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The optical variability of 3C 345

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Summary. A detailed analysis of the behaviour of the light curve of 3C 345 is presented here, using all available B magnitudes within the literature. This paper revises and updates a previous work by the author on this object (Kidger and Beckman, 1986—henceforth referred to as Paper I) in the light of the considerable new data available, which increases the number of points in the compiled light curve by a factor of more than 50% and extends the coverage by some seven years. A new and better $m_B - m_{pg}$ correction has also been applied to all the data. A rigorous analysis of the light curve by Fourier transforms using the Deeming method establishes that the light curve is effectively aperiodic, although brief epochs of semi-regular variability may occur. None of the various periods suggested in the past are found to be active in the light curve over more than a few cycles. It is also found that the power spectrum is not continuous, in the sense that even overlapping sections of light curve have very distinct power spectra. Such behaviour would be expected if the variations were random, whilst a periodic model is strongly ruled out unless the fundamental period is of the order of ten years or more. Use of the Jurkevich V_m^2 statistic supports these conclusions. The feature frequently seen in the power spectrum at around 140 days can be explained empirically given a random model.

Key words: quasars: 3C 345 – photometry

1. General characteristics of 3C 345

3C 345 was one of the first quasars for which variability was established and has been under more or less constant and detailed observation since 1965. The number of data points now available exceeds that for any other object except BL Lac. In terms of time resolution and evenness of sampling, the light curve of 3C 345 far exceeds any other object. In consequence, it is an excellent testing ground for models of quasar variability. Except in terms of length of light curve coverage it is better suited to such types of study than 3C 273, an object much commented on in the literature, due to the high mean rate and even distribution of the sampling of the light curve. 3C 345 is of the class of objects termed "Optically Violent Variables" (OVVs) by Penston and Cannon (1969). Over the twenty-three years of detailed light curve coverage this object has shown a range of types of behaviour from a highly periodic mode of flaring (Kinman et al., 1968), to near non-variability at other epochs.

2. Published observations

Table 1 below lists the available data for 3C 345 which has been used in this work. Only magnitudes in the B, or pg bands are included in this compilation.

In most cases the data have been presented as m_B, where they are presented as m_{pg}, the correction

$$m_B - m_{pg} = +0.28 \text{ (Lü, 1972)} \tag{1}$$

was adopted. All other magnitudes have ignored. This correction differs from the one used in Paper I and is felt to be a more reliable value. As before, when calculating ten day means each datum point has been weighted according to the reciprocal of the square of its rms error. Where individual rms errors are not given the weights are as listed in Paper I with the addition of a mean rms error of 0.1 magnitude being applied to the data of Babadzhanyants et al.

3. The nature of the light curve

The large quantity of data (1461 points over a 23 year period from 1965 to 1988) makes the full light curve somewhat confused, hence, to illustrate the trends in the light curve better, it is also plotted as ten day means. With the constant separation of the data it is easier to estimate the timescales of rapid variations directly from the light curve. The full light curve is shown in Fig. 1 and the 10 day means in Fig. 2.

Due to its high northerly declination, of approximately $+40°$, the yearly observing gap, caused by solar conjunction, is quite short, around eighty days in most years and hence the light curve is more nearly complete than in almost any other case. Over the period from 1967 to 1978, there were always a minimum of two monitoring programs being carried out simultaneously, with a maximum of six, in 1975–1976. This continuity of coverage helps to reduce the gaps in the light curve.

From June 1965 to July 1988, the range of variation is almost three magnitudes, from 17.65 on J.D. 2440028 to 14.70, on J.D. 2445230, with an average over the 23 yr of data of 16.55 and a standard deviation of $0^m.49$. This latter figure is exceeded by very few objects. The light curve confirms the major change in the variability which Paper I suggested may have occurred post-1975. After the decline of the third major outburst by 1974 to its minimum, which decline lasted nearly 2 yr, the more or less continuous high amplitude flaring was replaced by a period of much steadier behaviour. The flaring seen superimposed on this activity was of much lower amplitude (0.5–1 mag) and also far

Table 1. Published data on the light curve of 3C 345. Figures in brackets refer to data subsequently recalculated or represented and thus duplicated in the literature. The last point was taken by the author in late July 1988

Reference	No. points	Instrument
Sandage (1965)	(1)	200″ Hale Reflector
Goldsmith and Kinman (1965)	(24)	20″ Astrograh, 36″ Reflector (Lick Obs.)
Wampler (1967)	(9)	120″ Reflector (Lick)
Kinman et al. (1968)	292	20″, 36″, 120″ (Lick)
Penston and Cannon (1970)	(26)	26″Refractor (RGO)
Smyth and Wolstencroft (1970)	32	40 cm Schmidt (Monte Porzio, RO Edinburgh)
Tritton and Selmes (1971)	(52)	26″ Refractor (RGO)
Lü (1972)	132	40″ Reflector (Yale)
Visvanathan (1973)	18	100″ Reflector (Mount Wilson) and 200″ Hale
Markova, Fomin and Zhukov (1973)	22	35 cm and 38 cm telescope
Markova and Zhukov (1974)	46	40 cm Astrograph
Selmes, Tritton and Wordsworth (1975)	(9)	26″ Refractor (RGO)
McGimsey et al. (1975)	(105)	46 cm and 74 cm Reflector (Rosemary Hill, Florida U.)
Barbieri et al. (1977)	63	67 cm Schmidt, 122 cm and 182 cm telescopes (Asiago)
Pollock et al. (1979)	(166)	46 cm and 74 cm Reflector (Rosemary Hill, Florida U.)
Angione et al. (1981)	30	14″ Schmidt (JOCR, Harvard)
Lloyd (1984)	104	26″ Refractor (RGO)
Sitko, Schmidt and Stein (1985)	15	1.5 m reflector (Mount Lemmon)
Babadzhanyants et al. (1985)	421	Prime focus 40 cm reflector, 20 cm reflector (Byurakan, Leningrad Univ.)
Barbieri (1986)	24	67 cm Schmidt, 122 cm and 182 cm telescopes (Asiago)
Webb et al. (1987)	230	74 cm reflector
Kidger (1988)	20	1 m, 2.5 m reflectors (La Palma)
Kidger (1988a)	1	1 m reflector, La Palma
Xie et al. (1988)	9	1 m reflector, Purple Mt.

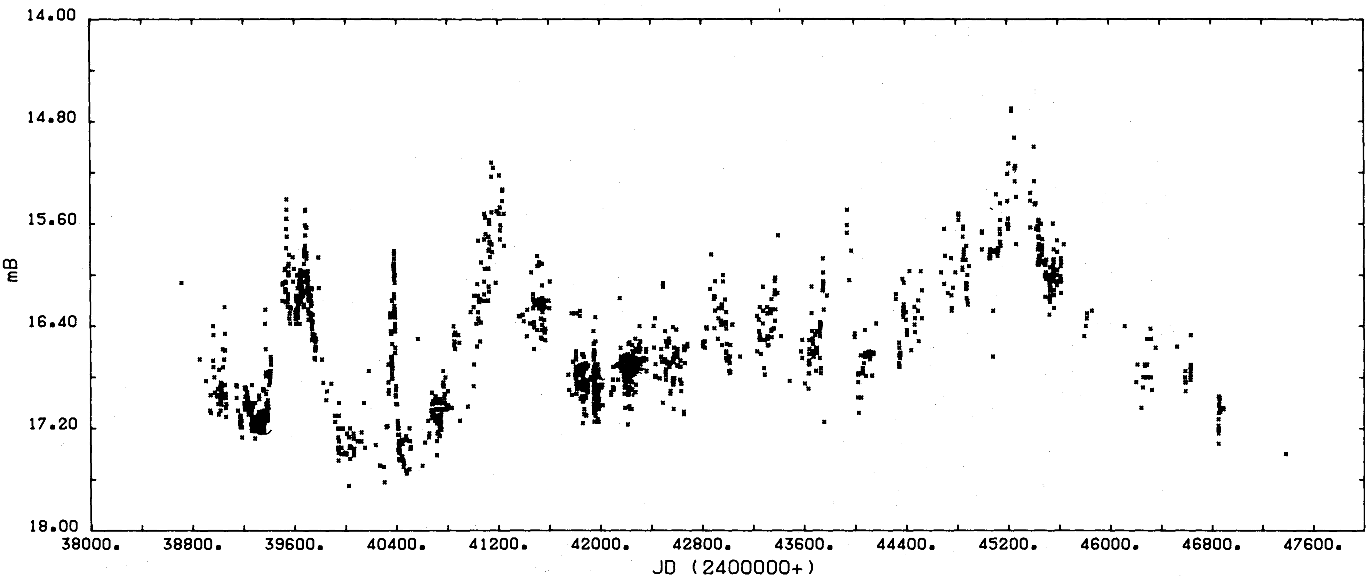

Fig. 1. The light curve of 3C 345 for the period 1965 to 1987 derived from the observations listed in the text. Data originally presented as photographic magnitudes has been converted to the Johnson *B* system

more frequent. There was also a pronounced brightening trend of 0.15 mag yr^{-1}. This trend seems to form a slowly varying baseline to the more rapid variations and is almost certainly identical to a combination of Kinman et al. (1968) light curve components "B" and "C". This change in the behaviour invalidates the claim of Barbieri et al. (1977) that the light curve shows strong periodicity in the outbursts, a claim that they repeated later (Barbieri et al., 1983; Cristiani et al., 1986). Webb et al. (1987) find further evidence for this in their analysis, finding that when the light curve is divided into two sections, both do show a strong peak in

