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TIME DELAY FOR THE GRAVITATIONAL LENS Q0957+561 A,B

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ABSTRACT. *We propose a method for estimation of the time delay between identical time samples with unequidistant data. We have analyzed Vanderriest's (1989) and Schild's (1990) photometric observations of Q0957+561 A,B, the first gravitational lens. The time delay is found to be 1.45±0.04 years. Using the Monte-Carlo simulations we compare reliability of time delay determination methods and define that the confidence level of our result is better than 99%. The problem of microlensing effects is briefly discussed.*

I. INTRODUCTION

Since the first gravitationally lensed quasar was detected (Wolsh et al., 1979), the interest of astronomers to such objects has been growing from year to year. This is not a consequence of mere curiosity about a new exotic phenomenon, but that of hopes to realize determination of the Hubble's constant by measurement of the time delay (Refsdal, 1964; 1966). Up to now the first gravitational lens has remained the most attractive object for time delay determination in view of the:

(1) fact it is bright enough for photometry with medium-size telescopes;
(2) easily separated images (6″ distance);
(3) possibility of determination of the lens parameters;
(4) possibility of correction of brightnesses for galaxy light contamination;
(5) time scale of the brightness variations is less than/or of the order of the

expected time delay value;

(6) possibility of monitoring during more than half a year every season;

(7) closeness of flux ratio A/B to 1;

(8) the longest monitoring data sets.

The results of the published attempts of time delay determination are briefly summarized in Table 1. We can divide the time delay estimates from Table 1 into three groups: 1-3 - the preliminary results on the basis of few data sets which are scattered in the interval 1.1 yr < τ_0 < 1.8 yr; 5,6 - two independent estimates (1.11±0.01) yr and (1.14±0.05) yr, which coincide within the quoted errors, but in the methods being used no attention has been paid to possible errors caused by the irregularity of the data set spacing; 4,7-9 - several independent investigations, which give τ_0 around 1.45 yr. Thus, now we have two statistically different estimates of τ_0. What is the reason of this discrepancy? Are some of these estimates incorrect (Beskin and Oknyanskij, 1991) or have the uncertainties in these values been under-estimated (Falco et al., 1990)? The main purpose of our work is to give answers to these questions and to determine the exact time delay.

Table 1. Time delay measurements

No	Reference		Sample length (years)	n	Range	Time delay (years)
1.	Florentin-Nielsen	1984	5	50	B_{pg}	1.55±0.10
2.	Schild & Cholfin	1986	4	29	r	1.03±0.10
3.	Gondhalekar et al.	1986	4	11	UV	1.80±0.20
4.	Lehar et al.	1989	8	41	radio	1.31±0.25
5.	Vanderriest et al.	1989	8	127	B	1.14±0.05
6.	Schild	1990	9	373	r	1.11±0.01
7.	Beskin & Oknyanskij	1991	8	127	B	1.45±0.04
			9	373	r	1.43±0.04
8.	Roberts et al.	1991	8	80	radio	1.41±0.10
9.	Press et al.	1991a	8	127	B	1.47±0.04
		1991b	8	207	B+radio	1.48±0.03

2. TIME DELAY DETERMINATION METHOD

The description of the algorithm for the time delay search has been given briefly in our recent paper (Beskin and Oknyanskij, 1991).

If no microlensing affected the brightness of the QSO images, the flux $a(t)$ of image A at time t would be, up to a constant factor μ (the ratio of magnifications of two images), identical to the flux $b(t+t_0)$ of image B a time τ_0 later:

$$m_t(\tau_0) = \frac{a(t)}{b(t+\tau_0)} \equiv \mu. \qquad (1)$$

In practice, the measurement and approximation errors lead to some variations of this ratio $m_t(\tau_0)$ near the value of μ. Naturally, at $\tau\neq\tau_0$ this ratio depends also on the real variability of images. Therefore the dispersion of the ratio $m_t(\tau)$ must have a minimum at $\tau=\tau_0$. We use this property of gravitational lenses as a priori information. Note, that this idea was used also by Vanderriest et al. (1989) and Falco et al. (1990) with some distinctions. Our method has some essential improvements which will be obvious from what follows. We do not interpolate the data into an evenly spaced grid. We take only real measured flux points for one of the images, namely B, $b(t_k+\tau)$ and couple them (if possible) with weight-averaged fluxes for the second image A

