CAN THE OPTICAL FLUCTUATIONS OF 3C 273 BE RANDOM?*

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Abstract. The fluctuations in optical brightness of the quasi-stellar object 3C 273 have been investigated to determine whether the suggested periodicity of ~ 10 yr is supported by the observational data extending over 80 yr. New methods of obtaining information from the power spectrum have been used, and moments and trends have also been investigated. No statistically-supportable evidence has been found in the power spectrum for such a non-random variation. The moments and trends are consistent with random fluctuations. If the observed fluctuations are of shot-noise character, due to random outbursts of light, the individual pulses must occur at the rate of 15 ± 5 per year and have an average effective length of 3.2 ± 1 yr. These conclusions were verified by computer-generation and power-spectrum analysis of such random signals. Thus any periodic variation in the brightness of 3C 273, if present, is completely obscured by random fluctuations. The power spectrum, moments, and trend are all consistent with random but long-lasting outbursts of light.

Although 3C 273 was not discovered to be a quasi-stellar object until 1963, we fortunately have an 80-yr record of its optical brightness. It is bright enough at thirteenth magnitude to show up on old sky survey plates extending back to 1887. Harlan Smith and Dorrit Hoffleit (1963), examining these plates, found that 3C 273 has been fluctuating in brightness by considerable amounts.

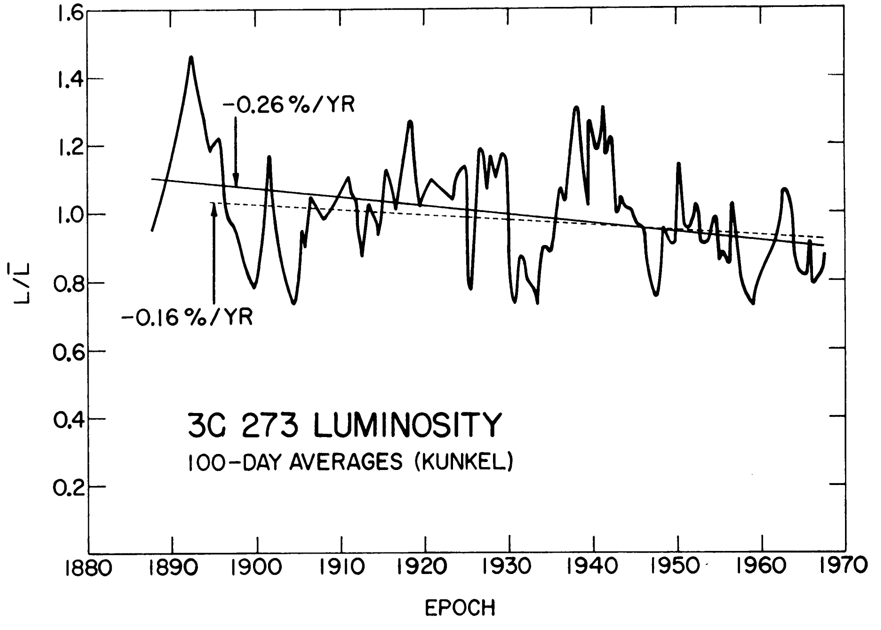

Fig. 1. Luminosity data for 3C 273, relative to the average luminosity, $\bar{L}$, based on photographic magnitudes averaged over 100-day intervals by Kunkel (1967). Least squares linear trends are shown, both for the full data (1887–1967) and for the truncated data (1894–1967).

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As seen in Figure 1, its brightness has continually varied by 10%, 20%, or more, occasionally doubling in brightness in a few days, sometimes dimming just as suddenly. There is also a trend toward lower luminosity, amounting to a decrease of 26% per century. If the first 2500 days of data are omitted as of little reliability, being more interpolation than data, this trend is reduced to 16% per century. The data shown here are as averaged by Kunkel (1967) over 100-day intervals.

Smith (1965) found indications of a 13-yr period, more or less sinusoidal, in this record. Gudzenko *et al.* (1967) analyzed the data and found a 9- or 10-yr period, with 99% certainty (or, more recently, 97%). Manwell and Simon (1966) found no evidence of periodicity and stated that the fluctuations could be reproduced by the superposition of about 25 very short outbursts of light per year. Kunkel found possible evidence of a fundamental 13-yr cycle, plus several harmonics.

