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QSO historical light curves

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Optical variability of 20 QSO's and three Seyfert or Seyfert-like galaxies has been studied based on light curves obtained from the Harvard historical plate collection. Individual light curves are presented along with discussion of their interpretation. Each of these 23 objects, selected solely because of apparent brightness, is found to be optically variable. The variations range from barely detectable ($\sigma > 0.13$ mag) to over two magnitudes. Correlation of the amplitude of variation with a measure of the intrinsic luminosity (assuming cosmological redshift) gives a relation very nearly that expected if each QSO consisted of an assemblage of randomly varying sources: the smaller the amplitude, the brighter the object. However, several objects appear to have exhibited systematic trends or quasi-periodicity with a time-scale of ten to twenty years. Also power spectra are not consistent with simple stochastic models, and some of the details of certain light curves seem to require a single small source for most of the light.

INTRODUCTION

SINCE QSO's have been known as "stellar" objects only since December 1960 (Matthews and Sandage 1960) and as large redshift objects only since 1963 (Schmidt 1963), the post-discovery observations can tell us very little about long-term behavior such as systematic trends, periodicity, and life-time of optical activity. The only resource is to search historical plate collections for chance occurrences of the objects on photographic plates. Until now this has been done for only two QSO's, 3C 48 (Smith and Hoffleit 1961) and 3C 273 (Smith and Hoffleit 1963; Sharov and Efremov 1963), and more recently for several Seyfert-like galaxies (Usher and Manley 1968; Usher *et al.* 1969). The marked success of this type of program (e.g. Smith 1965) using the Harvard plate collection strongly suggested that it be expanded to include all the known QSO's bright enough to have reasonable time coverage on the plates.

The program described here included a total of 23 objects; there are 20 QSO's, one Seyfert-like galaxy (3C 120), and two either QSO's or Seyfert-like objects (TON 730 and TON 1542). Excluding 3C 273, which is uniquely bright, the average number of plates per object found to have a detectable image of the object was 74, with extremes ranging from 12 (1354+19) to 289 (0405-12). All the plates for this study are in the Harvard collection, which contains approximately 500 000 plates taken with apertures from 60 inches

down to 1.5 inches. The faintness of these QSO's plus the extent of the various plate series limited the use to plate series from telescopes with apertures between 3–24 inches.

I. MEASUREMENT AND REDUCTION

Details of the measurement and reduction process have been discussed by Angione (1970). Since the 12-plate series used in this program differed in aperture, chromatic aberration, and optical aberration, and since different exposure times and emulsions were used, the accuracy of the magnitudes derived from these plates is greatly improved if the plates are used just to interpolate the QSO between known magnitudes of a photoelectric sequence. Such sequences were selected and observed for each of these objects (Angione 1971b). Each sequence consists typically of about seven stars, which cover a range of approximately three magnitudes, and which lie within ten arc min of the program object. Corrections for color effects, due to emulsion changes, chromatic aberrations, etc. were made for each plate series. In all cases these corrections were very small.

All plates on which the image was sufficiently dense were measured with the Harvard Askania iris photometer described by Ingrao and Menzel (1967). Although visual estimates of object brightness were also made for each plate, the iris photometry gives significantly improved accuracy. Reliance on the visual estimates was retained in those cases where the images were too distorted or faint, or where too few sequence stars were visible on the plate.

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TABLE I. Photographic gross statistics.

Object	<i>z</i>	<i>B</i>	s.d.	Number of Plates	Class	Notes
3C 120	0.032	14.79	0.23	136	Seyfert	13
TON 1542	0.0636	15.32	0.20	46	II	
TON 730	0.0877	16.32	0.21	62	II	
TON 256	0.131	15.85	0.31	45	II	
3C 273	0.158	12.76	0.21	240	(II) V	8,11,12
2135-14	0.200	16.35	0.22	130	(II) V	1
3C 323.1	0.264	16.27	0.28	45	(III) V	1
2251+11	0.323	16.16	0.18	18	I	1,2,8
3C 48	0.367	16.09	0.15	70	I	2,4,5,8
3C 351	0.371	15.64	0.25	56	III	2,8
PHL 658	0.450	16.13	0.16	45	I	2,3
2128-12	0.501	15.57	0.22	98	(II) V	
3C 232	0.534	16.03	0.27	64	III	2,8
3C 334	0.555	16.32	0.22	43	II	1,2,8
0405-12	0.567	15.13	0.18	289	(I) V	8
3C 345	0.595	[16.67]	0.55	24	IV	1,2,5,6,8
3C 263	0.652	16.19	0.25	56	III	2,8
0159-11	0.669	16.55	0.22	119	III	1,3
2344+09	0.677	16.37	0.19	12	I	1,8
1354+19	0.720	16.04	0.18	26	I	1,8
3C 454.3	0.859	[15.84]	0.62	46	IV	2,7,8,9,10
0350-07	0.962	16.62	0.13	118	I	
0237-23	2.228	16.51	0.13	124	(I) V	3

Notes to Table I

1. Hunter and Lu (1969).
2. Penston and Cannon (1970).
3. Peach (1969).
4. Smith and Hoffleit (1969).
5. Barbieri and Erculiani (1968).
6. Kinman (1968).
7. Lu and Hunter (1969).
8. Tritton and Selmes (1971).
9. Angione (1968).
10. Angione (1971a).
11. Smith (1965).
12. Burkhead and Stein (1971).
13. Usher *et al.* (1969).

