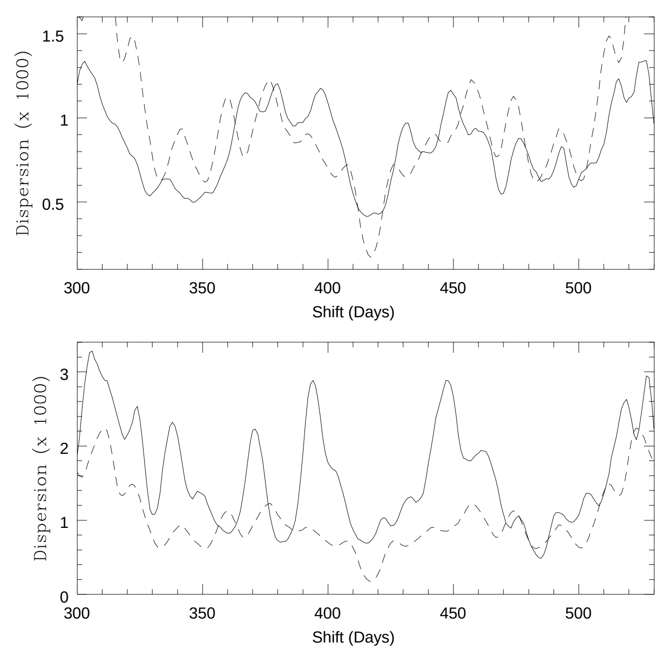

FIG. 3.—Spectra derived by applying the dispersion estimate 4.2 with $l(t) = l_0$ and $\delta = 5$ days to the A95(Smithsonian), B96(Smithsonian), and B96(IAC) data. D_{AA}^2 (Smithsonian-Smithsonian shifted by 417 days, *dashed lines*) is represented in the top panel together with D_{AB}^2 (Smithsonian-IAC, *solid line*), showing no evidence of microlensing. On the contrary, the absence of microlensing is not justified in the bottom panel, where D_{AA}^2 is plotted together with D_{AB}^2 (Smithsonian-Smithsonian).

peculiar shape (see Fig. 1, *bottom panel*), characterized by a main peak with amplitude of about 0.7 and a secondary peak with amplitude of about 0.6 (associated with a time lag of $\tau \sim 414$–418 days). Assuming a time delay of 417 days (see Fig. 1, *top panel*, and Kundić et al. 1997), we have derived the corresponding microlensing curve and showed that a strong microlensing event taking place from JD 2,450,150 to 2,450,200, together with other microlensing features, has modified the expected amplitude of the peaks (see Fig. 1, *top panel*). Consequently, the true delay in Figure 1 (*bottom panel*) could correspond to the lag associated with the secondary peak, instead of the lag associated with the main one.

We wish to comment on the usefulness of the dispersion spectra standard method in inferring the time delay when the light curves are seriously contaminated by microlensing. We have applied the dispersion estimate 4.2 with $l(t) = l_0$ and a decorrelation length of $\delta = 5$ days (Pelt et al. 1996) to the A95(Smithsonian), B96(Smithsonian), and B96(IAC) data, obtaining the spectra depicted in Figure 3. In the top panel is represented the autodispersion D^2_{AA} of the A95(Smithsonian) data set shifted by 417 days (*dashed lines*),