$$a_k \equiv a(t_k) = \frac{\sum w_i a(t_i)}{\sum\limits_{\text{bin}} w_i} \tag{2}$$

in intervals $\quad |t_i - t_k + \tau| \leqslant \varepsilon$, (3)

where ε is the halfwidth of bin; $w_i = 1/[\sigma_e^2(a_i) + \sigma_c^2(a_i)]$ is the weight of points $a(t_i)$. Each point $a(t_i)$ has been weighted according, first, to the measurement errors $\sigma_e^2(a_i)$ and, second, binning errors $\sigma_c^2(a_i)$, which depend on the closeness to the centre of the bin (the weighing function is taken from average variation of $a(t)$). Errors of the weight-averaged fluxes a_k are equal to

$$\sigma(a_k) = \frac{1}{\sqrt{\sum\limits_{\text{bin}} w_i}} \;. \tag{4}$$

Then we can calculate the values of $m_{t_k}(\tau) = \dfrac{a(t_k)}{b(t_k+\tau)} \equiv \dfrac{a_k}{b_k}$,

their errors

$$\sigma_k(\tau) = m_{t_k}(\tau) \sqrt{\frac{\sigma^2(a_k)}{a_k^2} + \frac{\sigma_e^2(b_k)}{b_k^2}} \,, \tag{5}$$

where $\sigma_e^2(b_k)$ - measurement error of b_k, and relative weights

$$p_k(\tau) = \frac{\dfrac{1}{\sigma_k^2(\tau)}}{\sum\limits_{k=1}^{n} \dfrac{1}{\sigma_k^2(\tau)}} \;. \tag{6}$$

In contradistinction to Vanderriest et al. (1989) and Falco (1985) we take into account different weights of sample values $m_t(\tau)$ by introducing special normalization.

For every value of τ we calculate two heuristic functions $R_1(\tau)$ and $R_2(\tau)$:

$$R_1(\tau) = \frac{S(\tau)}{S_0(\tau)}\ , \qquad (7)$$

$$R_2(\tau) = \frac{S_v(\tau)}{S(\tau)}\ , \qquad (8)$$

where

$$S(\tau) = \frac{n}{n-1}\sum_{k=1}^{n} [m_{t_k}(\tau) - \bar{m}(\tau)]^2\ p_k(\tau) \qquad (9)$$

is a sample weight-averaged dispersion of $m_{t_k}(\tau)$;

$$S_0(\tau)= \frac{n}{\sum_{k=1}^{n} \frac{1}{\sigma_k^2(\tau)}} \qquad (10)$$

is a theoretical weight-averaged dispersion of individual value m_{t_k};

$$S_v(\tau) = \frac{1}{n-1}\left[\frac{\bar{a}(\tau)}{\bar{b}(\tau)}\right]^2 \left[\frac{\sum_{k=1}^{n}(a_k - \bar{a}(\tau))^2}{\bar{a}^{\,2}(\tau)} + \frac{\sum_{k=1}^{n}(b_k - \bar{b}(\tau))^2}{\bar{b}^{\,2}(\tau)}\right] \qquad (11)$$

is a theoretical sample dispersion of $m_{t_k}(\tau)$, which is defined only by variations of a_k and b_k, respectively;

$$S(\tau) = \frac{1}{n-1}\sum_{k=1}^{n} [m_{t_k}(\tau)- \bar{m}(\tau)]^2 \qquad (12)$$

is a sample dispersion of $m_{t_k}(\tau)$;
n is the number of independent values of ratio $m_{t_k}(\tau)$ for fixed τ; $\bar{a}(\tau)$, $\bar{b}(\tau)$, $\bar{m}(\tau)$ are sample averaged values a_k, b_k, $m_{t_k}(\tau)$, respectively.

