THE NATURE OF THE OPTICAL VARIATIONS OF SEYFERT GALAXY 3C 120

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ABSTRACT

We present 61 years of optical observations of the Seyfert galaxy 3C 120. A previously published model of the 3C 120 light curve that we derived from power spectrum analysis is found to be valid for historical as well as current data. We conclude that the optical variations of 3C 120 can be separated into a linear component, a sinusoidal component, and rapid, high-amplitude flares. We also suggest possible sources of the regular variations observed in 3C 120 in the context of accretion models and other theoretical models.

I. INTRODUCTION

The Seyfert galaxy 3C 120 has been observed at the University of Florida's Rosemary Hill Observatory (RHO) since 1971. Webb *et al.* (1988), hereafter referred to as Paper I, presented photographic monitoring observations of 3C 120 taken at RHO and used linear regression and unequal-interval Fourier transform techniques (Bevington 1969; Deeming 1975) to analyze the light curve. The resulting linear and periodic components were shown to fit the 3C 120 data adequately when short-term variations of less than two months were neglected. The model fit was of the form

$$M(\mathrm{JD}) = 12.99 + (5.52\times10^{-5}) \times \mathrm{JD} + 0.40 \cos(2\pi\,\mathrm{JD}/4547.36 + 0.3),$$

where $M(\mathrm{JD})$ is given in B magnitudes and JD is in Julian Days minus 2400000. This model was based only on data between JD 2441240 and 2446496. The constant and linear terms were derived from linear regression and the period of 12.45 yr was derived from Fourier analysis. The amplitude and phase of the periodic term were estimated from the power spectrum and then adjusted by least squares to obtain the best possible fit. No claim that the model had predictive power was made because of the limited number of observations.

In the present paper, we present historical observations that extend the light curve of 3C 120 back to 1928 and examine the validity of the model presented in Paper I. We also perform new linear regressions and periodic analyses using the entire light curve and compare these results with those of Paper I.

Takayanagi (1968) published observations from Harvard Patrol archival plates between JD 2425505 and 2431051 (September 1928–November 1943). Most of the observations were reduced using an iris photometer and a 27 star comparison sequence. No attempt was made to subtract the galactic component from the data. We have converted Takayanagi's PG magnitudes to B magnitudes by applying a $B-PG$ offset of 0.3 mag based on the $U-B$ color of 3C 120. Additional Harvard patrol plates taken between JD 2427660 and 2429240 from Usher *et al.* (1969) were combined with the Takayanagi observations. The Takayanagi observations, corrected to B magnitudes, and the Usher observations were found to agree within expected error whenever there was sufficient overlap for comparisons to be made. These combined observations form a reasonably consistent dataset covering the time period 1928–1948.

Observations from Kinman (1968) and the RHO observations complete the light curve of 3C 120, which extends over 60 years. In spite of the complications inherent in comparing the different datasets, Fig. 1 shows that the original model derived from the RHO data alone (Paper I) is consistent with the historical observations. The Kinman data show the decline of a rapid outburst, possibly representing short-term activity not related to the long-term variations represented by the sinusoidal model.

II. ANALYSIS

We analyzed the entire set of optical observations using linear regression and periodograms in order to study the variations seen in 3C 120. We removed the long-term linear trend from the 3C 120 data by subtracting a linear component determined by regression analysis (Bevington 1969). We then tested the data for periodic components using both the Lomb–Scargle periodogram method (Press and Teukolsky 1988) and the unequal-interval Fourier transform and CLEAN method (Roberts, Lehar, and Dreher 1988). Both methods indicate the presence of a periodic component

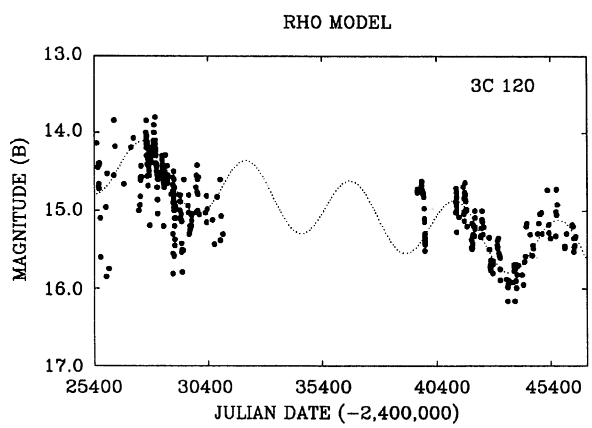

FIG. 1. Original model determined from only Rosemary Hill optical observations is shown as a dotted line with the entire 61 year light curve of 3C 120. The solid points represent optical magnitudes taken from all of the sources described in the text.

