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THE OPTICAL VARIABILITY OF THE QUASAR 3C 446[1]

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ABSTRACT

The statistical characteristics of the optical variability of the quasar 3C 446 are examined, using new observations covering the 1988 burst, in order to solve the apparent contradictions among several recent analyses. Following two different approaches, power spectrum and structure function analyses, it is confirmed that the variability of 3C 446 exhibits a periodic component with period of about 1540 days. It is also shown that the nonstationarity of the processes describing the time behavior of 3C 446 can explain some of the features observed in its power spectrum.

Subject heading: quasars

I. INTRODUCTION

The variability of 3C 446 has been extensively investigated by several authors at different wavelengths since the first work by Sandage, Westphal, and Strittmatter (1966) up to the most recent ones (Barbieri *et al.* 1985, hereafter BCOR; Smith *et al.* 1987; Haddock, Aller, and Aller 1987; Salonen *et al.* 1987; Bregman *et al.* 1988; Webb *et al.* 1988). In the optical range, the power spectrum (PS) analysis of the optical photometry data has provided evidence of two possible periodicities at about 1540 days (BCOR; Webb *et al.* 1988) and 2130 days (BCOR). Recently, however, Bregman *et al.* (1988), using the structure function (SF) analysis, suggested the presence of a "flickering with a time scale of days to weeks and major outbursts that last for a month to a year."

In this paper we present a number of new observations (§ II) and analyze them along with all the material available in the literature. In § III, we show that there is no contradiction between the two mentioned statistical approaches. The apparent discrepacy can be explained by the fact that the PS and the SF analyses are suitable for investigating periodic and stochastic variability, respectively.

II. OBSERVATIONS

The Asiago survey of optical variability of quasars is a long-term ongoing program carried out since 1967. A description of the survey and of the reduction technique can be found in Barbieri *et al.* (1988*b*). The QSO 3C 446, as one of the most violent variable extragalactic objects, has been included in the target list of the survey since the beginning. Observations of this object at the Asiago Observatory were mainly secured at the 67/92 cm Schmidt and 182 cm telescopes with the standard combination (Kodak 103a-O plate and GG 13 filter) to match the *B* band. In Table 1 the plate number, date, Julian Day of new observations, and magnitudes are reported. The table includes also some observations performed at the Danish 1.5 m telescope at La Silla. Photographic magnitudes have been estimated by visual inspection against the sequence of stars used in BCOR. The internal error of the estimates is of the order of 0.1 mag (Barbieri *et al.* 1988*b*). Figure 1 shows the historical light curve from 1964 to 1989. The Asiago data from the present work and BCOR are marked as full circles, while open circles include observations by Sandage, Westphal, and Strittmatter (1966), Kinman, Lamla, and Wirtenen (1966), Westerlund and Wall (1969), Penston and Cannon (1970), Angione (1971), Westerlund (1980), Miller (1981), Lloyd (1984), Smith *et al.* (1987), Kidger and Allan (1988), and Webb *et al.* (1988). The optical variability of 3C 446, characterized by recurrent bursts and strong, rapid luminosity variations, already discussed in BCOR, is even more emphasized after the inclusion of the recent 1988 flare (Perez 1988; Barbieri *et al.* 1988*a*).

III. DISCUSSION

The main problem faced with the statistical analysis of QSO photometry is the irregular sampling. One of the most used (and sometime misused) techniques for dealing with observations unevenly spaced in time is Deeming's PS analysis (Deeming 1975). He demonstrated that, in the case of unevenly spaced data, the observed discrete Fourier transform (DFT) of a stationary time series (a time series whose mean value and PS does not depend on time) is the convolution of the true DFT with the spectral window:

$$W(\omega) = \frac{1}{N_0} \sum_{i=1}^{N_0} \exp(i\omega t_i) ,$$

where N_0 is the number of the observations and t_i is the sampling time. The stationarity condition is fundamental because, in case of nonuniform sampling, a time series is not characterized by a unique Nyquist frequency ω_{Ny}. Therefore, the behavior of the PS at a given frequency ω does not depend on all the observations, but only on those parts of the time series whose ω_{Ny} is larger than ω. This fact is not so serious for stationary time series, but for nonstationary ones the situation can be completely different.

Although Deeming's method is able to detect periodicities, it cannot determine their statistical significance. Scargle (1982) has given a new definition of the PS which avoids the latter

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[1] Based on material collected at the Asiago Astrophysical Observatory.