If $\tau \to \tau_0$, then function $R_1 \to 1$ and must at least have a minimum, and function R_2 must be essentially more than 1 and reach maximum. The statistic R_2 is necessary to verify the nature of R_1 minimum, which can be reached at occasionally small scattering of the fluxes a_k and b_k. If, for example, $R_1(\tau')$ is about 1 and has a minimum, but $R_2(\tau')$ is also about 1, then we can say that the minimum of $R_1(\tau')$ is the consequence of small dispersion of the sample fluxes for this τ'.

III. RESULTS AND DISCUSSION

Figs. 1 and 2 show the results of calculation of the statistics R_1 and R_2 for Vanderriest et al. (1989) (basic sample) and Schild (1990) (control sample) data, respectively. The most noticeable extrema in both statistics for these samples correspond to τ_0=540±30 days (ε=15 days) and - 525±15 days (ε=7.5 days). To estimate the significance level of this result, we used Monte-Carlo method, because usual parametrical analysis may be incorrect for this case. We applied our method to thousand synthetic light curves of A and B, which have the same dispersion, mean, time distribution, and power spectrum, as actual data, and estimate that the confidence level of the result obtained is about 99%. For both samples the time delay is about 530±15 days with the confidence level better than 99%.

We generated Monte-Carlo data sets, as mentioned before, but with (simulated) measurement errors identical to the true data (for basic sample) and with assumed time delays equal to 420 (case 1) and 540 (case 2) days.