Thus the question whether the light from 3C 273 has a fundamental fluctuation period, or is due to the overlap of random unrelated outbursts, has been a controversial one, and the result obviously has a bearing on models of quasars. Ken Olsen and I undertook to find the most definite answer possible, using the techniques of moment and trend analysis and power spectra.

Figure 2 shows the result of a straightforward determination of the power spectrum of these light fluctuations. The power spectrum is essentially the square of the coefficients of a Fourier series representation of the data. It represents the fluctuation power as a function of frequency – extending in this case from zero to $\frac{1}{2}$ cycle per year.

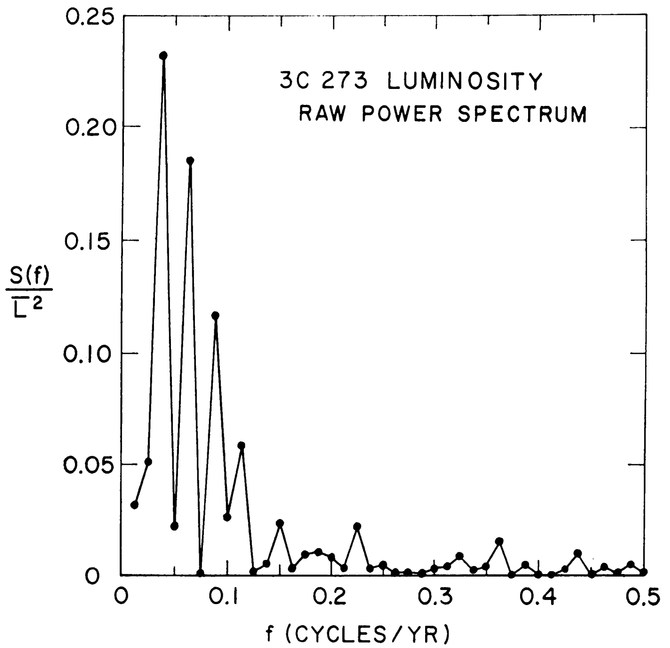

Fig. 2. Power spectrum for 3C 273 luminosity, 1887–1967, based on Kunkel's averages, not detrended. The spectrum is raw, i.e., not smoothed to reduce random fluctuations.

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In the raw, unsmoothed form seen here the points fluctuate considerably, being uncertain by a standard deviation of $\pm 100\%$. Thus these many narrow peaks are not proof of many resonances, but of the lack of smoothing.

Figure 3 shows the result when a standard form of smoothing, due to Parzen, is applied to the power spectrum. The spectrum is much smoother. There still appear