An important consideration is to establish a valid estimate of the probable error of a single QSO magnitude. Residuals of the sequence stars were computed with respect to the computed iris-magnitude relation for each plate. The average standard deviation found for the sequence stars is 0.094 magnitudes. Although the comparison-star residuals for a given plate could have been used to infer a formal error of each individual QSO measurement, this was not felt to be meaningful because too few sequence stars are available and the residuals depend in a complicated manner on the faintness and position of the object in question. Therefore a standard deviation of 0.10 mag has been adopted for the iris measurements. (The visual estimates showed a standard deviation of 0.17 mag when compared to iris measurements of the same plates, and this value has been adopted where the visual estimates have been used.) The individual plate residuals do allow one to reject obviously bad plates or measurements. Plates were rejected for iris photometry either if one sequence star had a residual greater than 0.3 mag or if two or more stars each had residuals greater than 0.2 mag. In the case of rejected iris photometry, the visual estimate was used.

II. THE LIGHT CURVES

A. General Results

The general statistics from the historical light curves are combined into Table I. The second column gives the redshift (*z*) from Burbidge and Burbidge (1969), *B* is the mean magnitude computed from the iris photometry, s.d. is the standard deviation computed from the iris photometry, and Class refers to the appearance of the light curves (discussed below). The final column gives references to the more extensive monitoring programs. The mean magnitude for 3C 345 and 3C 454.3 as given in brackets have little significance, because an inordinate number of measurements were made during a few flares. Since the QSO's exhibit almost continuous variability with time scales as great as 10–20 yr, neither a single magnitude measurement nor even measurements covering several years will yield a reliable average magnitude. The mean magnitudes given in Table I are based on measurements covering 30–60 yr and are thus more characteristic of the QSO. This is important especially when comparing QSO's with one another, in studying their general properties, and for any statistical analysis.

An important conclusion can be drawn from Table I; namely, that every QSO studied in this program is found to be an optical variable. This conclusion is based on the fact that the magnitudes of each QSO exhibit a standard deviation greater than the 0.10 mag measurement error. The only objects of questionable variability, based on the standard deviation criterion, would be the three QSO's (3C 48, 0237-23, and 0350-07) with standard deviations of 0.15 or less. However, 3C 48 is a known small-amplitude variable (e.g., Sandage 1964). While the standard deviation for 0350-07 is only 0.13 mag, this is computed just from the iris measurements, but there are numerous visual estimates 0.4–0.5 mag brighter than the mean value. In the case of 0237-23 where the intrinsic scatter is also only 0.13 mag, there is strong indication of a systematic change of 0.25 mag.

These conclusions are reinforced by the serendipitous inclusion of two nonvariable stars (TON 883 and 3C 68.2 originally reported as QSO discoveries) in the list of objects studied in the Harvard plate collection. Standard deviations for these objects, reduced as though they were QSO's, proved to be 0.08 and 0.13 mag, with no other abnormalities in the distribution of points.

This result of finding detectable variability in each program QSO is not in conflict with the other published surveys (Barbieri and Erculiani 1968; Hunter and Lu 1969; Peach 1969; Penston and Cannon 1970). In these surveys, which cover only the last five or so years, variability was detected in roughly half the objects; the completeness found in the present work arises from the time span of nearly 60 yr within which variation could manifest itself in various ways.

FIG. 1(a-i). QSO light curves. The filled circles ● are iris photometer measurements, and the open circles ○ are visual estimates. The standard deviations are 0.10 and 0.17 mag, respectively.

The 23 objects have been divided into five groups on the basis of amplitude and time-scale of their activity. In Class I are eight QSO's showing a standard deviation less than 0.20 mag, and consequently only small-amplitude activity. Some of the objects presumably fall into this class by virtue of the fact that few plates were found for them.

Class II contains seven objects with standard deviations equal to or greater than 0.20 mag, but with a total range of activity less than 1.0 mag.

Class III is similar to Class II, but contains four objects showing a range of activity greater than 1.0 mag. In addition, the light curves for Class III objects show numerous flares.