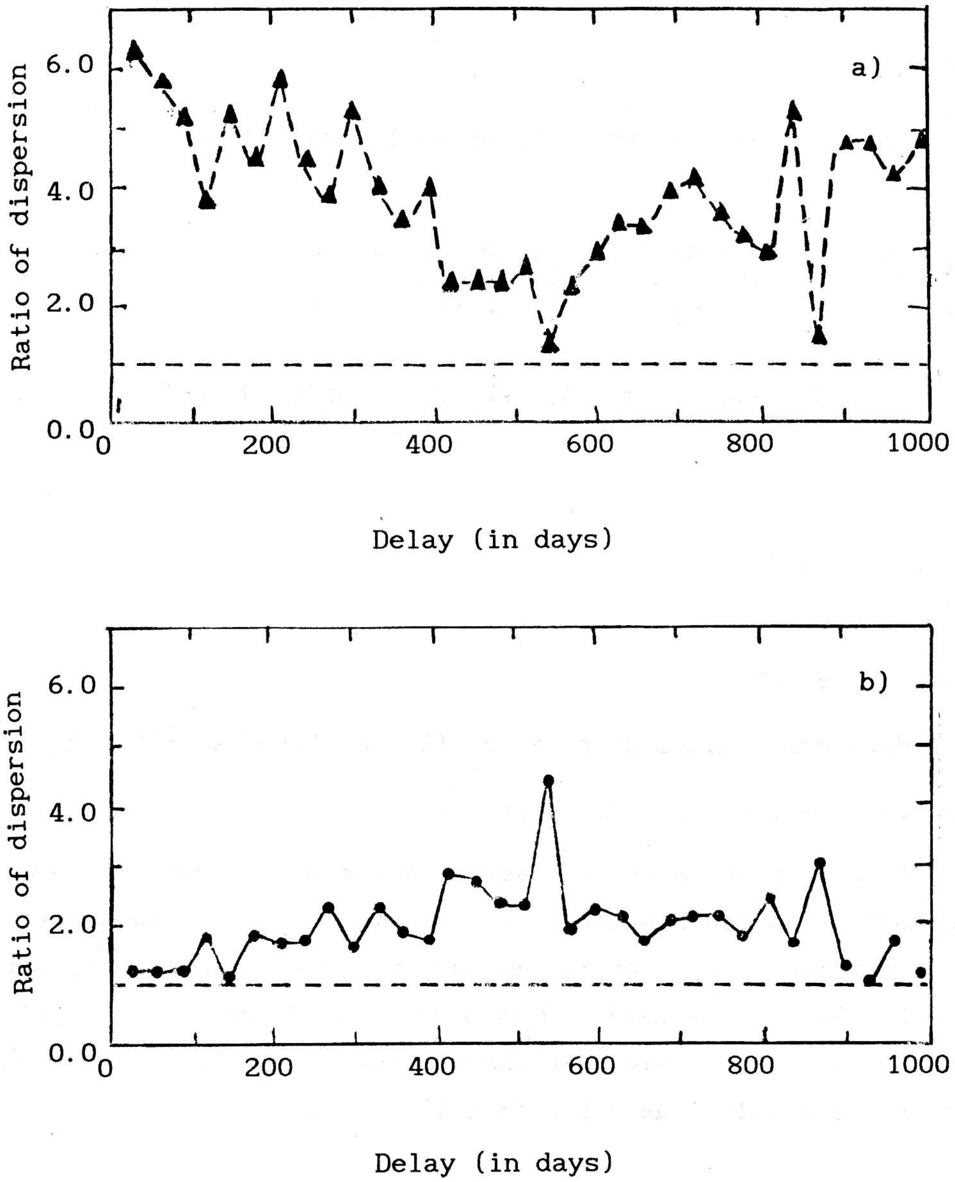

Fig. 1. Heuristic functions for the basic sample: a) function $R_1(\tau)$ with a minimum near 540 days, b) function $R_2(\tau)$ with a maximum near 540 days.