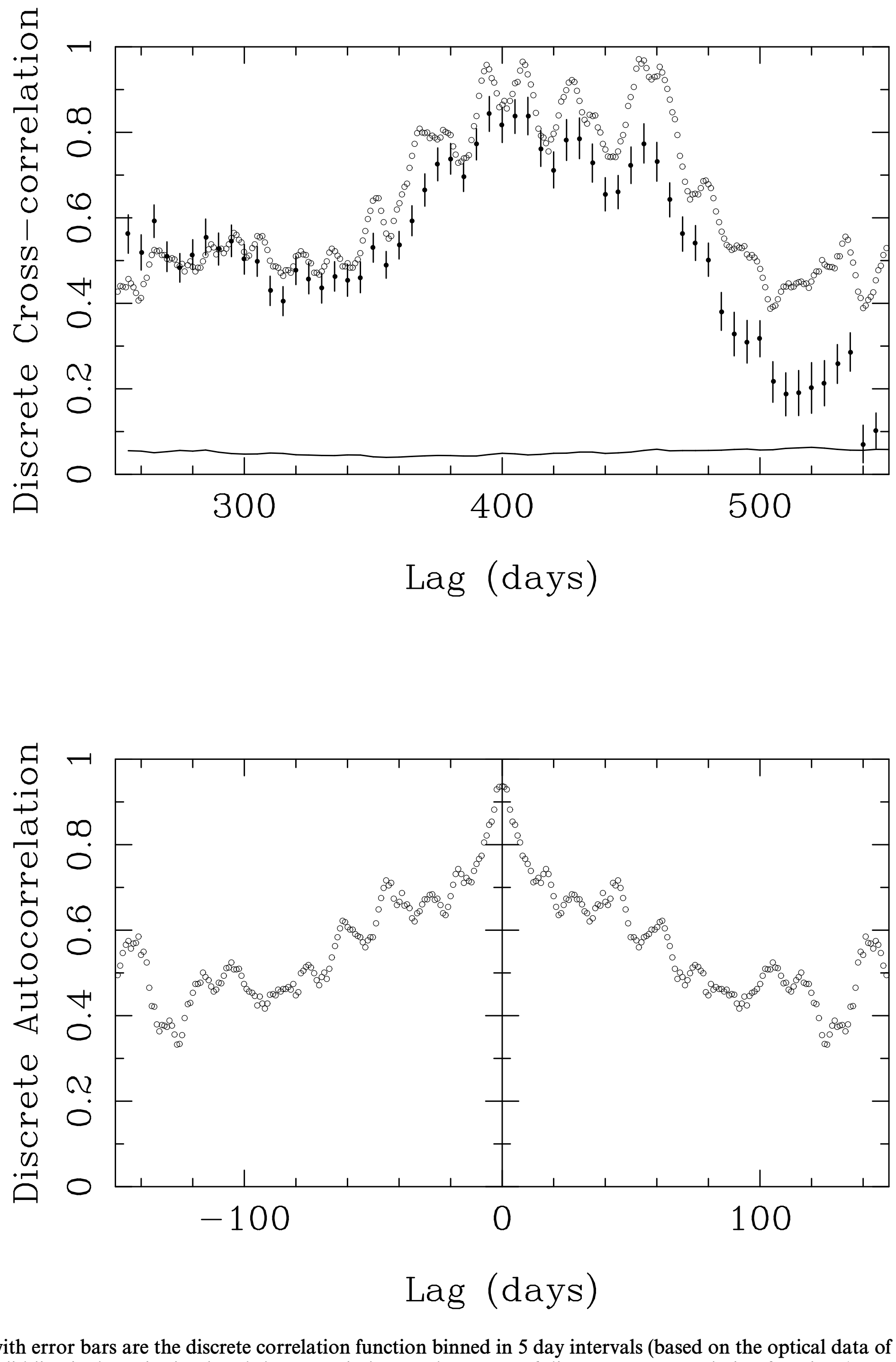

FIG. 4.—The points with error bars are the discrete correlation function binned in 5 day intervals (based on the optical data of 0957+561 used by Schild & Thomson 1997), the solid line is the noise level and the open circles are the *corrected* discrete cross-correlation function (*top panel*) and the *A-A* discrete autocorrelation function (*bottom panel*). For these last correlation functions (*open circles*), the separation between consecutive bins (*centers*) is of 1 day, and the bin size is 5 days.

together with D^2_{AB} (Smithsonian-IAC, *solid line*). The conclusions arising from both spectra are that no global distortion due to microlensing is detected, and so our hypothesis $l(t) = l_0$ (absence of microlensing) is reasonable, and a time delay close to 420 days is again confirmed. On the contrary, the trends of D^2_{AA} and D^2_{AB} (Smithsonian-Smithsonian, *bottom panel*) indicate that the standard hypothesis $l(t) = l_0$ is not justified in this last comparison. The dispersion spectrum D^2_{AB} (Smithsonian-Smithsonian) has a meaningless minimum at 485 days (remember that the cross-correlation function applied to these data sets gave a maximum at 344 days; see Fig. 1, *bottom panel*).