There is no very sharp apparent division between Classes I, II, and III, but rather a continuum of increasing activity from Class I (total range of 0.5 mag) through Class III (total range of less than 1.5 mag). Some of the objects in less active classes might well have been found to be more active if there had been more photographic coverage.

Two objects definitely, and one possibly, fall into Class IV. These objects show rapid flares of over two magnitudes, as opposed to 1.3 mag for the greatest activity in Class III. Photographic coverage was generally poor because these objects were above the plate limit only when flaring up in brightness.

FIG. 1 (a)-(i) (*continued*)

In Class V we have what seems to be a real distinction with respect to the other QSO's. The light curves for these objects show systematic trends, or quasi-periodicity, with time-scales on the order of ten to twenty years; the class based on activity alone is given in parentheses. The prototype for this class is 3C 273. Parkes 0405-12 bears a strong resemblance to 3C 273 and is definitely a member of this class. Three to five other objects (0237-23, 2128-12, 2135-14; more questionably TON 730 and TON 1542) may also be members of this class.

B. Light Curves and Descriptions

The individual light curves are given in Fig. 1. The iris-magnitudes are plotted as filled circles, the visual

estimates as open circles, and the McDonald photoelectric measurements (Angione 1971a) as circle-plus-dot. The abscissa of each figure is the Julian date of observation; the corresponding Gregorian date is given at the top of each figure. The ordinate is the *B* magnitude determined with respect to the photoelectric stars. The standard deviations are 0.10 for the iris and 0.17 for the visual measurements. In some cases the time-scale is expanded in a second light curve to illustrate short time-scale activity.

The three QSO's (3C 345, 3C 323.1, and 3C 454.3) form part of a set of objects, which Penston and Cannon (1970) call OVV (optical violent variable). The other members are 3C 446 and 3C 279 (both faint for this program). While 3C 454.3, 3C 345, 3C 446, and

FIG. 1 (a)-(i) (continued)

3C 279 seem distinctly different from the other QSO's by virtue of their large scale activity, 3C 323.1 seems somewhat intermediate between the two groups, indicating the possibility of a continuum of activity rather than any qualitative distinction. Out of 24 QSO's originally selected by apparent brightness, three are members of the OVV class, or roughly 10%. Penston and Cannon (1970) find from 15% to 25% for the number of OVV objects, while Peach (1969) found no OVV objects among his sample of 30 QSO's. However, with an average of only about ten plates per object, OVV activity could be missed. The combined results indicate that the fraction of QSO's showing OVV

activity is probably near the 10-percent value. It must be remembered that the QSO's for these programs were selected on the basis of apparent brightness, and in this sense do not represent a random sample.

Several other objects may belong to Class V. 3C 273 is certainly a member (see Smith 1965). Both TON 730 and TON 1542 showed some indication of time-correlated activity, but it was not as pronounced as for the objects discussed here. 0237-23 may also be a member based on its small but systematic change in brightness. It is interesting that 3C 273, 0405-12, and 0237-23 are all among the intrinsically brightest QSO's (assuming cosmological redshift). Not only do these

FIG. 1 (a)-(i) (continued)

three objects show unusually small intrinsic scatter (as opposed to the other QSO's), but each could be quasiperiodic.

Finally there were two identified galaxies (3C 120 and Zw I 0120+34) in this program. Zw I 0120+34 did not exhibit any definite variability (Fairall and Angione 1969) and will not be discussed here. Parkes 0430+05 (3C 120) shows clear variations both photographically and photoelectrically. The variations here also seem to be systematic, and this light curve is not unlike those of TON 730 and TON 1542, the two objects which may be intermediate between QSO's and variable galaxies. The variations for 3C 120 are also very similar to 2135-14. The results presented here are in good agreement with Usher *et al.* (1969);

they measured different plate series than the ones used here.

III. ANALYSIS AND DISCUSSION OF RESULTS

The results presented in the previous sections bear in several ways on the still unknown nature and structure of the QSO's. The most general finding is that each of the twenty-two QSO's investigated in this program shows optical variability. It has been generally assumed that optical variability is the normal rule for QSO's; now this assumption rests on a considerably more firm footing. To be sure, the QSO sample in this program is affected by selection, particularly by apparent brightness, and in a few cases by variability itself (3C 345 and 3C 446, normally too faint for the Harvard

FIG. 1 (a)-(i) (continued)

plates, were included because of their known variability). A preliminary discussion of some of these results has been given by Angione and Smith (1972).

As is not surprising, the fluctuations have been occurring with about the same frequency and amplitude for the duration of the Harvard plate collection coverage—since approximately 1900. The general nature of the variations found in this study agree well with those found in the recent extensive monitoring programs (e.g., Peach 1969; Penston and Cannon 1970; Tritton and Selmes 1971). An analysis for possible mean brightness trends, to be discussed shortly, shows that the mean brightness of each QSO has remained essentially constant during the 60–70 years of photometric

coverage. The rate of change of brightness showed no preference for a faster rate of increase than decrease.