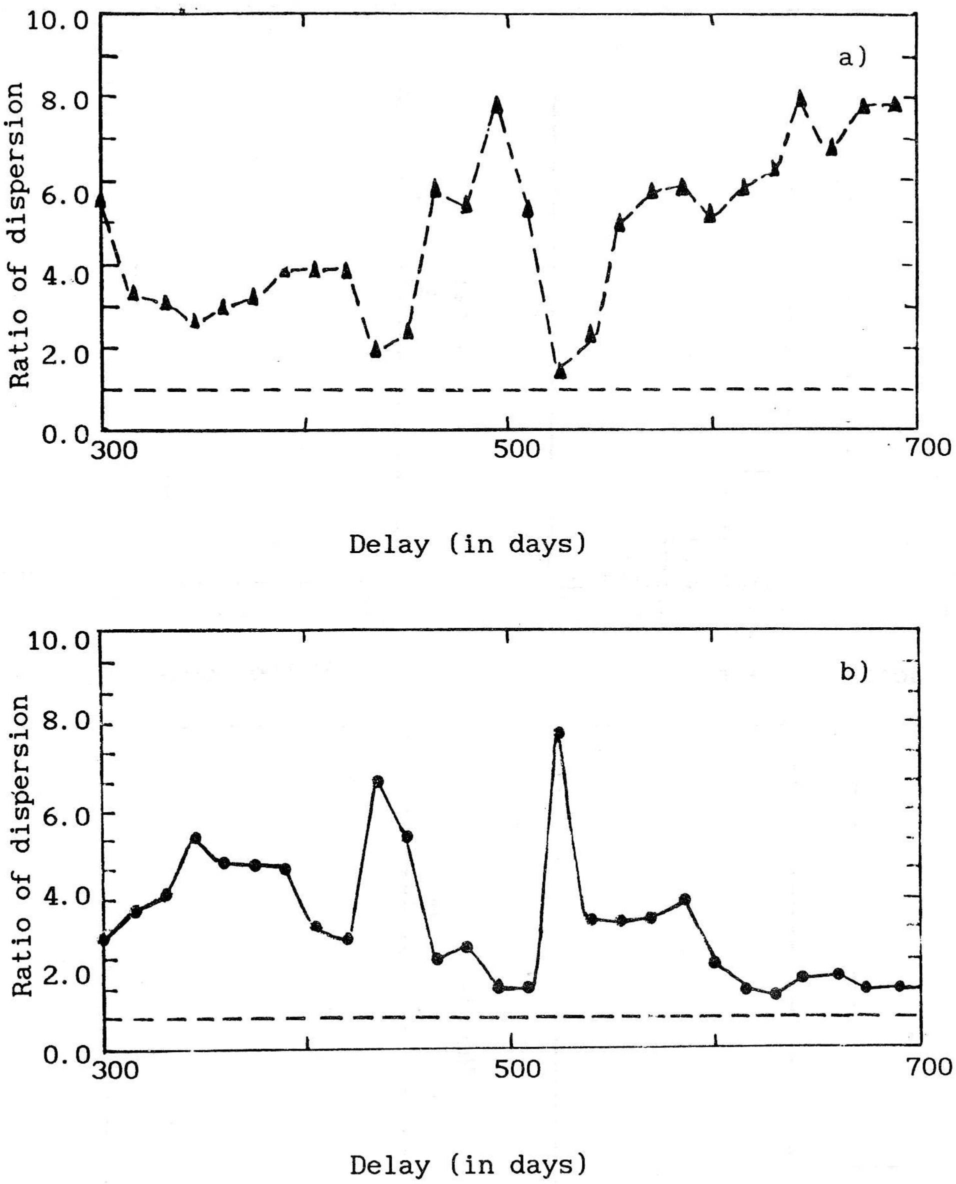

Fig. 2. Heuristic functions for the control sample: a) function $R_1(\tau)$ with a minimum near 525 days, b) function $R_2(\tau)$ with a maximum near 525 days.

Then we applied these simulated data to time delay determinations by two different methods: ours and the cross-correlation method using interpolation (see Gaskell and Spark, 1986). Figs. 3 and 4 show the result of 100 simulation data sets, each being analysed, by means of the two methods, for two cases of the actual time delay. In our method we adopted any value of τ as a determined time delay only for the cases when both R_1 and R_2 had absolute extrema at this delay. Thus, we have no values of time delay for part of the synthetic data sets. In the case 1 (Fig. 3), when the actual time delay is about a year, both methods have approximately equal power and reliability. We see that a probability to find a delay of 540 days or more, if the actual one is 420 days, is <1%. In case 2 the advantage of our method is obvious. The width of histograms for our method is essentially smaller than for the cross-correlation one of Gaskell and Spark (1986). As it can be seen from Fig. 3b, the probability of finding a delay equal to/or less than 450 days for the actual time delay of 540 days is about 10%.