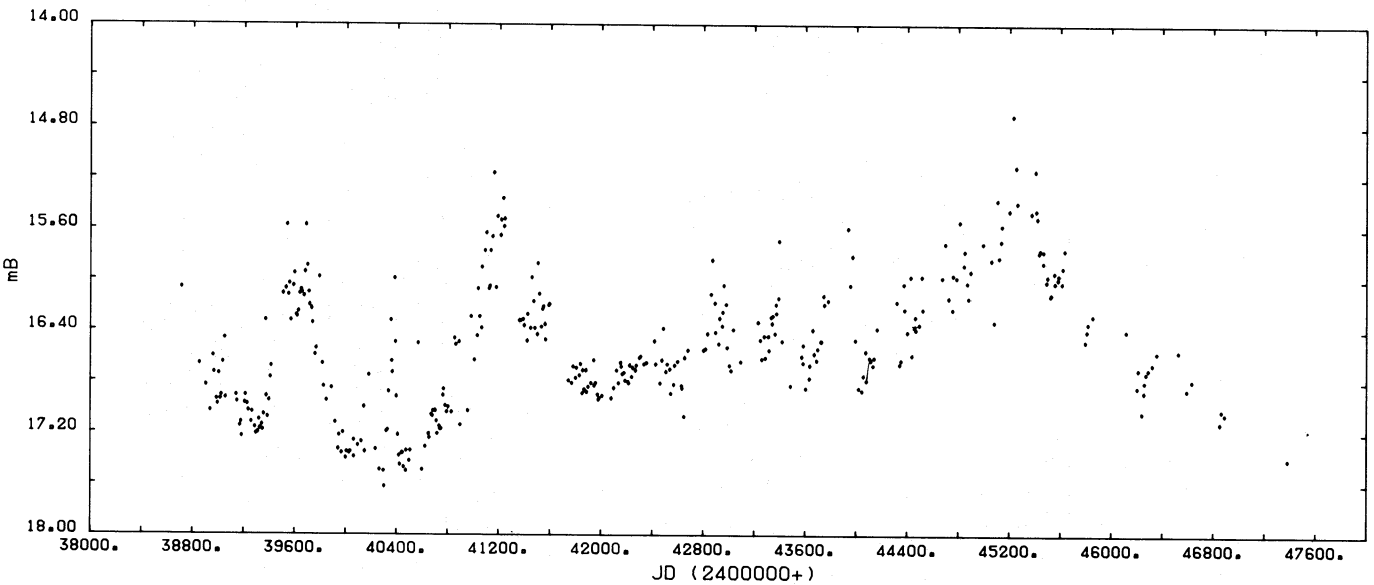

Fig. 2. Ten day means of the light curve of 3C 345 derived from the data presented within the text

the power spectrum at a period of four years, but that the phases of the respective peaks are incompatible. A new major flare ended this period of behaviour. After a long rise maximum occurred at around JD 2445230 when the magnitude was the brightest that has ever been recorded. This very high level was maintained for around 50 d. A second maximum occurred around JD 2445400, but was not well covered. If, as seems probable, the peak of this second outburst was not observed, it is possible that this maximum was even brighter than the former one. All four large maxima observed in the light curve over the period 1965 to 1987 have shown double peaks, with a second comparable maximum occurring within a few hundred days of the first. Three of the four maxima were broad, the one exception, the very narrow peak observed near JD 2440400, has the two components of the maximum separated by only thirty days and of considerably different amplitude.

At the start of the final rise to the maximum of the most recent major outburst, at JD 2445230, an increase in brightness of $0^{m}.48$, was registered by Babadzhanyants et al. (1985) in just half an hour. Occurring as it did at an already high level of activity, in energy terms this may be one of the fastest variations ever observed in a quasar.

Although the major maxima predicted by Barbieri et al. to occur in 1976 and 1980 did not occur in any easily recognisable form, the 1983 maximum corresponds fairly well to the expected date from their suggested light curve fit. This may be no more than coincidence, but suggests that some form of pseudo-periodic mechanism may be active in the light curve. This does not imply though that the dominant mechanism of the variability is truly periodic. Further evidence of this is the failure of the light curve to show evidence for a major outbutst in 1986 or early 1987 despite the occurrence of the previous maximum. Since this maximum the brightness has declined slowly and continuously, the last available observations (those by the author) showing that the magnitude had fallen to below 17 by JD 2446860 (the very latest available observation was taken in late July 1988 and shows that the magnitude had fallen as low as 17.40, very little above the historical minimum of the light curve). The rate of decline appears to have been almost constant over the last 5 yr of observation. During this period the coverage of the light curve has been relatively sporadic, but there seems to be little or no evidence for rapid flaring, something that had previously been a constant feature of the light curve even in its more inactive phases. This seems to mark yet another change in the character of the variations.

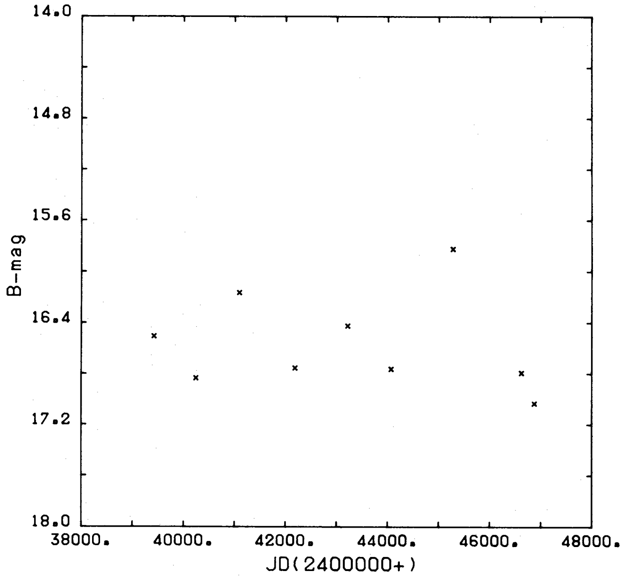

Fig. 3. One thousand day means of the light curve of 3C 345. There is little evidence of a systematic trend of the form calculated by regression analysis being present in the data, although there is some evidence for a slight systematic fading

Despite the fact that the most recent data show a return to a very low level of brightness there is a very strong overall upward trend visible in the light curve. This trend amounts to

0ᵐ033 yr^{-1}. This is very much greater than the mean trend found in the light curve of 3C 273 by authors such as Terrell and Olsen (1970). The existence of trending has been central to the controversy over possible models of the light curve of quasars, being seen as a tool to distinguish between models. In neither case though is there good evidence that the trend is truly systematic. Figure 3 shows two thousand day means of the light curve of 3C 345. Such large bins allow long term patterns to be revealed more easily and suggest that the trend in the light curve of 3C 345 is not systematic.

There are very strong reasons to hope that fairly detailed monitoring of the light curve will continue to be carried out in the future, to attempt to define these changes in the character of variability and relate them to each other. Such a project would be suitable for a small, dedicated telescope of perhaps 50 cm aperture. Apart from such considerations, monitoring of the light curve is extremely useful in the interpretation of spectrophotometric monitoring. This last aspect has been covered in more detail by Bergman et al. (1986).

The general characteristics of the light curve over the twenty three years of the monitoring record can be summed up as follows:

1. Occasional very large peaks, with widely differing rates of rise to and fall from maximum. Possibly the largest peaks are marked by the slowest rates of rise and fall and the lowest peaks by the most rapid rates of variation.

2. A very slowly varying underlying baseline component with an amplitude of about 0ᵐ8 and a characteristic timescale of variation of possibly 10 yr which is responsible for observed trending.

3. Rapid flaring of up to 1 mag in amplitude which can take on pseudo-periodic characteristics, with timescales of the order of from ten to a some tens of days.

4. Ultra-rapid flaring of approximately constant amplitude above the baseline, shown in the light curve as individual points at a much brighter than expected level. This can be most clearly seen in the otherwise quiescent period from 1975 to 1980.

To these could be added a fifth component of the variations which is not as clearly confirmed as the four modes listed above.