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with a period of 12.43 ± 0.05 yr in the data. The Lomb–Scargle periodogram tests the strongest peak in the power spectrum for significance by supposing the data are independent random Gaussian values. The probability that a period as strong as the one in question could arise in the random dataset is then calculated. The significance calculated for the 12.43 yr peak was 6×10^{-33}, indicating an extreme unlikelihood that this periodic trend could arise by chance. The Lomb–Scargle periodogram of the 3C 120 observations described above is shown in Fig. 2. The largest peak represents the 12.43 yr period.

The unequal-interval Fourier transform algorithm of Roberts *et al.* (1988) was used to produce the "dirty" power spectrum of 3C 120. This dirty spectrum consists of real spectral features convolved with aliases that are essentially artifacts of the uneven data spacing. The CLEAN algorithm uses the spectral window to locate and remove these aliases, leaving only the real features in the power spectrum. Figure 3 shows the CLEAN power spectrum of 3C 120. The 12.43 yr peak is the most prominent feature in the power spectrum.

To assess the possibility that the obvious periodic trend in the recent data was dominating the analysis, we separated the data into two segments. The first segment consisted of the Harvard archival data before 1944, and the second segment consisted of the RHO and Kinman observations that were made after 1966. These segments were analyzed independently and the results indicated that the periodic nature of the variations was present in both segments. The periodogram for the early Harvard data showed a peak at $P = 12.35 \pm 0.29$ yr with a significance of 9.5×10^{-16}. The errors quoted for the periods are determined by the sampling density in frequency space. Analysis of the RHO observations verified the existence of the strong peak around $P = 12.33 \pm 0.3$ yr, with a significance of 3.1×10^{-16}. Fourier analysis agreed with periods determined by the Scargle method in each case, within expected uncertainties.

A sinusoidal curve with a period of 12.43 yr was then fitted to the corrected data, varying the amplitude and phase but holding the period constant. The model is shown along with the 3C 120 light curve in Fig. 4. Figures 5(a) and 5(b) shows, respectively, the early portion of the light curve (before JD 2432000) and the later portion (after JD 2439000), with the time axis expanded to facilitate evaluation of the general agreement between the model and the observations. Table I summarizes the results of the linear and periodic analyses along with the values of most parameters determined in Paper I. The differences between the values of the parameters derived from RHO data alone and from all the data are within expected uncertainties. Note that the phase was listed incorrectly in Paper I. Column 1 lists the parameters that are defined in the equation at the beginning of the table. C_1 and C_2 are the intercept and slope of the linear component, and C_3 and C_4 are the amplitude and phase of the periodic component. P represents the period of the sinusoidal component. Column 2 lists the values of the parameters found in Paper I, and columns 3–5 give the values of the constants found by evaluating only segment 1, only segment

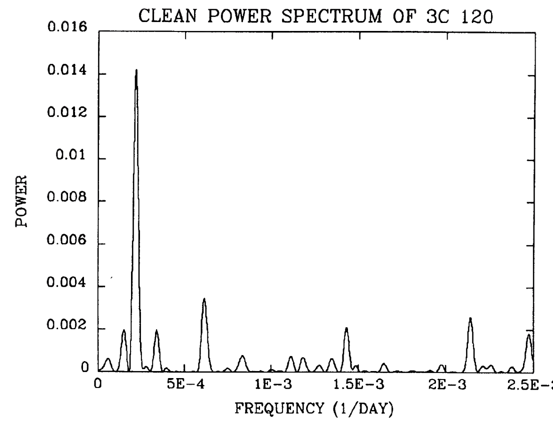


FIG. 3. CLEAN power spectrum of 3C 120. The unequal-interval power spectrum was CLEANed 100 times using a gain of 0.2. The major feature visible in the CLEAN spectrum corresponds to a frequency of 2.2×10^{-4}/day.

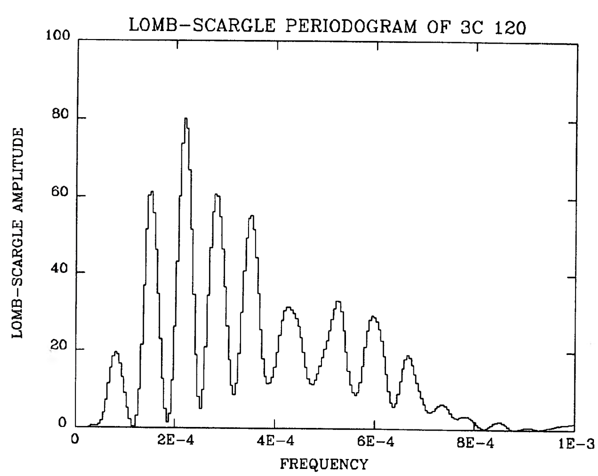


FIG. 2. Lomb–Scargle periodogram of 3C 120. The largest peak is at 2.2×10^{-4}/day (12.43 yr). The other peaks are artifacts of the irregular data spacing.