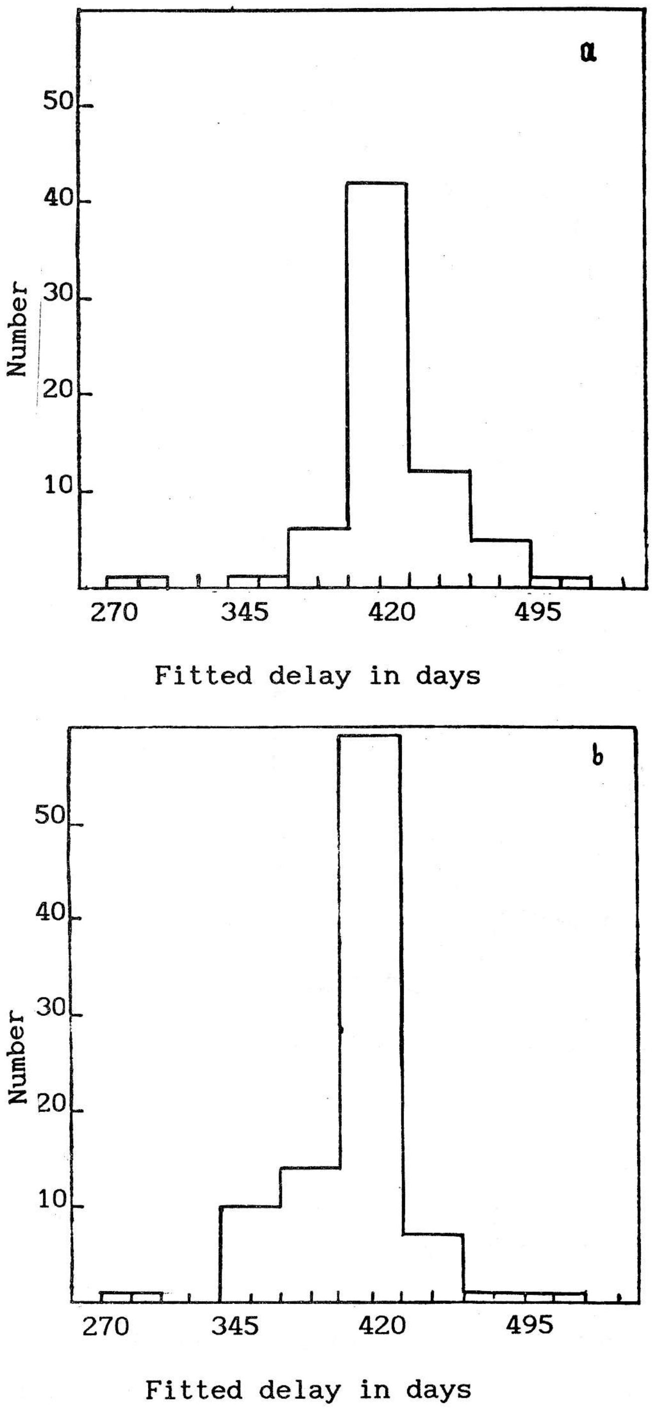

Fig.3. Distributions of the fitted time delays for the case 1: a) our method, b) cross-correlation method.