5. Flickering on timescales of hours with amplitudes of ~ 0ᵐ1 or 0ᵐ2?

This last component can be seen on CCD photometry which was performed on the 1 m Jacobus Kapteyn Telescope of "el Observatorio del Roque de los Muchachos", on La Palma in the Canary Islands, Spain, on July 20th 1986 (Fig. 4). An RCA type CCD was used at the *f*/15 Cassegrain focus. Relative photometry was performed against stars D, E and F of the standard sequence, using a pseudo-aperture of 6″ (seeing 1.4–2″ during the observations). The light curve shows the change about in the mean magnitude in the Johnson *V* band (crosses) and Kron-Cousins *R* band (diamonds). This method of presentation allows a continuous light curve to be drawn up for two and a half hours permitting direct comparison of timescales and amplitudes in two bands. The curve shows that comparable variations are seen in both bands. The rms errors from the relative photometry used average about 0ᵐ02.

4. Previous analytic studies

As Paper I included an extensive review of previous analyses of the light curve of 3C 345 the reader is referred to it for details of pre-1985 studies of the light curve and also to Table 2 in which a summary of all known previous periodic analyses of the light curve is presented. However, several further analyses and/or new data sets of major importance have been presented since Paper I was written.

Babadzhanyants and Belkon compiled all observations available to 1983. They found that the trend was 0ᵐ05 yr^{-1}, rather higher than the value found by this study (this difference is due to the pronounced fade post-1983). Fast optical flashes were found to show a 327 day periodicity over 1972–1975 in close agreement with the value of 321 days found by Kinman et al. (1968) for the period 1965–1967. They also find evidence for a slow periodic component of period fifteen years (qv. a sample length of 18 yr). A third component is found with a period of 10 d and variable amplitude. This last refers to a characteristic rate of variation though and not to a genuine periodic term. The mean data spacing 1965–1987 is one point per 5.6 d and was even better (mean spacing 5.1 d) over the period covered by Badadzhanyants and Belkon, hence the light curve is capable of providing information on such rapid variations. Their analysis of the large outbursts found in the light curve leads them to predict that a further one should be expected in 1986–1987. However they point out that the prediction of such outbursts as those expected in 1976 and 1980 assumes that such outbursts exhibit a rigorous periodicity, an assumption which they find unfounded. This is not to say that the characteristic frequency of occurrence is not a genuine property of the light curve.

The data presented by Babadzhanyants et al. (1985) are important for two reasons, not only is it numerically the most

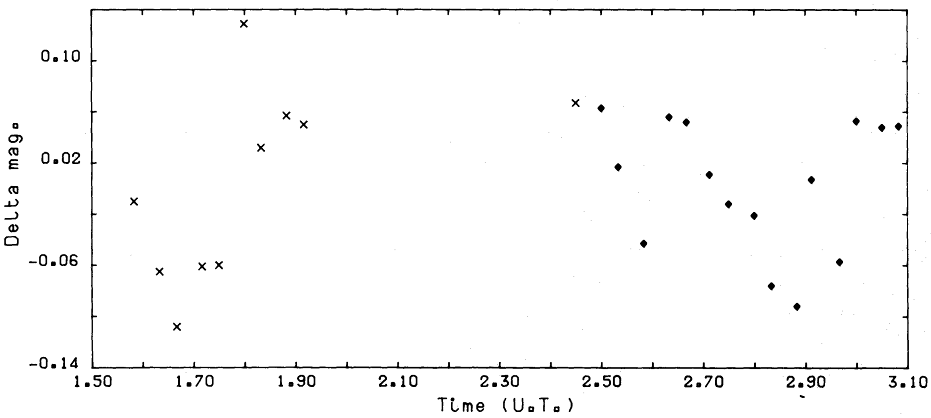

Fig. 4. Photometry of 3C 345 taken with an RCA CCD on the 1 m Jacobus Kapteyn Telescope in the *V* (crosses) and *R* (diamonds) bands. To allow the photometry to be presented as a single light curve, it has been referred to the mean level of the light curve in each filter. This allows timescales and amplitudes of variability in the two bands to be compared directly

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extensive sample to be presented as yet, but also the data cover a period of poor, or non-existent coverage of the light curve by other groups. Babadzhanyants et al. noted that "typical" behavior of the light curve was the occurrence of flares of about 1 m in amplitude, lasting for about 20 d. To assess more rapid variability, they compared 72 pairs of magnitude estimates for dates when observations were taken by them and at Rosemary Hill Observatory (Pollock et al., 1979) with a separation no greater than 0.8 d. They concluded that systematic differences between the two data set amounted to no more than $0^{m}.03$. After correction for the spreading effects of observational errors they conclude that ythere was no evidence for variations on a systematic level, of amplitude greater than $0^{m}.2$ on timescales of 5 to 20 h, whilst accepting that isolated cases might occur. They do not mention the best case of such a variation, that of $0^{m}.48$ in 30 min found within their own data. The significance level of this variation is uncertain as individual errors are not quoted on the data points however, given a quoted mean error of $0^{m}.10$ and the brightness of the object at the epoch of observation, it may be suggested that the variation is probably close to three sigma and thus may be genuine, although the possibility that it is a random effect of observational errors cannot be ruled out.

Bregman et al. (1986) include a few previously unpublished Johnson *B* points in a very large compilation of simultaneous multiband monitoring. They find that the amplitude of the light curve in *V* is about half a magnitude more than in *U* and *B*. This difference is attributed to the presence of the 3000 Å bump and the contamination of the *B* band by the strong Mg II 2798 Å emission line. Given that these two features are non-variable they will serve to dilute the non-thermal continuum which, if this is true, can best be studied in the *V* band.

Webb et al. (1987) presented updated results from the Rosemary Hill Observatory programme which include new data covering the years 1979 to April 1986. These data fill some of the gaps in the post-1980 coverage of the light curve. When combined with historical data this gave them 1052 points in total. Periodic components of 11.4 and 5.6 yr are found in the Rosemary Hill data (sample length 15 yr) which has only a very small trend. When historical data is added the former period is confirmed, but not the latter. Instead, components of period 2.16 and 3.9 y were seen. They conclude that the sample is too short to be reliably dissected into periodic components.

The most recent data of all, a number of points kindly communicated to the author by Barbieri and his collaborators at Asiago and those of the author (Kidger, 1988) follow the trend of the slow fall from the large peak in 1982. A single point has been included from a period of monitoring in July/August 1988 which shows that the trend set by the previous data of a slow but continuous decline has continued. Historical precedent suggests that a renewed outburst or, at least, a reversal of the decline may be expected soon. In this data set the very rapid variations normally observed within the light curve seem to be less prominent, although the sampling is very poor in that the data is heavily clustered, a highly undesirable characteristic in such studies. Clearly, if the data is very unevenly spread, it is difficult to comment on the level of bursting activity referred to previously in this work, which operates on timescales of weeks. Hence it is dangerous to claim that the character of the variation is genuinely different within these last data.

Table 2 below gives a summary of results obtained by periodic analysis of the light curve by different groups up to the present.

5. New analysis

In Paper I Kidger and Beckman used the new observations and improved data published since the study of Barbieri et al. (1977). Applying the suggested $m_B - m_{pg}$ correction from Pollock et al. (1979) to previously rejected data, they were able to extend both the period and the temporal resolution of the light curve relative to other previous studies. This analysis is developed and extended here in view of the increase by 50% of the number of

Table 2. Previous periodic analyses of the light curve of 3C 345. Very few features are seen to be repeated in subsequent studies

Method	Periods found	Reference	Notes
Phase analysis	80.37, 321.5 d	Kinman et al. (1968)	80 d peak at 99.8% confidence
Barning (1962)	1025 d, amp $0^{m}.57$ 556 d, amp $0^{m}.18$ 165 d, amp $0^{m}.20$	Smyth and Wolstencroft (1970)	Sample < 1600 d of data
Deeming	1600 d, amp $0^{m}.35$ 800 d, amp $0^{m}.32$ 140 d, amp $0^{m}.25$	Barbieri et al. (1977)	"Best multiple" period selected
	15 yr, amp $0^{m}.8$ 327 d, amp $1^{m}.0$ 10 d	Babadzhanyants and Belkon (1984)	
Deeming	1470 d, 685 d, 140 d, 83.9 d, 74.5 d	Kidger and Beckman (1986)	
Deeming	11.4 yr, amp $0^{m}.35$ 2050 d, amp $0^{m}.36$	Webb et al. (1987)	Rosemary Hill data (11.4 yr = 4200 d)
	11.4 yr, 3.9 yr, 2.16 yr	Webb et al. (1987)	RHO + most archive data. 11.4 yr marginally significant

available data points and the considerably improved and extended coverage of the light curve, 23 yr of data instead of the previous 13. A different value of the $m_B - m_{pg}$ correction has also been adopted, that which was suggested by Lü (1972) which agrees closely with the value of $0^m.30$ adopted by the Asiago group (Barbieri, 1986, private communication). This and the fact that the data set used here is considerably better than any previously analysed data set, being very much larger than the data set used by Webb et al. and extended temporally compared to that studied by Babadzhanyants and Belkon. This allows a new and critical examination to be made in an attempt to confirm the results of other studies.