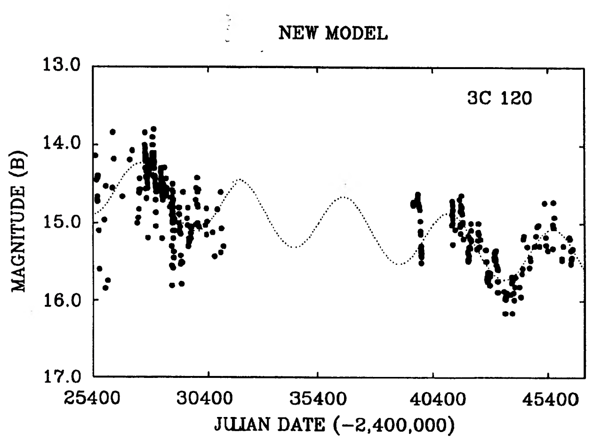
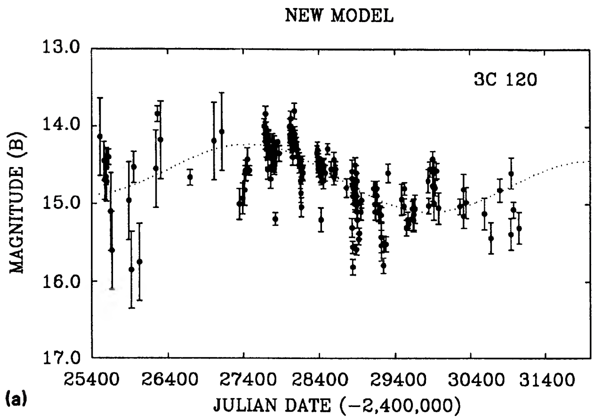


FIG. 4. New model determined from the linear regression and periodogram analysis of the data. The model is represented by the dotted lines and the data are represented as solid points. The scatter around the model curve is attributable to observational error and short-term, high-amplitude variations not modeled in the periodic analysis.



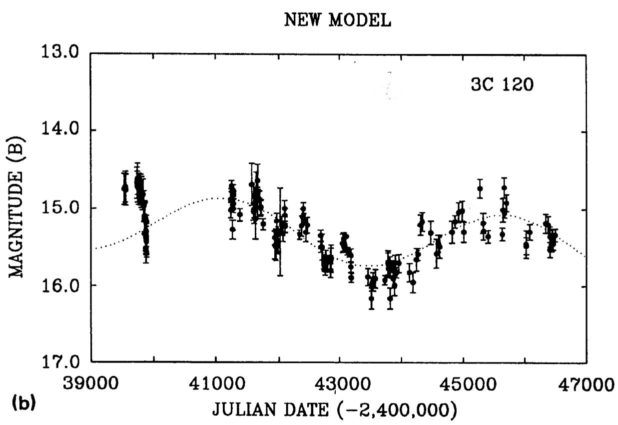


FIG. 5. (a) Early part of Fig. 2 blown up to facilitate comparison of the model with the data. The error bars represent rms error whenever it is known. A default of 0.2 mag is shown when no individual expected errors are known. (b) Later part of the light curve, also enlarged. Error bars are as described in (a).

2, and the entire light curve, respectively. Table II shows the significance of the linear and sinusoidal fits, listing the correlation coefficient R, the χ^2 value for the fit, and the value of the F test for goodness of fit. The probability of a random sample of data points having a correlation coefficient R as high as or higher than the ones found here for both the linear and sinusoidal fits was less than 4×10^{-8}. We found all fits to be statistically significant as the 0.001% level.

We subtracted the model from the original data and a plot of the residuals is shown in Fig. 6. The residuals were then analyzed for short-term variations, but the results were complicated by the large gaps and the uncertainties present in the early data. The large amplitudes of the residuals are probably due to a number of different effects. The uncertainty inherent in determining photographic magnitudes (on the order of 0.1–0.2 mag) and the inconsistencies with galaxy subtraction discussed previously add to the scatter. The larger deviations are probably due to rapid, high-amplitude flares or bursts similar to those seen in many active galactic nuclei (AGN) on very short timescales. These rapid variations can be used to estimate the size of the emission region and to study the energetics of individual flares (Webb and Smith 1989). These variations will be analyzed elsewhere.