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TABLE 1

OBSERVATIONS

Plate	Date	J.D.	B
1087	1967 12 1	39826.29	18.10
12186	1983 9 4	45582.40	15.85
12219	1983 10 2	45610.38	16.15
12308	1983 11 9	45648.38	16.35
12341	1983 11 29	45668.35	15.50
12577	1984 8 4	45917.50	18.10
13412	1986 9 29	46703.41	18.40
13437	1986 10 3	46707.34	17.90
13869	1987 8 18	47026.47	17.05
13891	1987 9 18	47057.36	17.65
13905	1987 10 18	47087.29	17.90
14188	1988 8 10	47384.54	16.20
14194	1988 8 12	47386.44	16.05
14211	1988 8 17	47391.41	16.10
14215	1988 9 6	47411.52	16.15
14219	1988 9 7	47412.48	16.35
14223	1988 9 8	47413.46	16.45:
Danish 1.5	1988 9 17	47422.5	17.55
Danish 1.5	1988 9 19	47424.5	16.87
14247	1988 11 1	47467.31	16.25
14253	1988 11 5	47471.26	16.25
14584	1989 8 2	47741.51	17.90
14627	1989 10 4	47804.40	17.00
14645	1989 10 23	47823.35	17.55
14677	1989 10 30	47830.33	17.80

problem: the power level Z_0, which will be exceeded by noise fluctuations for a fraction P_0 of the time, is given by the so-called *false alarm probability*:

$$Z_0 = -\ln[1 - (1 - P_0)^{1/N}] ,$$

when an important ingredient for the calculation of Z_0 is the number N of independent frequencies. This number for evenly sampled time series is equal to $N_0/2$ but, for irregularly sampled data, it is *a priori* unknown. To determine N, Scargle suggests a method based on the *spectral window* $W(\omega)$. As Lomb (1976) has shown, the correlation coefficient between the values of the PS at two arbitrary frequencies ω_a and ω_b is equal to the *spectral window* evaluated at $\omega_a - \omega_b$. Therefore a set of equispaced $\omega_n = n\omega_1$ ($n = 1, 2, 3, \ldots$), for which $W(\omega) = 0$, constitutes a set of uncorrelated frequencies. For Gaussian processes the frequencies are also independent. In our case, as for evenly spaced observations, N is approximately equal to $N_0/2$. In any case the *false alarm probability* Z_0 calculated with $N = N_0/2$ will be an upper limit compared to the real one.

Figure 2 shows Scargle's PS of 3C 446 in the period range from infinity to 100 days for all available data. In this interval there are several peaks statistically significant at a 95% confidence level. Among these, there are two peaks at about 1540 and 2000 days that correspond to those at 1540 and 2130 days found by BCOR. However, the simple superposition of two sinusoids, with period 1540 and 2000 days, is not able to reproduce the observed PS. The peaks due to the two sinusoids and the corresponding aliases are prominent, but a lack of power at the other low frequencies is also evident in the PS of the simple two-period model. An excess of power at low frequencies could be produced by a secular trend in the luminosity variation. However, a linear least-squares fit to the observations gives no support to this hypothesis. The other possible explanation is that the time behavior of 3C 446 is not sinusoidal, which complicates the time series analysis. In fact, the presence of strong peaks in the PS of a nonsinusoidal time series does not necessarily mean that any periodicity is really present in the data. Let us suppose for a moment that the light variations of 3C 446 are due to a sequence of luminosity bursts (shot-noise). In this case the PS of the time series would appear as a set of low-frequency, statistically significant peaks related to the Fourier