A second non-trivial concern is that the data sample now has a record length more than five times that of the major 4 yr period found by Barbieri et al. and is now about double the length of any periodicity of the order of that found by Ozernoy et al. (1977) and references therein, in the light curve of 3C 273, even allowing for relativistic effects. However, a serious problem with most analyses is that the major period found by periodic analysis is frequently of the order of the length of the data sample. A good example is the early analysis of the light curve of 3C 345 performed by Smyth and Woolstencroft (1970). It is often difficult to accept such results unless the light curve is obviously periodic when plotted and, at very least, it is hard to estimate what level of significance to give such a result. If a hypothetical component of variability of this timescale is not strongly periodic, it is unlikely to be unequivocally revealed in such a short sample. The absence of such terms in the power spectrum of the light curve or their non-repeatability would only suggest that there are no strongly periodic components active on this timescale.

The same method of analysis was used as in Paper I. The light curve was analysed by computing the power spectrum and spectral window for the magnitudes of the full data set, without further treatment apart from the subtraction of the mean (e.g.: daily means, rejection of points calculated originally as photographic magnitudes, or removal of the trend. This last is usual but, except in the case of an infinite data set, distorts the results and loses information. Even so, were the trend systematic it would still be necessary to remove it even from a comparatively short data sample; the trend shown in Fig. 3 is clearly not such a case). It was sampled at intervals of $0.000025\ d^{-1}$ and then smoothed with a five-point running mean which gives a resolution in the final plotted transform equal to the theoretical resolution of the data. In addition, the fourier transform of the autocorrelation function of the light curve was calculated as in independent check of results as per a suggestion by the referee.

At least part of the divergence between the results of different groups making periodic analyses of quasar light curves is due to differences in the treatment of the data before analysis. As a check of this detail, two distinct treatments were also applied to the same original data which were then analysed in the same way as before.

The form of the spectral window, shown in Fig. 3 is very similar to that found in Paper I, with a narrow central maximum (increased coverage has the effect of narrowing this peak) and three prominent peaks at 1 yr, 30 d and 27 d. The resolution has now improved sufficiently that some significant structure can be seen at very low frequencies corresponding to several years (2900 d = 8 yr and 1600 d = 4.4 yr respectively). Both peaks are sufficiently large that they will influence the power spectrum significantly. It can also be seen that the relative amplitude of the one year (solar conjunction peak) and the 29.5 d (synodic month) peaks has altered somewhat from earlier studies. Modern data are relatively less affected by the latter sampling effect than the older data.

Figure 4 shows the normalised power spectrum for 3C 345. By the method of Deeming (1975) a true peak in the power spectrum will reveal itself with secondary peaks from interference "beats" with the peaks in the spectral window. If there is a true peak at frequency ν_0 and a spurious peak at a frequency ν_1, then we will see peaks in the power spectrum at frequencies

$$\nu_0, \nu_1$$

and at

$$\nu_0 + \nu_1, \nu_0 - \nu_1$$

The power spectrum is thus a combination of real and spurious peaks.

6. Results

Power spectra were calculated up to a frequency of $0.125\ d^{-1}$ but no evidence whatsoever was found of significant power at frequencies corresponding to periods shorter than 40 d. However, considerable structure is seen at lower frequencies, including several very large peaks at the very lowest frequencies. The noise level away from the low frequency end of the data is very low. Measured between 0.004 and $0.030\ d^{-1}$ it is just 0.00062 units. This notional result implies that some twenty peaks in the power spectrum in the range 0–$0.025\ d^{-1}$ are potentially real. Here, a fundamental limitation of Deeming type analysis is encountered which at least partly accounts for the discrepancies found between the conclusions derived from identical analyses of essentially similar data, by different workers. The standard procedure is to confirm "true" periodicities by encountering their corresponding aliases in the power spectrum due to interference with known sample intervals. Such a procedure is very effective for powerful peaks in the power spectrum interacting with strongly defined sample intervals. When, as in this case, there are many potential peaks, most of which are weak (although above the level of the noise), the expected aliases are almost invariably too weak to be detected. Similarly, in the case of a very crowded low frequency end of the power spectrum it is extremely difficult to confirm the presence of aliases with a high degree of certainly. In such cases a common-sense approach to the problem is necessary as the classical method is rendered impotent. The principal peak seen in the power spectrum is a double structure centred at:

$$\nu_0 = 0.00064\ d^{-1}$$

or

period = 1560 d (4.3 yr)

The amount of power found in this peak is only about a third of that found in Barbieri et al. pioneering study, which is further evidence that the term is not strictly periodic. The other dominant low frequency peak seen originally by Barbieri et al. is reduced in amplitude by an even greater amount and has a complicated structure centred at $0.00138\ d^{-1}$ (725 d). The peak at the extreme low frequency end at $0.00008\ d^{-1}$ is due to the length of the data sample, a knee is seen in this peak at $0.00022\ d^{-1}$ (4550 d = 12.4 yr) which probably corresponds to the structure seen by Webb et al., it is though notably weaker than either the

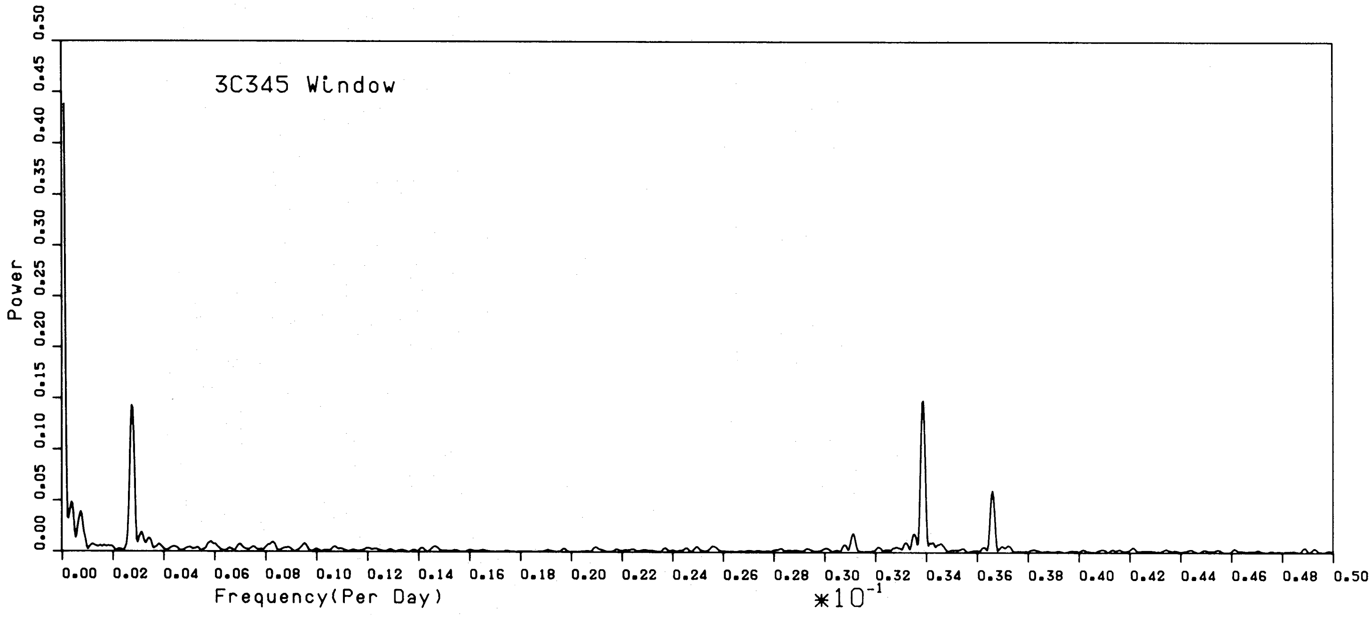

Fig. 5. The spectral window of 3C 345 calculated by the method described in the text

1600 or the 700 d peaks and also not clearly resolved in this power spectrum. It is precisely such low frequency peaks which will be most affected by the employment of such techniques as de-trending [eg: Barbieri et al. (1977)], or subtraction of a quadratic term [applied by Bertaud et al., (1973) – to BL Lac]. In addition, the addition of a single point from July 1988 to the light curve makes a significant change in the form of the power spectrum at low frequencies, reducing the power in both principal low frequency peaks, but considerably enhancing the power at the very lowest frequencies.

When the criterion of finding the spurious peaks caused by interference is used as "proof" of reality the evidence for the 11.4 yr periodicity is very marginal in this data. The 700 and 1500 d peaks though do show most, although not all of the expected interference peaks. The 320 d period of Kinman et al. (1968) and of Babadzhanyants and Belkon is not seen as such, but there is a fairly large double peak with components at 307 and 289 d, although the latter component corresponds closely to the frequency of one of the aliases from the 1500 d peak.