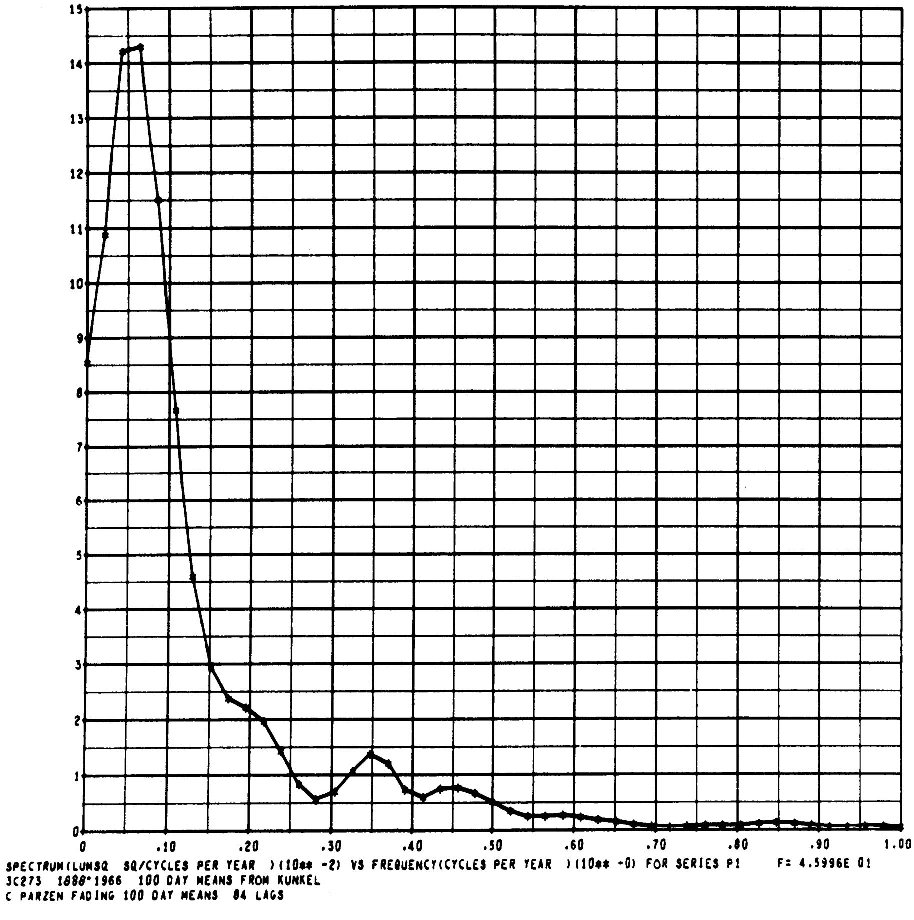

Fig. 3. The power spectrum of 3C 273 smoothed by the standard method of Parzen.

to be a number of weak resonances – but each peak has a standard deviation of $\pm 40\%$. There is thus no real evidence for resonances or harmonics in the spectrum, except perhaps the peak near a frequency of 0.07 – about a 14-yr period. However, the part of the power spectrum nearest to zero has unfortunately been reduced in height by the standard methods of analysis, which involve removing the average, removing the trend, and Parzen smoothing. Removal of the average reduces the zero-frequency point to zero, and smoothing then averages this value into the lowest frequency points.

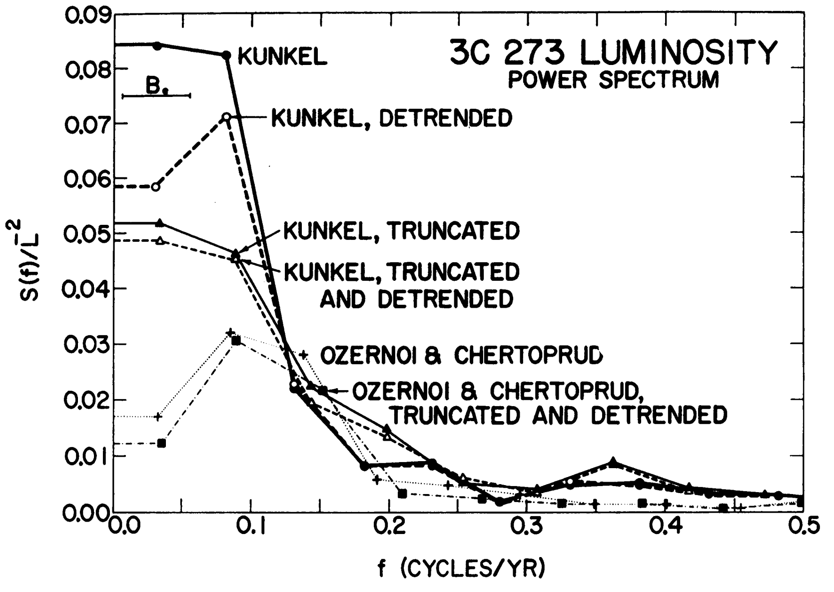

Fig. 4. Power spectra for 3C 273 luminosity for various forms of the data. The points shown have been smoothed over four Fourier harmonics, giving the effective bandwidth B_e shown (for Kunkel's full data), and standard deviations of $\pm 50\%$ for individual estimates.