Finally, we include a remark on the cross-correlation function derived by Schild & Thomson (1997). By using optical data for Q0957+561 (from 1992 October to 1995 June), they derived an *A*-*B* cross-correlation function with a broad peak and a maximum at 404 days. We have reproduced their analysis in Figure 4 (*top panel*): the points with error bars are the discrete cross-correlation function, binned in 5 days intervals, and the solid line is the noise level. The broad peak is dominated by the signal at 395–410 days and, at first sight, a time delay of 404 days would be a reasonable choice. However, this value, based on a 3 yr program, disagrees with the one ($\sim$420 days) we deduced previously, and the differences may arise from an unfortunate selection of data. It is well known that, in the case of 0957+561, there is an excess time delay of (roughly) 1.1 yr associated with image *B*, relative to image *A*. So the procedure would be to compare the two first-year *A*-data with the two last-year *B*-data. However, the inclusion of the "edges" (the last data of light curve *A* and the first data of light curve *B*) in the calculation of the time delay can be dangerous in a relatively short duration sampling (when the monitoring time is of 2–3 times the time delay) and can lead to confusion. When the edges are removed, the correlation function obtained is slightly different, as can be seen in Figure 4 (*open circles in top panel*), and, in this case, the signal in the region of interest (390–460 days) shows a maximum at $\tau = 453$ days. On the other hand, the *A*-*A* autocorrelation function (see Fig. 4, *open circles in bottom panel*) shows a narrow central peak, in disagreement with the broad structure of amplitude close to 1 (in the interval 390–460 days) that appears in the cross-correlation shape. The problem is solved assuming a symmetric widening, which allows the relation of the broad cross-correlation to the autocorrelation peak, and so, a time delay of $\sim$425 days is derived. The extreme values (400 or 450 days) are not favored.

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REFERENCES

Edelson, R. A., & Krolik, J. H. 1988, ApJ, 333, 646
Gould, A., & Miralda-Escudé, J. 1997, ApJ, 483, L13
Haarsma, D. B., Hewitt, J. N., Lehár, J., & Burke, B. F. 1997, ApJ, 479, 102
Irwin, M. J., Webster, R. L., Hewett, P. C., Corrigan, R. T., & Jedrzejewski, R. I. 1989, AJ, 98, 1989
Kundić, T., Colley, W. N., Gott, J. R., III, Malhotra, S., Pen, U., Rhoads, J. E., Stanek, K. Z., Turner, E. L., & Wambsganss, J. 1995, ApJ, 455, L5
Kundić, T., Turner, E. L., Colley, W. N., Gott III, J. R., Rhoads, J. E., Wang, Y., Bergeron, L. E., Gloria, K. A., Long, D. C., Malhotra, S., & Wambsganss, J. 1997, ApJ, 482, 75
Oscoz, A., Mediavilla, E., Goicoechea, L. J., Serra-Ricart, M., & Buitrago, J. 1997, APJ, 479, L89
Oscoz, A., Serra-Ricart, M., Goicoechea, L. J., Buitrago, J., & Mediavilla, E. 1996, ApJ, 470, L19
Pelt, J., Kayser, R., Refsdal, S., & Schramm, T. 1996, A&A, 305, 97
Refsdal, S. 1964a, MNRAS, 128, 295
———. 1964b, MNRAS, 128, 307
Schild, R. 1996, ApJ, 464, 125
Schild, R., & Smith, R. C. 1991, AJ, 101, 813
Schild, R., & Thomson, D. J. 1995, AJ, 109, 1970
———. 1997, AJ, 113, 130