Possible peaks at higher frequencies are extremely difficult to confirm. One frequency which has been noted by all previous studies is the power at a frequency corresponding to 140 d. Some power is still evident at this frequency, but it is very much reduced and is not greatly above the noise level. Most of the possible minor peaks are at very similar levels. This is indicative of epochs of characteristic behaviour, or scales of activity, which leave a strong imprint in the power spectrum before decaying and being replaced by new types of activity. The "strong" signal at 140 d seen in previous studies is now being replaced by power at around 300 d as the third characteristic timescale in the light curve. An interesting frequency seen at the higher frequency end of the power spectrum is that at 0.02144 d^{-1} (46.6 d). This frequency contains comparatively little power, but is seen in an area of the power spectrum of extremely low noise and is at an unusually high frequency. There appears to be no frequency which could cause an alias in this part of the power spectrum.

7. Effects of different pre-analysis treatment

When embarking on an analysis of a quasar light curve it is essential to know what effects the pre-analysis treatment will have. Within this work and Paper I the only treatment was conversion of *pg* mag to the Johnson *B* system. In the case of a non-periodic (i.e. random) model of the light curve and a non-infinite data set this is the best option. If the light curve is strongly periodic with a superimposed systematic trend. subtraction of the trend is essential. If the trend is clearly systematic such a subtraction is advisable even if the light curve is not strongly periodic. At least one paper which presents periodic analysis of a quasar (in this case, BL Lac) advocates the subtraction of a quadratic term from the light curve before analysis (Bertaud et al., 1973). Changes in the low frequency end of the power spectrum will in turn effect the higher frequency end by changing the position and strength of aliases and may even offer a more reliable method of alias identification in crowded power spectra than that normally adopted. When the data base used in this paper was subjected to de-trending and removal of a quadratic term considerable changes in terms of amplitude and structure were seen at frequencies less than 0.0005 d^{-1} and some significant ones in the region up to about 0.005 d^{-1}, even though most peaks are seen in approximately the same position in all three cases.

At higher frequencies there is usually little change in the power spectrum although a few clear changes can be seen in the structure. The peak at 46.6 d remains identical in the treated light curves and thus appears to be real. On the other hand, the shape of the peaks at 95.4 and 84.5 d does vary significantly with

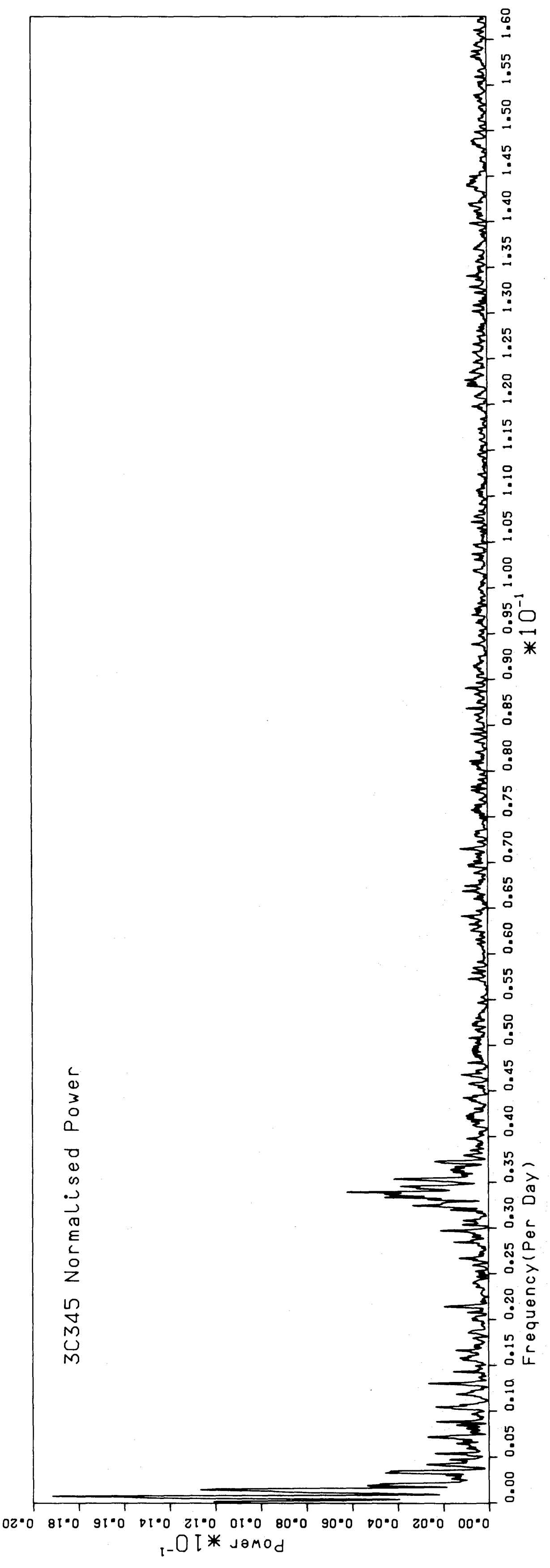

Fig. 6. The power spectrum of 3C 345 calculated by the method described in the text. As in all power spectra presented herewithin, the entire range of frequencies which contain useful information have been plotted at the theoretical resolution

Table 3. Principal low frequency peaks seen in the power spectrum of the full light curve of 3C 345 when different pre-analysis treatment of the data are applied

Mean subtracted	Trend subtracted	Quadratic subtracted
12500 d (34.2 yr)[a]	5560 d (15.2 yr)	5260 d (14.4 yr)
1890 d (5.2 yr)	1890 d (5.2 yr)	1890 d (5.2 yr)
1410 d (3.9 yr)	1520 d (4.1 yr)	1470 d (4.0 yr)
730 d (2.0 yr)	710 d (2.0 yr)	710 d (2.0 yr)

[a] A knee is seen in this peak corresponding to 4550 d = 12.4 yr.

treatment. These peaks quite possibly contain significant amounts of spurious power due to aliasing from lower frequency structures.

8. Division of light curve into separate parts

The light curve of 3C 345 is now sufficiently extensive that it is not possible to consider splitting it into separate sections to investigate the evolution of the power spectrum with time and, in doing so, to keep sufficient data and resolution in each section to have some real possibility of gaining meaningful results. A form of analysis of this type was attempted by Webb et al. who cut their data set at JD 2441087.4, coincident with the peak of the 1971 outburst. Whilst not presenting detailed results they comment that the power spectra of the two sets are clearly distinct. In this work the data has been divided at 1974 cutting the sample into two sections of somewhat more equal length. The rational is that there is obviously some change in character of the light curve after the decline of the third major outburst. This change being manifested by a slower rate of variation in the underlying component, hence the data set has been split at the point where the change apparently occurs.

Unsurprisingly, the power spectra of the two section are completely distinct. Pre-1974 the power spectrum is dominated by the low frequency components described by Barbieri and his collaborators (Barbieri et al., 1977). Apart from the powerful low frequency peaks there are a number of other significant ones which are clearly seen above the noise. Post-1974 the power spectrum is almost completely devoid of possibly significant peaks. Apart from a structure seen at 0.0004 d^{-1} (2300 d = 6.4 yr), a period slightly more than double the length of the data sample and extremely weak compared to the signal seen pre-1976 by Barbieri and others at a period of about 4 yr, there is little low frequency power of the type previously seen.