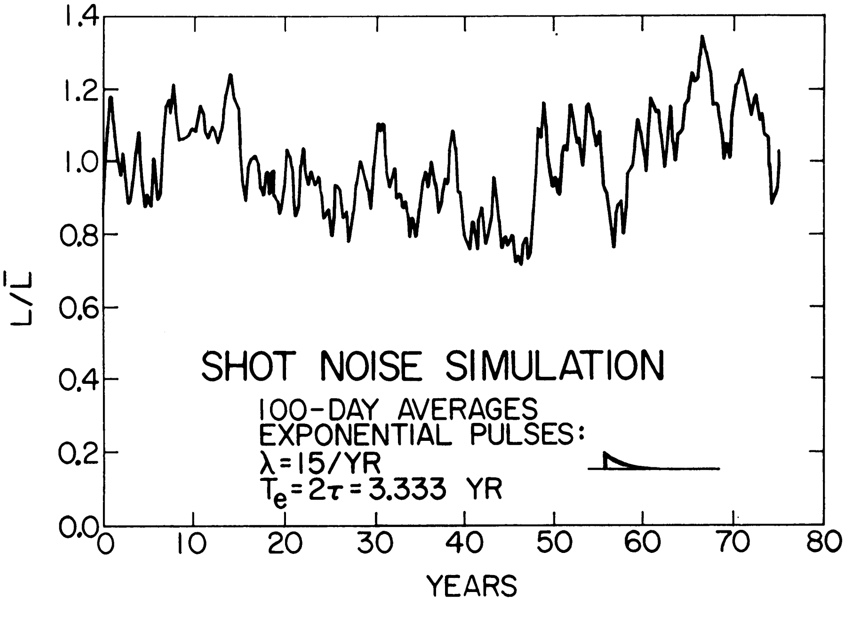

Fig. 5. Typical shot noise generated by computer, consisting of random exponentially-decaying pulses, as shown, with rate and pulse length T_e similar to 3C 273 parameters.

Detrending removes more power from the lowest frequencies, and the end result is misleading evidence of a low-frequency peak.

Figure 4 shows the results we obtained using a different method of smoothing, which does not give such a misleading result by reducing the power at low frequencies. The uppermost curve is the power spectrum obtained from Kunkel's data without detrending. The power spectrum points are each averaged over four Fourier coefficients – not including the one for $f=0$ – and have a standard deviation of $\pm 50\%$. They are also essentially independent. Notice that when the trend is removed from the data before analysis the low frequency power is thereby decreased, giving a false indication of a resonance. When the first 2500 days of data, representing mostly interpolation, are truncated, the result shown here is a power spectrum of somewhat less low-frequency power but otherwise similar. The data as averaged by Ozernoy and Chertoprud (1966) give even less low-frequency power, and a possible resonance – with considerably less than 50% certainty. It should be noted that their data are

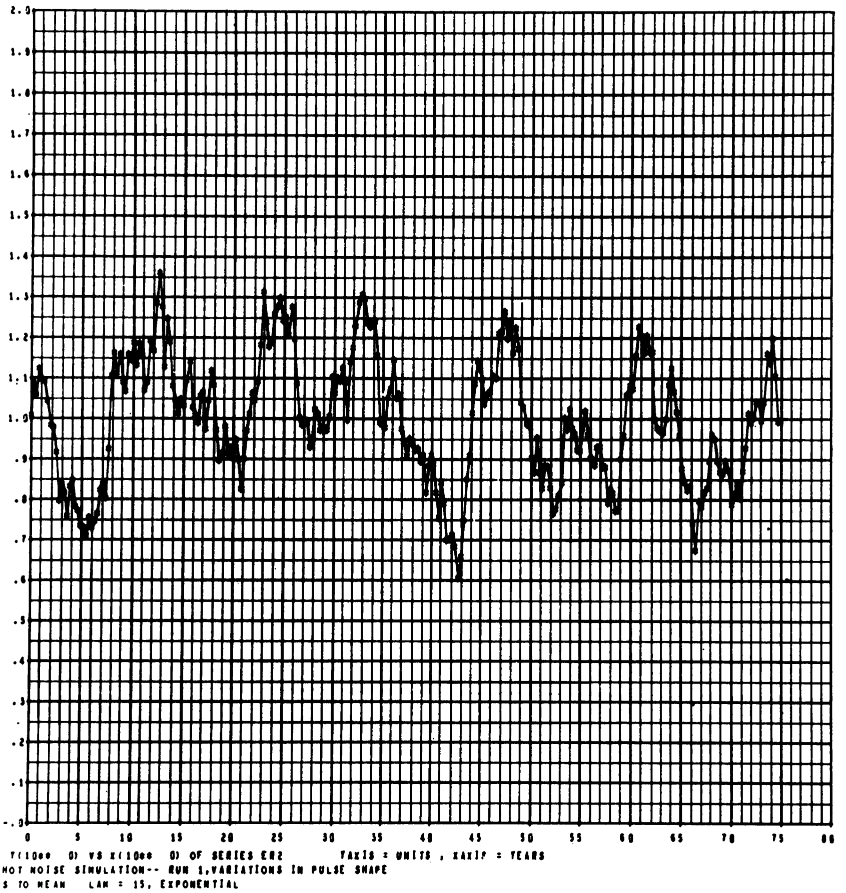

Fig. 6. Another example of shot noise generated by computer.