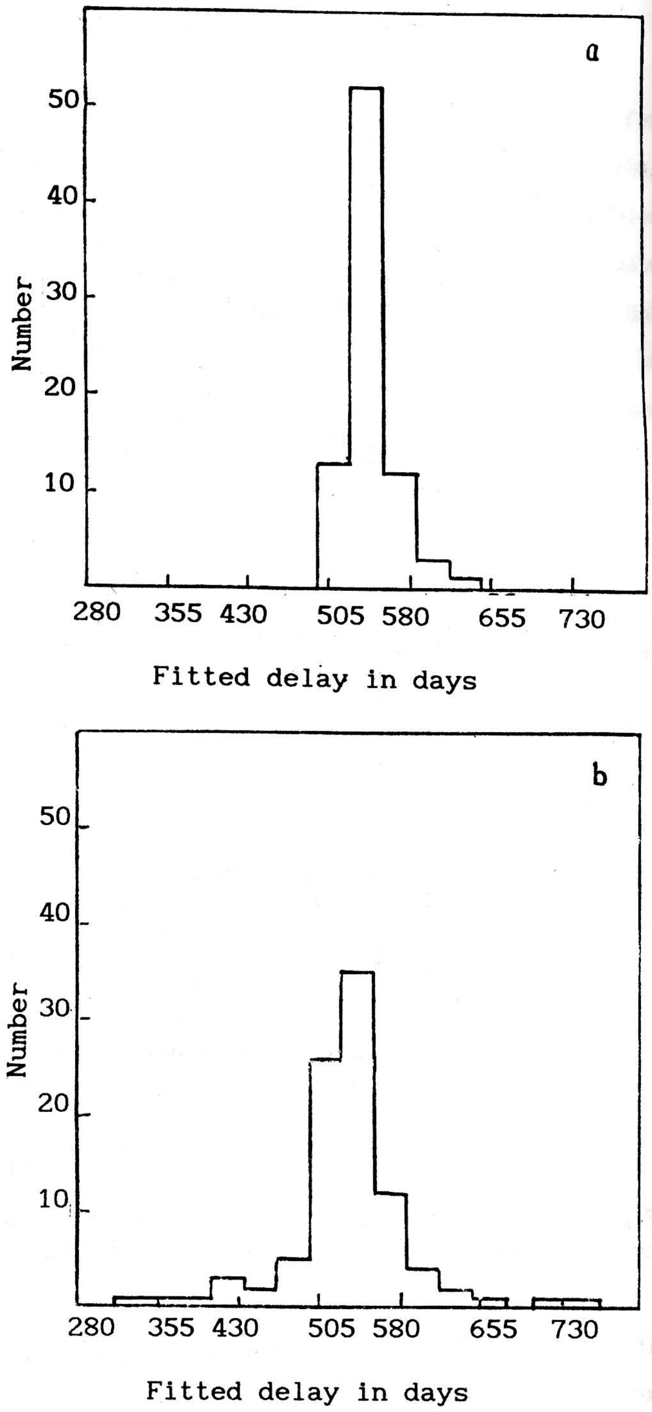

Fig.4. Distributions of the fitted time delays for the case 2: a) our method, b)cross-correlation method.

Now from Figs. 3a and 4b we can deduce 1σ confidence levels obtained by application of these histograms to our results: τ_0=530±15 days.

The recent papers by Vanderriest et al. (1989) and Schild (1990) based on the longest uniform photometric series of 8-9 years' duration deserve more detailed analysis. We briefly discuss possible reasons which might lead to a false result in these papers. In our opinion the main reasons are the following: the influence of the data spacing and the fact that the approximation errors have not been taken into account.

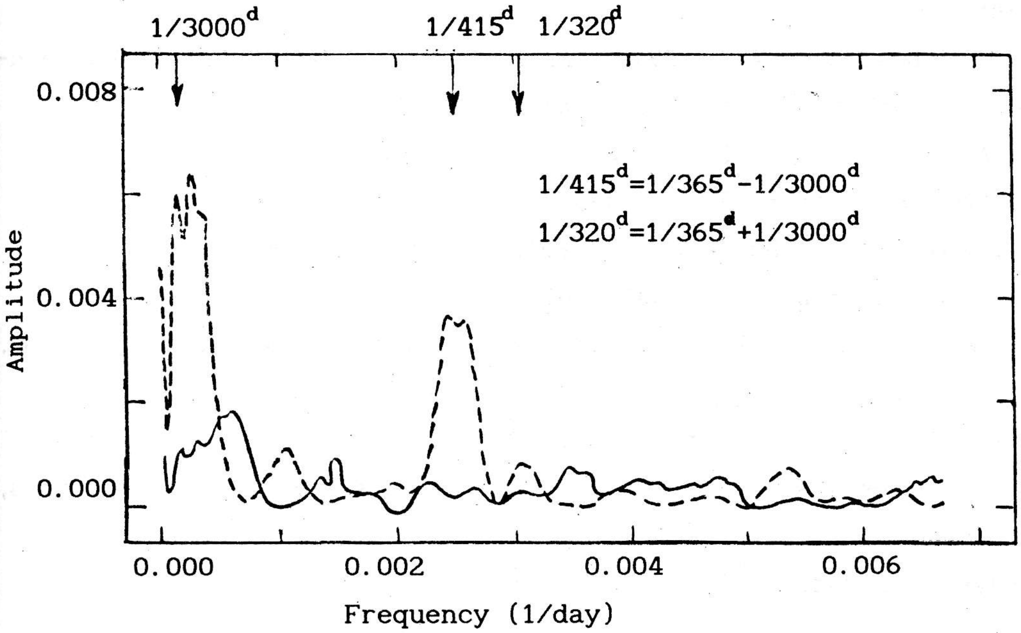

Fig.5. Power spectrum for the flux variations of A and B (dashed line) images for the basic sample.

Fig.5 shows the power spectra of the basic sample. The maximum at $\nu=1/415^d$ in the power spectrum of the B image is a result of interference of the frequencies corresponding to the trend with a characteristic time of $\simeq 3000^d$ and a period of a year in the spectral window (see Deeming, 1975). This artifact maximum may lead to considerable maxima in the autocorrelation and cross-correlation functions, and naturally they are artifacts too.

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