At higher frequencies, the peak seen at around 140–160 d in all previous analyses of the whole light curve is either not repeated here, or seen at a significantly lower frequency. A clear peak is observed at 0.00540 d^{-1} (185 d), this though has to be compared with the value of 156 d measured by Smyth and Woolstencroft (1970) which is the most divergent of the previous determinations of the frequency of the "140 d" peak. This large difference makes it seem probable that the two peaks are distinct in cause. Only two other possible real peaks are seen, both purely in the 1974–1987 section is 0.0158 d^{-1} (63 d) and there is also some evidence of the excess power post-1974 at 0.0418 d^{-1} (23.9 d). This latter is three times the mean data spacing which

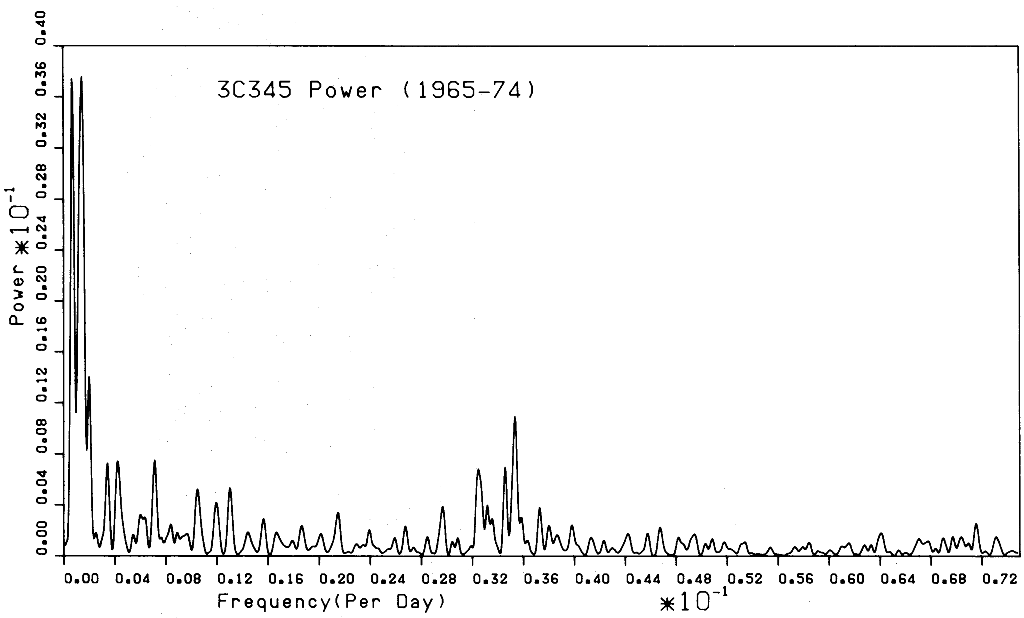

Fig. 7. The power spectrum of 3C 345 for the period 1965–1974 calculated as defined in the text

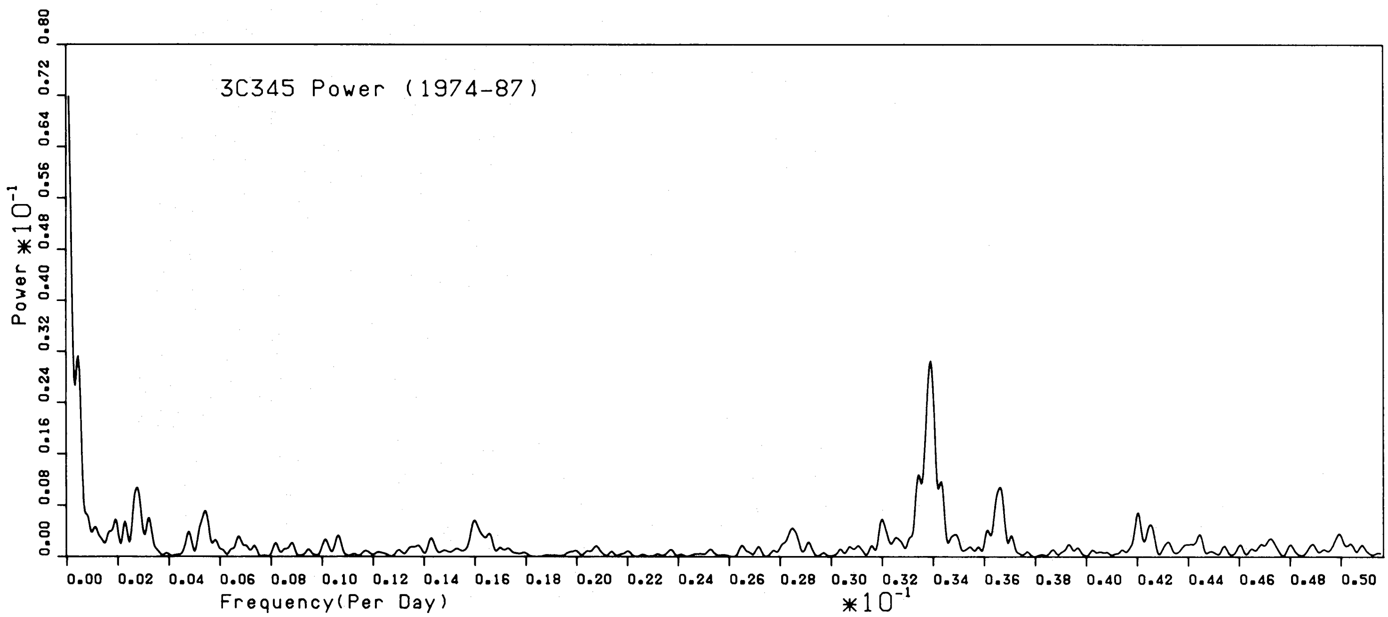

Fig. 8. The power spectrum for the interval 1974–1987

implies that theoretically there is sufficient information in the light curve to reveal such rapid variations and that this frequency may genuinely be present. On the other hand, the previously dominant periodicities at 800 and 1600 d have completely disappeared post-1974. This reinforces the conclusion in Paper I that the presence of power at these frequencies is a residual effect from the 1965–1974 outbursts. This conclusion was apparently misinterpreted by Webb et al. (1987) as meaning that there were no significant peaks found in the power spectrum calculated in Paper I— a subtly different (and erroneous) conclusion.

As a further test, a third, transition section of the light curve was defined which corresponds to approximately 1970–1978. This was chosen to give a reasonable length of light curve which would be evenly weighted by the pre and post-1974 data. Of the 631 points from this epoch, 341 (54%) are from the interval 1970–1974 and 290 (46%) from the section 1974–1978, thus the resultant power spectrum should be of a genuinely intermediate sample of the light curve. Despite this, the resultant power spectrum show little similarity to those previous calculated. There is no single peak in the power spectrum of the 1970–1978

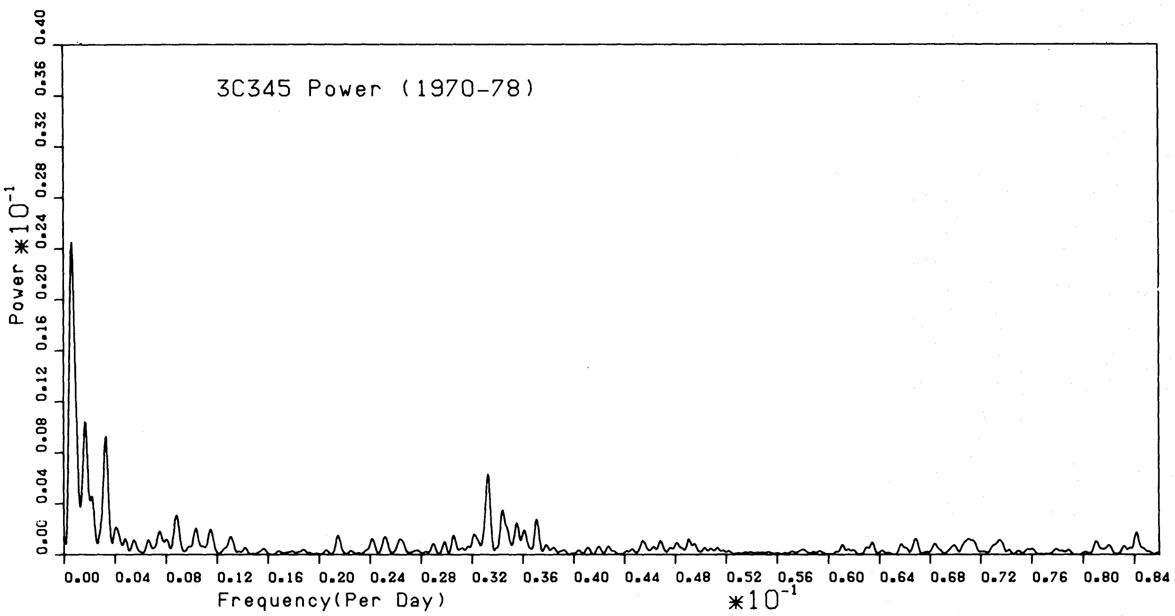

Fig. 9. The power spectrum for the intermediate interval of light curve from 1970–1978. The power spectrum of this section bears little resemblance to the power spectra (see Figs. 7 and 8) of the two sections of the light curve which overlap it

Table 4. Characteristics of the separate sections of light curve which were analysed by Deeming analysis. The slight differences in resolution and mean rate of light curve sampling are not sufficient to account for the changes which are seen in the power spectrum

Interval	Range of JD	Resolution of power spectrum	Mean magnitude	No. points	Mean sampling
1965–74	2438715–42050	0.00030 d^{-1}	16.665	831	3.969 d
1974–87	2442050–46888	0.00021 d^{-1}	16.386	620	7.750 d
1970–78	2440590–43500	0.00035 d^{-1}	16.621	631	4.571 d
1965–87	2438715–46888	0.00012 d^{-1}	16.546	1451	5.633 d

section which is clearly seen in either 1965–1974 or in 1974–1987, apart from the 4 y peak which appears in both the early and the middle sections but not from 1974 to the present. There is a small peak in the 1970–1978 power spectrum at about 120 d, but again this is not in close accord with the period of peaks in the power spectrum in either of the principal sections of the data set.