TABLE II. Significance of the linear and sinusoidal fits.

	Linear fit statistics	
R		0.66
Chi sq		13.31
F		290.81
	Cosine fit statistics	
All observations		
R		0.73
Chi sq		6.08
F		221.47

III. DISCUSSION

The most popular interpretation of the AGN continuum power source is accretion of gas onto a supermassive black hole. In terms of accretion models, the regular optical variations seen in 3C 120 can be associated with the accretion rate or instabilities in the inner regions of the accretion disk. The linear component of 3C 120 seems to suggest a slow, monotonic decline in the accretion rate. As the continuum emission decreases, 3C 120 will look more and more like a "normal" galaxy.

The most likely explanation for the periodic component is either thermal or viscous instabilities in the disk itself (Sitko 1986). The circular and vertical timescales in the inner regions of the disk are much too short (on the order of hours or days) to account for the period of the observed regular variation, but the thermal and viscous timescales are of the correct order of magnitude (tens of years). Viscous instabilities tend to spread the accreting matter into rings that then accrete onto the black hole. Periodic feeding of the hole might cause the regular variations seen in the light curve of 3C 120.

Abramowicz, Szuszkiewicz, and Wallinder (1989) have proposed a specific mechanism in accretion disks that would result in periodic variations on thermal timescales. They suggest that thermal instabilities and a general relativistic effect called advective cooling could produce cyclic structural changes in the inner regions of "slim" accretion disks (Abramowicz *et al.* 1988). These cyclic changes would cause regular variations in the luminosity of the disk and could account for the periodic variations seen in the light

TABLE I. Summary of linear and periodic analyses.

$$M(t)=C_1+C_2\times t+C_3\times\cos(2\pi t/P+C_4)$$

Parameters	Paper I	1st segment	2nd segment	All
C_1	12.99(0.52)	12.0(0.7)	12.0(0.5)	13.34(0.09)
C_2	5.5×10^{-5}	$11.0(0.3)\times10^{-4}$	$8.0(0.1)\times10^{-5}$	$4.6(0.1)\times10^{-5}$
C_3	0.4(0.2)	0.36	0.39	0.38
C_4	2.0	2.75	2.02	2.75
P	12.45	12.35(0.3)	12.33(0.3)	12.43(0.05)

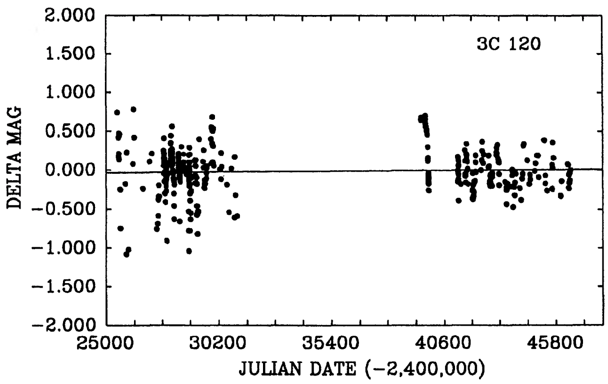


FIG. 6. Light curve of 3C 120 with the model substracted out, leaving only the rapid, high-amplitude variations. Some of these residuals are likely due to calibration problems, while some are due to rapid, high-amplitude flares.

curve of 3C 120. A determination of the accretion rate of 3C 120 would provide a further test to the validity of this model since the instability is effective only within a range of accretion rates.

The rapid, short timescale variations are best interpreted as magnetic eruptions on the surface of a magnetized disk. Analysis of the individual flares could be used to estimate parameters such as the accretion rate, the mass of the hole, and limits on the viscosity (Shields and Wheeler 1976).

A number of other models have been proposed to explain the variability of quasars. The magnetoid model of Ozernoy *et al.* (1967) predicted sinusoidal variations along with rapid flaring activity similar to what is seen in the 3C 120 light curve. This model has received very little attention in the current literature but seems capable of accounting for all of the types of variations seen in 3C 120.

Another recent model for quasars has been proposed by Valtonen *et al.* (1989). This model assumes that orbital periods of two or more massive black holes revolving around each other modulate the quasar light curve, producing periodicities. This model could account for the variations seen in 3C 120.

IV. CONCLUSIONS

We conclude that the light curve of 3C 120 can be separated into a linearly decreasing component, a periodic component, and a series of rapid, high-amplitude flares. A statistically significant fit consisting of linear and periodic terms is found from periodogram and regression analysis. These linear and periodic components are interpreted in terms of variations in the accretion rate and disk instabilities in the continuum source of 3C 120.

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