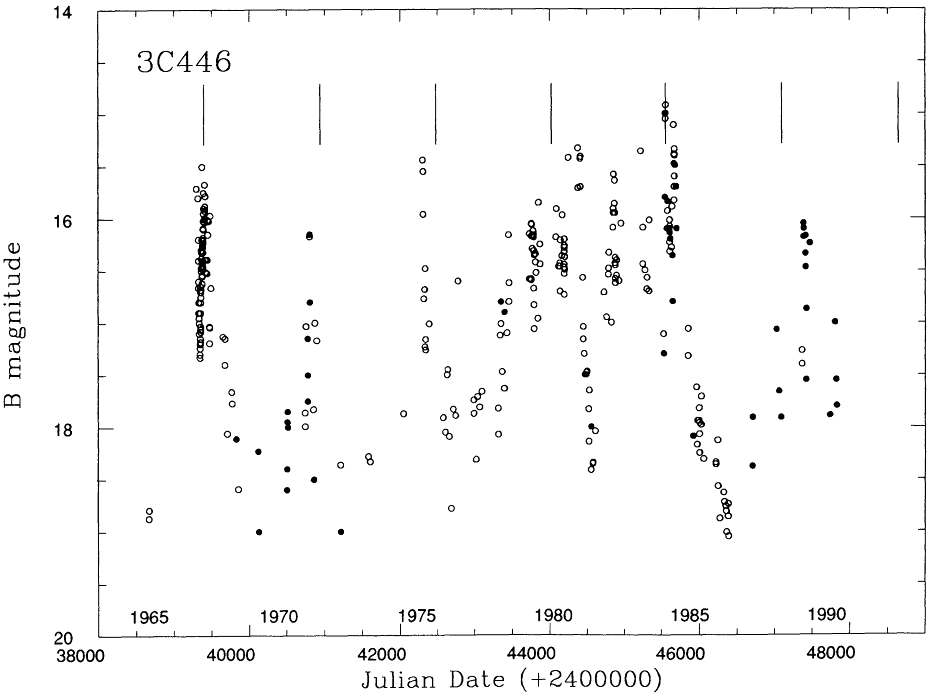

FIG. 1.—Optical light curve of 3C 446. Full circles are Asiago data, while open circles are data from literature. The expected positions of the bursts, following the 1540 days periodicity, are reported with vertical marks.

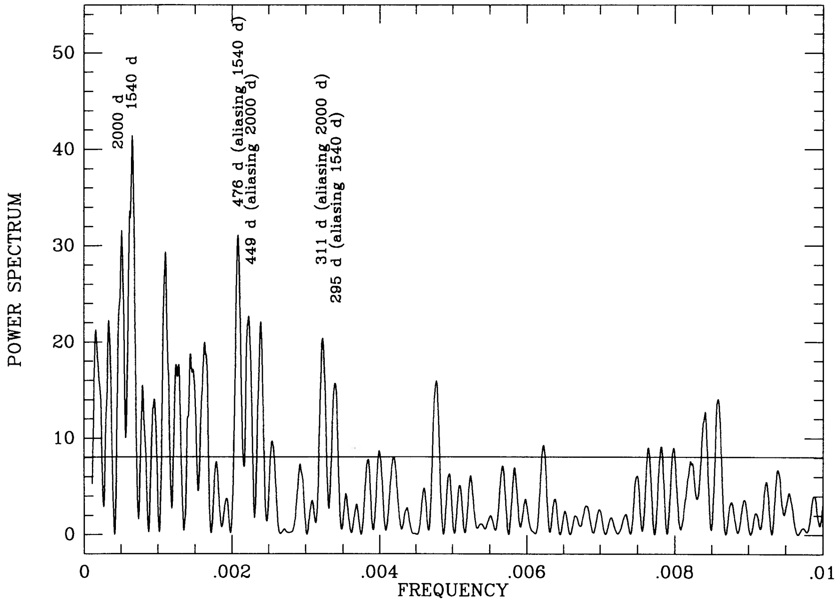

FIG. 2.—Scargle's power spectrum of the 3C 446 optical observations. The ordinates are in unit of day^{-1}. The horizontal line is the 95% confidence level of the noise.

transform of the burst's profiles. Moreover, if the bursts have different time lengths and shapes, as is the case for 3C 446, the corresponding shot-noise process is not stationary. What we expect from the PS of such a process is a set of low-frequency peaks that change quickly both their position and strength as the sampling times and the number of observations are varied. This last point can be useful, if the sampling is not pathological, for searching periodicities. In fact, if some periodicities are really present in the data, then the corresponding peaks in the PS must always keep the same position (within the errors) and increase their strength with respect to the noise level, when longer and longer time series are considered. The Scargle analysis has been applied to the data discussed by BCOR. The resulting PS, which duplicates the features of Figure 2 of BCOR, has been compared with our Figure 2. It appears that:

1. the peak at 1540 days has increased its power with respect to the mean level of the noise; in fact, the new data reported in Table 1 cover the 1988 burst which appears to be related to this periodicity.
2. The peak at 2000 days has changed its position and decreased its relative power with respect to the corresponding 2130 days peak of BCOR.
3. Some "new" strong peaks have appeared at low frequencies.

Therefore this analysis suggests that the 1540 days periodicity is present in the data, whereas the other peaks in the PS are related to the nonstationary behavior of the time series. This result is consistent with the finding of Webb *et al.* (1988). We stress that the nonstationary light variability can represent an alternative explanation to the recurrent reports in literature of transient periodicities in the variability of some quasars.