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published in detrended form, and thus with reduced low-frequency power. Truncation of their data does not have much effect.

If the fluctuations of 3C 273 are due only to random outbursts of light – a situation known as shot noise – it can be shown that the maximum power *must* occur at $f=0$.

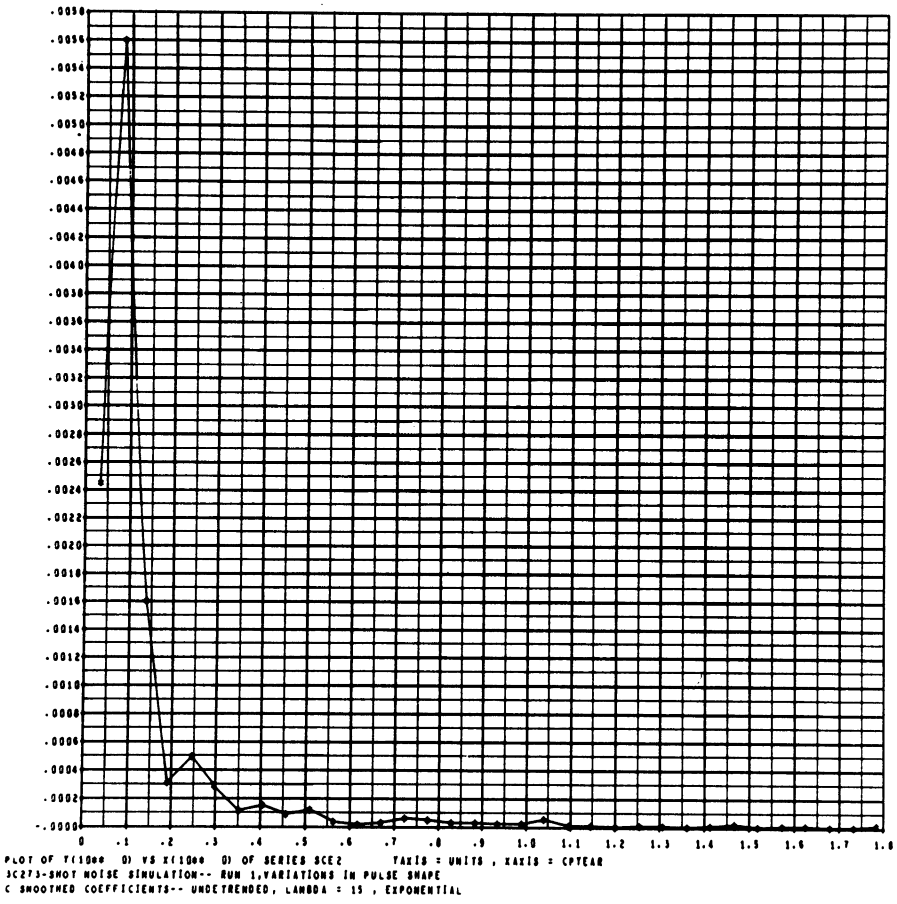

Fig. 7. The power spectrum for the shot noise run of Figure 6.

The value of the two-sided power spectrum at this point, when normalized as here, is equal to $1/\lambda$, where λ is the rate of occurrence of the pulses. We see that if these fluctuations are random shot noise, the rate of occurrence from Kunkel's data is $\lambda = 15 \pm 5$ per year.

The pulse length is then given essentially by the width of the zero-frequency peak, including both positive and negative frequencies, and a more precise analysis gives an effective pulse length $T_e = 3.2 \pm 1$ yr. Thus Kunkel's data can be produced by about 15 outbursts per year of 3.2-yr long pulses, which leads to the average overlap of 48 pulses at a time. The area under the power-spectrum curve is equal to the variance, which, of course, corresponds to an average of about 48 overlapping random pulses, or a standard deviation of ±14%. Thus, if these fluctuations of 3C 273 are due to random pulses, the pulse parameters are given directly and simply by the power spectrum. The moments and trend of the data have also been found to be consistent with random shot noise (Terrell and Olsen, 1970).