It is thus seen that the principal periodicities seen in the light curve are in no sense continuous, but rather each are found at certain distinct epochs and then are very rapidly damped. No single periodicity seems to have remained active in the light curve for more than ten years and the majority seem to be even more ephemeral. When viewed this way it seems that the occurrence of an event in the light curve in 1982–1983, in approximate accordance with the 4 yr cycle, is almost certainly no more than coincidence, especially as, up to April 1987 there was no evidence at all of the onset of the next expected outburst.

This last conclusion is strengthened by an examination of the Fourier transform of the autocorrelation function. Apart from sampling intervals previously mentioned there is almost no significant structure at frequencies corresponding to periods less than 1000 d hence this plot is not shown. The 700 and 1400 d periods are extremely weak and, indeed, the latter of these is of lower amplitude than two possibly real frequencies at 0.0034 d^{-1} (300 d) and 0.0058 d^{-1} (170 d).

Table 4 summarises the differences between the distinct sections of the light curve as regards extent and sampling and shows that, whilst sampling differences may cause slight modifications to the resulting power spectra of the two principal sections (1965–1974 and 1974–1987), sampling itself is not the reason for their distinct appearance, rather some phenomenon intrinsic to 3C 345 itself. It is noted that the mean level of the light curve between the three epochs which are defined varies to some degree, although it is stable to about 25%. If the mechanism of energy release within the quasar is assumed to be some variant of the basic Lynden-Bell/Hills model [Lynden-Bell, (1969); Hills (1975, 1978)] involving the consumption of material (e.g.; stars) by a massive singularity, this stability of the mean brightness the stability (or otherwise) of the light curve serves to constrain models, as such a process must have a strong stochastic element which should be reflected in the variation of the mean level of the light curve. If the mean level of the light curve is highly stable it implies that, except for the most luminous objects in which the rate of consumption of discrete masses is very high, the stochastic part of the energy release is supplemented by a strong element of direct emission from the accretion disc.

9. The power spectrum of a stochastic process

There has been a prolonged controversy also the periodic or shot noise nature of quasar light curves and specifically that of 3C 273 (there reader is referred to extensive discussion of this in the literature (see e.g.: Fahlman and Ulrych (1976); Ozernoy et al. (1977); Wheeler (1972); Angione and Smith (1985); and references within these works). Some discussion of this point is necessary in the context of 3C 345. This debate is fundamental and has important implications for energy generation mechanisms. Whilst the length of light curve sampling of 3C 345 (22 yr of good data plus a very few historical points) cannot match the 101 yr of available data for 3C 273 (the first observation of 3C 273 occured on April 14th 1887), the *quality* of 3C 345's light curve is considerably greater, the mean sampling being a factor of five better than even the best covered period of 3C 273's light curve. This is a valuable analytic tool which can help, if not to resolve the debate, at least to indicate the direction in which the truth lies.

Paper I made the suggestion that the 140 d peak seen in the light curve had the correct general characteristics for it to be indicative of the mean rate of a stochastic process. If shot noise is to be considered as a working hypothesis as the principal light curve model, when considering the power spectrum of quasar light curves it is necessary to consider what the characteristic signature of shot noise would be. Two papers have considered this problem from different points of view. Fahlman and Ulrych (1975) examined the power spectrum of a simulated light curve built of pulses of the form suggested by their light curve analysis of 3C 273 which had a Poisson distribution. Such a distribution implies that the largest probability is of a small separation between pulses with decreasing probability as the separation increases and is the expected form for a random sequence of events. Terrell and Olsen (1970) also used a poissonian distribution in their analysis of shot noise simulations based on their own parameters for 3C 273. They analyse the expected form of the power spectrum for shot noise finding that it is the same as that for an individual shot. The expected form of the power is

$$P=\frac{1}{\lambda}[1+2\pi\nu\tau)^2]$$

for exponentially decaying pulses where τ is the decay rate and λ the shot rate. Simulated shot noise light curves with parameters intended to match those of 3C 273 were analyzed by Terrell and Olsen. The power spectra found not only to be similar to the expected form (and that of 3C 273), but also to be capable of wide variations about that form, including low frequency peaks. Such structure is thus not incompatible with a random process. Fahlman and Ulrych (1975) made a similar analysis with similar conclusions although their input shot parameters differed somewhat from those of Terrell and Olsen. Considerable low frequency structure was seen including a peak near period = 17 yr somewhat similar to that seen in the actual light curve of 3C 273. In both cases there is little power at frequencies greater than about one cycle per year. Thus the presence of strong stable peaks, at high frequencies, would suggest a non-randomness incompatible with a pure shot noise model.

The suggestion made in Paper I of a signature in the power spectrum at the mean shot rate is thus seen at face value to be rather unlikely. This though is only the case in a "perfect light curve". It is not impossible to produce power at the shot frequency under certain circumstances. Given an infinite data sample with a perfectly random shot distribution the power spectrum would be exactly described by the formulation of Terrell and Olsen which is given above. If the data sample is not infinite, or the shot distribution is not a perfect poissonian, it appears possible that some residual signal may be left at the shot frequency. Extensive shot simulations (which are not presented here) have been performed by the author using the best available pseudo-random poissonian sequence which was available, that of the NAG library. Such simulations are unsatisfactory in that they can never attain perfect randomness, although they may approach it closely. The results of these simulations support the suggestion that residual power can appear at the shot frequency if the shot rate is low ($<3\ \mathrm{yr}^{-1}$). Such power would tend to diminish with time as the shot sequence approaches a truly random statistical sample. An alternative mechanism for generating power at the mean frequency of light curve events would be accretion as described by a Hills-type Black Tide model at, or very close to, the Eddington limit. Under such conditions the input sequence of events becomes non-random as the initiation of one event (e.g.: a stellar disruption) prevents further events by radiation pressure.

A characteristic of the power generated by shot noise is that over intervals of time not greatly in excess of the mean shot spacing the position of the peak in the power spectrum will vary due to statistical variations in the mean rate of events. The movement in the peak nearest to 140 d in the various sub-sets of the data is around $\pm 25\%$ in frequency. This corresponds closely to the expected movement due to statistical fluctuations in a stochastic process at a rate around one per 140 d (approximately the square root of the number of shots which occurred in the measured interval). From this point of view the identification proposed in Paper I at least does not contradict the evidence. Whether coincidentally, or otherwise, this is approximately the level of variation in the mean level of the light curve within the three section which are defined. Whilst this is in no way conclusive proof of stochastic origin, it is somewhat suggestive. Penston and Cannon (1970) pointed out that the constancy of the mean magnitude of 3C 273 is inconsistent with a stochastic process. If the mean of the light curve is calculated at a time interval such that an average one hundred events will occur within it, the standard deviation of the number of events which actual occur in that interval is $\sqrt{100}=10$; i.e.—we would expect a 10% variation in the mean level of the light curve. Given the low rate of events implied for 3C 345, the expected level of variation of the thousand day means would be $0^{\mathrm{m}}.35$; the observed value is $0^{\mathrm{m}}.36$. Again, without being in any way conclusive evidence of the stochastic nature of the light curve, it is in good agreement with the expected value on a stochastic model.

10. The Jurkevich V_m^2 statistic

Due to the inherant limitations of even Deeming type analysis, an independent method of periodic analysis, which does not use the

Fourier transform, was used, Jurkevich (1971) points out that when the light curve is folded about some supposed period with the data grouped in bins of phase, the sum of the variances of the individual groups is a sensitive test for possible true periodicities. In the case of such a true period the total variance of the individual groups will be reduced relative to the variance of the entire, unfolded light curve. When the total variance, V_m^2, is plotted against the trial period, a true periodicity will reveal itself as a minimum in the curve. The sensitivity of the test depends on the number of bins used. Since the number of available data points is very large, a comparatively large number of bins may be used and each will still contain an acceptable number of points. For this study twenty bins were used.

The trend and a quadratic terms were subtracted from the light curve before binning. This removes possible slowly varying components with timescales greater than the length of the data sample. V_m^2 was then calculated for a run of periods from 4 to 9000 d. This is the entire range of periods which can be studied given the sample length and the mean data separation.

The output (Fig. 10) reveals possible true periods as "dips", there are also a number of narrow "spikes" of uncertain origin. These are "anti-periods" around which the folding of the light curve apparently gives an especially noisy result. Below 400 d it is seen that the light curve is completely aperiodic. At periods higher than 400 d the noise in the run of V_m^2 increases greatly. The only feature which appears to be clearly above the noise level is one at around 4000 d (11 yr). This is very close to a period suggested by Webb et al. (1988), but it must be pointed out that there have only been two complete cycles of this period since monitoring began; this is insufficient to define the feature as periodic. There is no clear evidence of the much discussed period near 4 yr, which Fourier analysis has already shown was of very dubious significance except in a short section of the light curve.