The picture coming out the PS analysis is in fair agreement with the results of the SF analysis. As is known (Simonetti, Cordes, and Heeshen 1985), one of the most useful features of the structure functions is their ability to discern the time scales that contribute to the variation in a data set. For a finite sequence of measurements $f(i)$, $i = 1, 2, \ldots, N_0$ the first-order SF is defined as

$$D(k) = \frac{1}{N(k)} \sum_{i=1}^{N_0} w(i)w(i+k)[f(i+k) - f(i)]^2 ,$$

where

$$N(k) = \sum_{i=1}^{N_0} w(i)w(i+k)$$

and the weighting factor $w(i)$ is 1 if a measurement exists for the ith interval, 0 otherwise. If a given time series is characterized by a time scale T_0 the behavior of $D(\Delta t)$, with Δt lag between two observations, would be

$$D(\Delta t) = \text{constant} \quad \text{for} \quad \Delta t \gg T_0 ;$$
$$D(\Delta t) \propto (\Delta t)^2 \quad \text{for} \quad \Delta t \ll T_0 .$$

Therefore the position of the turnover of $D(\Delta t)$ gives an estimate of the searched time scale. We have applied this analysis to all the optical observations of 3C 446. The resulting SF is shown in Figure 3, where the sampling times have been binned in one day intervals. Figure 3 does not show a simple behavior: a number of slope changes appear between 300 and 800 days. Numerical simulations indicate that such a behavior of the structure functions can be related to a process characterized by different time scales. Therefore, the SF analysis suggests that the luminosity bursts of 3C 446 have time scales from one to two years (we stress that shorter time scales, even if present, cannot be derived with this analysis from the available data). It is worth noting, however, that from the $D(\Delta t)$ function we do not have any information on the temporal position of the bursts: they could be as well equispaced or not. We remind the reader that the SF analysis requires the time series to be stationary. However, numerical simulations show that, even in case of nonstationary burst processes, the SF is able to detect time scales of the processes.

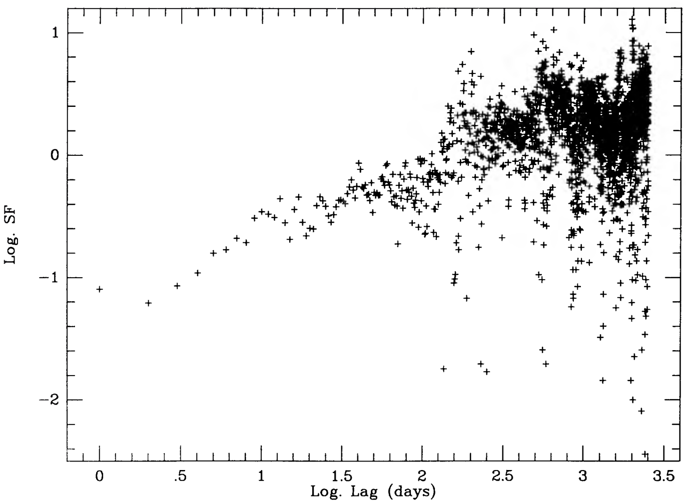

FIG. 3.—Logarithm of the first-order structure function of the 3C 446 optical data.

In conclusion, from our analysis, it seems that most of the features of the 3C 446 light curve can be explained by a periodic burst process with period of about 1540 days. The expected positions of the bursts, marked in Figure 1, appear in agreement with the observed peaks, especially considering the uncertainties on both the derived period and the epoch of maxima, the latter due to the complex structure and the incomplete coverage of the bursts. The bursts have different lengths and shapes and the process is therefore not stationary.

The physical picture of 3C 446 coming out from our analysis is unclear. Bregman *et al.* (1988) suggest a model in which a plasma of electrons, with constant power-law spectrum and with an abrupt cutoff at some energy, flows through regions of different magnetic field. With this model it is possible to explain the variability and the amplitudes of the luminosity variations that, in 3C 446, are proportional to the frequency (Bregman *et al.* 1988). In their analysis, however, Bregman *et al.* do not consider the periodicity at 1540 days, which the model is not able to explain.

Periodic variability in quasars can be produced, in the standard scenario, by instabilities of the accretion disk surrounding the central black hole (Abramowicz and Szuszkiewicz 1988). Although such a physical mechanism is very attractive, in this field we are still in a pioneering stage.

We think that to gain further insight on the 3C 446 physics it is still necessary to obtain more and better observations. The data available on 3C 446 are not always of good quality and have a temporal distribution which is too irregular. This does not permit us to study the variability of 3C 446 in great detail, for example, on short time scales (from some minutes to some days). The use of CCDs instead of photographic plates, and an observational program dedicated to the short and intermediate term variability, can improve the situation remarkably.

IV. CONCLUSION

We have investigated the optical variability of 3C 446 using a new set of observations that extend the available data till 1989. Two different techniques, PS and SF analysis, have been used. The principal results of this work are the following:

a. there is no contradiction between the PS and the SF analyses;

b. the presence of the 1540 day periodicity (corresponding to 640 days in the QSO rest frame) is strengthened by the occurrence of the 1988 luminosity peak and suggests that the next burst will take place in the (northern) spring of 1992;

c. the time series of 3C 446 is nonstationary. The light variations are determined by a sequence of luminosity bursts, mostly regularly spaced in time (1540 days), and lasting up to 2 yr.

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