Figure 5 shows random shot noise fluctuations which we generated in a computer, with pulse rate and length similar to those determined from the 3C 273 spectrum, in order to verify our results. The pulses in this case were taken to be of exponentially-decaying shape, with an effective pulse length of 3.333 yr. Figure 6 shows the generated shot noise in another run. This particular run is the one (out of five) which most resembled an oscillation, with a period of perhaps 10 yr. Figure 7 shows the power spectrum for the shot-noise run just shown – and it does seem to have a peak corresponding to a 10- or 15-yr period, but not a statistically defensible one.

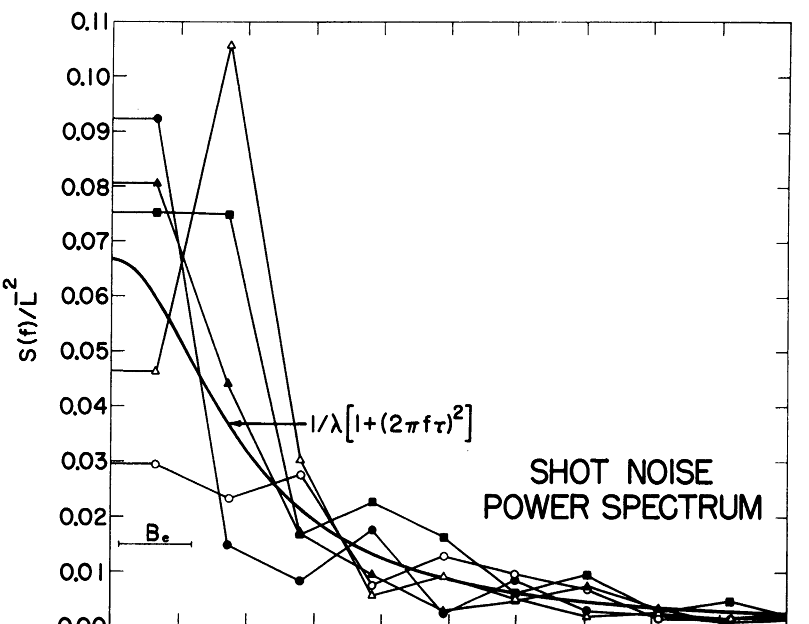

Fig. 8. Power spectra for five 75-yr runs of generated shot noise, not detrended, with parameters similar to those given by 3C 273 data. Also shown is the expected form of the power spectrum for the exponentially decaying pulses used. The points have been smoothed over four Fourier harmonics to decrease statistical standard deviations to ±50%.

Figure 8 shows our power spectrum results for all five runs with the 3C 273 parameters. Although the power spectra show the expected fluctuations of ±50%, the results fall close to the expected theoretical curve – for exponentially decaying pulses in these examples – and give on the average the expected value of zero-frequency

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power and peak width. We also generated and analyzed some shot noise cases with rectangular pulses with rather similar results.

Thus, to summarize, we find that the luminosity fluctuations of 3C 273 give no definite evidence of a 10- or 13-yr period, but are quite consistent with random outbursts of 3.2-yr equivalent length and at a rate of about 15 per year. Unfortunately, this still does not tell us whether 3C 273 is necessarily many independent sources or a single fluctuating light source, since randomness can never be proved – only non-randomness. However, if any periodic variation is present in the brightness of 3C 273, it is completely obscured by random fluctuations. The power spectrum, moments, and trend are all consistent with random outbursts of $\sim$3-yr pulses of light.

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Discussion of Papers Read by Smith and Terrell

Lasker: I would like to make some comments on the power spectra which we have just seen. Firstly, it is often useful to present power spectra in a log P–log f plane. Then one frequently notes that the data over many spectral elements can be represented by a straight line. This simplicity is of possible physical importance. Secondly, it is noteworthy that Dr Smith's power spectra frequently have two peaks. This is very different from what we find for variable stars in an admittedly very different frequency range; the power spectra of ordinary irregular variable stars is generally monotonic.

Smith: QSOs are probably quite different from variable stars.

Terrell: We found the power spectrum of 3C 273 to be of the form f^{-2} at high frequencies. This corresponds, in the case of random pulses, to a finite discontinuity in the pulse amplitude.