11. Conclusions

The data base for the light curve of 3C 345 has been nearly trebled since the major analysis performed by Barbieri et al. (1977) and increased by 50% over Paper I. A new and better $m_B - m_{pg}$ correction has also been applied. Even casual inspection of the light curve is sufficient to show that there are no obvious periodicities. An analysis of the power spectrum of the present light curve indicates no evidence for the sinusoidal periodicities which have been reported by various authors in the past. A periodic model of the light curve may be completely ruled out from the data. There is no either strongly or even moderately periodic component of period from 5 d to about 10 yr.

There is some evidence of a pseudo-periodic element with an approximate period of 1400 d (4 yr) principally seen in the large outbursts in the light curve. The sporadic nature of this *possible* component and hence proof that it is not truely periodic in any sense, is illustrated by the absence of several of the expected outbursts (whilst all four major ones can be fitted approximately to this suggested interval, three further expected outbursts have failed to occur), thus it has little or no predictive power, even if real.

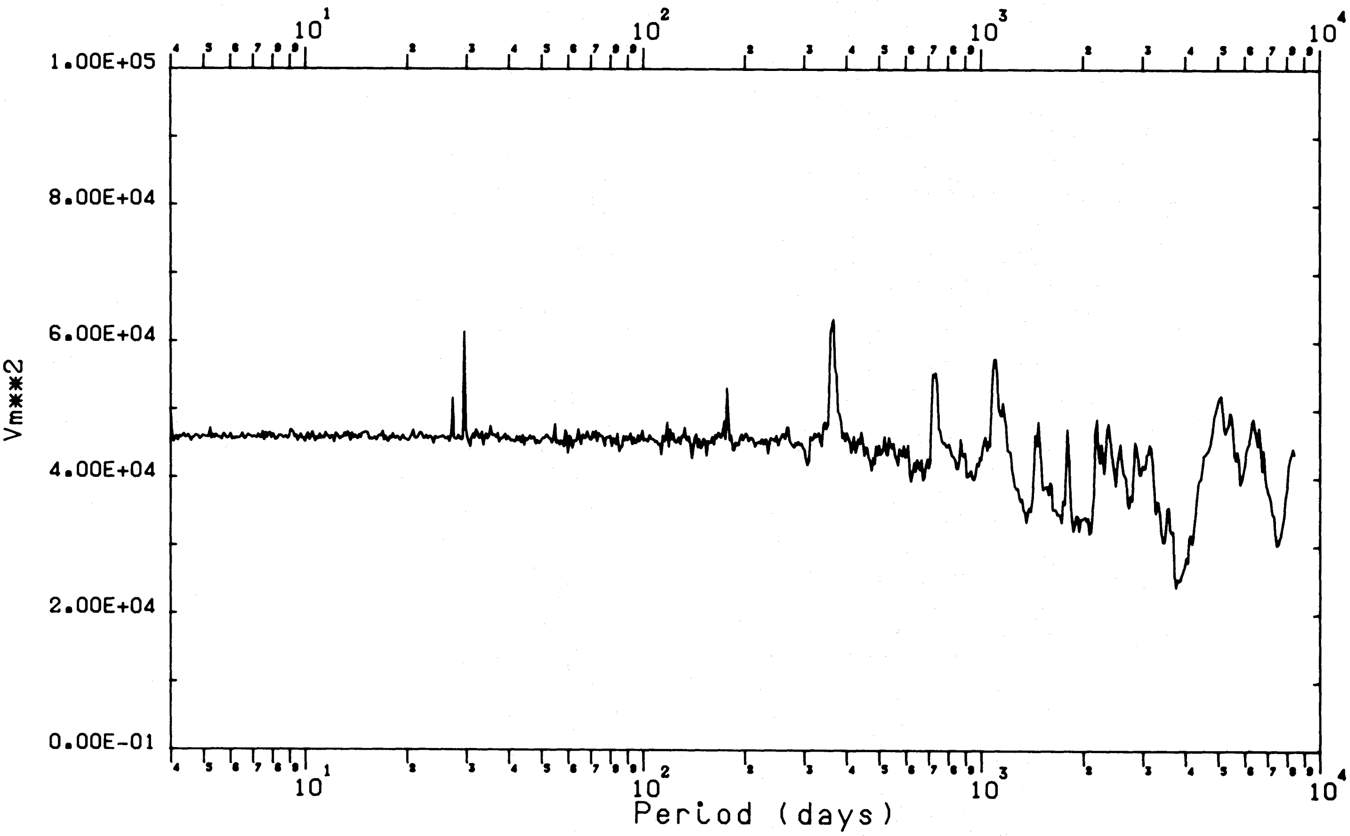

Fig. 10. The run of V_m^2 for periods between 4 d and 23 yr in the light curve of 3C 345. True periods are shown as dips in the function. The origin of the peaks which are seen is uncertain (see text)

No evidence is seen of any long enduring frequency in the power spectrum, whilst the general form of the power spectrum is seen clearly not to be continuous from one epoch to another, even over timescales as short as 10 yr. Even when over-lapping sections of light curve are defined there is little evidence of repeated structures. Attempts to extrapolate the behaviour of the light curve using the 4 yr flaring have broken down, as have all such attempts at extrapolation of the light curve using periodicities from 0.5–5 yr found in the power spectrum. Further attempts in this direction may be regarded as superfluous at present.

There is strong evidence for the existence of a baseline magnitude within the light curve, upon which all the variations are superimposed and that this baseline shows strong variations over scales of around ten to twenty years (similar to 3C 273). At present though it seems premature to assign a definite period to it as less than two cycles of the suggested 11.4 yr frequency have been completed through the entire observational record to date. This feature can only be confirmed by a considerable extension of the monitoring record.

Even the 140 period seen strongly in at least three previous studies of the light curve seems to be no longer active although one possible explanation for this is the random variation of its precise period. An alternative explanation, that is is the signature of a stochastic process in the light curve (i.e.: shot noise) cannot be ruled out. The variations in the exact period of this feature are consistant with those expected from a shot noise process in a qualitative way. Further investigation of this possibility would be highly desirable. The only periodicity which has been recorded which was in any way genuine was that seen by Kinman and his collaborators from 1965 to 1968 at 99.8% confidence throughout a number of cycles. It can perhaps be explained by the assumption of a temporary stable mode within an accretion disc. There is still power at close to the frequency of this periodicity which suggests that it may still be marginally present.

Apart from possible pseudo-periodic components, the compilation of the light curve and the new data presented here show that the characteristics of the light curve are even richer in variation than previous workers have suggested. The presence of an underlying slow component to the variations is confirmed. Apart from a need to extend the light curve if the possible 11.4 yr period is to be confirmed, continued observation is needed to extend the database further and hence attempt to extract information as to be characteristics and behaviour of the pseudo-periodic elements which are seen in it. Questions about the light curve which remain unanswered include: how often does it show a strong periodicity of the type seen by Kinman et al.? Are such periodicities ever repeated, perhaps in epochs separated by tens of years? Was the occurance of a major outburst in 1983 (about the time expected given a 1400 d cycle in the major outbursts) simply a coincidence, or will further outbursts in this series also occur? Apart from such concerns, a rigorous analysis of the light curve as performed in the case of 3C 273 by Fahlman and Ulrych, requires the longest possible time base of data if the evidence for a stochastic nature is to be in any sense convincing. Since the *quality* of the 3C 345 light curve is much higher than that of 3C 273, it is possible that despite the lesser length of the data sample a further extension of the light curve and subsequent autoregressive decomposition analysis may aid considerably in resolving the conflict between the various possible models. A further benefit may accrue from comparison between such an analysis of 3C 345 and those previously made of 3C 273. This will assist greatly in the interpretation of the light curve of 3C 273. At very least it is desirable that at least another object should have a sufficiently detailed light curve coverage to permit such analysis.

Whilst the light curves of 3C 345 and 3C 273 are clearly different in detail and the variations of the former are more rapid and of higher amplitude, this study indicates that there are more similarities than previously thought, the slow component being one example. Like 3C 273, 3C 345 has shown a capability to change completely its dominant mode of variation within a comparatively short period of time (yr or less). In certain epochs there is strong evidence of a dominant pseudo-periodic component, in others there is very little variation at all. Flaring activity also seems to be sporadic in its occurrence, at some times appearing to be the dominant mode of variation on shorter timescales, at others it has virtually disappeared. A variation of the type observed by Babadzhanyants implies an increase of about 10^{38}W in the luminosity in the Johnson *B* band occurring in a volume little greater than the inner solar system. This too may indicate something of the mechanisms of the central engine of the quasars. Alternatively, such variations may be due to occultations of the accretion disc by more distant and comparatively cool clouds. This could potentially give some extremely interesting information on conditions within the central zone of the quasar.

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