We generated a number of sets of random shot noise data, some with exponentially-decaying pulses and some with rectangular pulses. There was no detectable difference in the appearance of these two types of time series, nor in the trends.

Noerdlinger: Have you separated the long – and short – period amplitudes to examine their correlation with luminosity, or do you consider this worth doing when more data are available?

Smith: We have not done this, but it should be worthwhile to try.

J. Barnothy: I know that many look at the gravitational lens as if it were a sledge hammer which destroys the possibility of beautiful speculations regarding the nature of these new and interesting astronomical objects, but to deny the existence of gravitational lenses would be the equivalent of denying the existence of Newton's gravitational law. On the other hand, if the majority of QSOs were gravitational lens images of, say nuclei of Seyfert galaxies, then the variation in the brightness of the image becomes an inherent characteristic of QSOs. The power spectrum of these brightness variations does not depend on the number of secondary light sources within the object, it depends merely on the speed with which the optical axis scans the object disk. A simple computation as well as a trial scan over a random source field shows that the pattern and power spectrum of the variations of 3C 273 can be faithfully reproduced at a scanning speed of 25000 km s^{-1} in the frame of the object. Considering the rotation of the galaxy, that of the supergalactic system and the galactic and supergalactic coordinates of 3C 273, such an extremely high scanning-speed would follow if the lens were nearer than about 12 Mpc. As 3C 273 is in the direction of the Virgo cluster, which is at a distance of 11.4 Mpc, this suggests that the lens is a compact galaxy (of the type Zw 0930–5527 or Zw 1117–5141) in the Virgo cluster. The nuclei of the two compact galaxies mentioned are small enough that from a distance of 12 Mpc their apparent diameter would be less than one arc sec. The faint wisp-like nebulosity seen near the radio source of *A* of 3C 273 could then be the irregular nebulosity often accompanying compact galaxies.

Ozernoy: Gudzenko, Chertoprud and I analyzed the paper by Terrell and Olsen and found that their conclusions are invalid. The reason is that Terrell and Olsen reach their conclusions on the basis of the behaviour of sampling power spectrum in the low-frequency region where it is not representative. For example, it can be seen from Figure 8 of their paper, that the sampling variability coefficient becomes near to one. The second point is the following. Even if we shut our eyes to the inconsistency of Terrell's and Olsen's parameters of the pulses with natural physical requirements upon pulses, they are inconsistent with the statistical properties of the 3C 273 light curve. Namely, we have shown using analytic techniques (instead of numerical calculations by Terrell and Olsen) that the sampling variability coefficient of the envelope of 3C 273 brightness, v, must exceed 0.34 with 98% confidence. Meanwhile, for 3C 273 it has been found earlier that $v = 0.34$. Of course, choosing pulses of complex form with a great number of parameters, it would be possible to approximate the statistical characteristics of the observed process as well as we like. However, this would rather resemble the description of the motion of the Sun and the planets around the Earth by epicycles and deferents, performed as is well known by Ptolemy with very great precision.

Terrell: Apparently Dr Ozernoy has misunderstood our results. We were not presenting physical arguments, but merely investigating whether there is any reliable evidence for nonrandom fluctuations in 3C 273. The reasons for the usual unreliability of low-frequency power spectra were, in fact, pointed out in our paper. Using new methods which avoided these pitfalls, we found that there was then no remaining evidence of periodicity.

The complex methods used by Ozernoy and his co-workers depend critically on the assumed existence of a fundamental dynamical period of ~ 9 yr, plus perturbations (and would thus seem to have more connection with epicycles than ours). We find that random shot noise generated by computer often gives the impression of such a period, which we deduce to be ~ 10 yr (by methods similar to Ozernoy's) for *random* data similar to the 3C 273 data used by Ozernoy and Chertoprud. (*Astron. Zh.* **43**, 20, 1966).

Furthermore, it seems premature to draw such firm conclusions as Ozernoy's from the deviation of one parameter ($v = 0.34$) by 2 standard deviations from the value (0.52) calculated for random fluctuations. As a matter of fact, we find this parameter, the variability coefficient of the envelope for a 9-yr period, to be given by the data of Kunkel as $v = 0.56$, which is quite closely the expected value for random pulses. It is surprising that Ozernoy and his co-workers (*Astron. Zh.* **46**, 1317, 1969) did not discover this in their re-evaluation of their results based on Kunkel's data.