The twenty-two QSO's did show a range of activity, and they were accordingly divided into activity classes, as discussed in Sec. III. These divisions are somewhat arbitrary, and there may well be a continuum of activity through at least classes I, II, and III rather than a physically discrete set of jumps in activity. However, the class IV objects, those showing rapid changes of several magnitudes, may actually constitute a distinct set. Such rapid, large-amplitude variability is rare, occurring in less than 20% of the objects. Nor is it a brief transient instability; only those objects which currently possess this kind of violent activity have shown it historically in the plate collection. Further

FIG. 1 (a)–(i) (*continued*)

arguments for a physically distinct set of objects in class IV include their apparently discrete amplitude–luminosity relation (discussed shortly), and their apparent correlation with flat radio spectra (Penston and Cannon 1970).

Another group that may be unique consists of those objects showing systematic changes or quasiperiodicity (class V); unique both in that these objects show systematic trends (at least on a 50-yr time scale) and only small fluctuations about their slow trends. These can be further divided into objects with simple systematic trends (2128-12, 2135-14, and 0237-23) and those showing quasiperiodic behavior (3C 273, 0405-12, and possibly 0237-23) on a time scale of 10–20 yr. In the short period range, some support is found for the

approximately 600-day period suggested by Kinman *et al.* (1968) for 3C 345.

A. Characteristics of the Brightness Changes

The rate of change in brightness is of considerable interest because of the limitation it sets on the size of at least the momentary principal optical source element (barring the unlikely contingency of coherent emission). The most rapid change reported so far is 0.3 mag/hr in 3C 454.3 (Angione 1971a), observed photoelectrically. The historical data confirms this rapidity of variation yielding a change of 0.9 mag/day (3C 351), and 0.4 mag/day (3C 454.3). This sets a dimension scale on the order of 10^{10} km.

FIG. 1 (a)-(i) (continued)

The question arises, how often do these brightness changes occur? A lower-limit estimate of the average frequency of substantial changes in brightness was obtained from the photographic data by simply counting the number of change-of-brightness-events greater than 0.2 mag (twice the standard deviation of measuring error). The resulting number of events was divided by the time span of the data, typically 50 yr, resulting in an average of about one detected substantial event per year per QSO. This is the same frequency that Harris (1969) found for radio events. Due to the incompleteness of the photographic coverage, the true frequency of events could be many times greater. This frequency does say that for QSO's in general the momentary varying component is no larger

than about one light-year, and in some cases it is presumably smaller than a light-day.

Figure 2 presents the time rate of change in brightness for four QSO's representative of the different kinds of activity: violently active (3C 454.3), very active (3C 323.1), slightly active (0237-23), and quasiperiodic (0405-12). In this presentation, the logarithm of the absolute value of the rate of change ($\Delta M/\Delta T$) is plotted versus the time interval (ΔT). The values of $\log(\Delta M/\Delta T)$ and $\log(\Delta T)$ were obtained by comparing each photographic observation with the next succeeding observation in time and computing the difference in magnitude, ΔM , and the time interval, ΔT . Points which fall off a diagram are plotted as X's at edge of diagram.

FIG. 1 (a)-(i) (*continued*)

The solid lines in Fig. 2 represent the standard deviation, σ (0.10 mag), 2σ , and 3σ due to the observation and reduction errors. The most striking feature of these plots is that the amplitude, ΔM , appears to be independent of the time interval, ΔT . For each QSO, there is an upper envelope consisting of a straight line (dashed line in Fig. 2) parallel to the lines representing the standard deviation; any line parallel to the standard deviation line is a line of equal amplitude. Thus, each QSO could be represented as varying in a mode wherein the peak amplitude is almost independent of the time-scale of the variation. This peak amplitude is typically about 0.7, with a range of 0.4–1.3 mag (tabulated in Table II). The main difference between the QSO's is the height of the upper envelope, which increases with

increasing activity and thus allows an estimate of an amplitude of activity.

The plotted points show a preference for two time intervals, one near 30 days and one near 360 days, in each of the diagrams. This is, of course, the result of lunation and seasonal selection causing photographs to tend to be taken at intervals of approximately a month and a year. Beyond the effects of observational selection there seem to be no obvious preferred time-intervals or rates. This lack of preference sets at least one limitation on the possible models of variation. Specifically, the variations cannot be represented by the superposition of infrequent (less than 10/yr) sharp-rise pulses followed by slow declines; if this were the case, then the rate diagrams (i.e., Fig. 2) would

FIG. 1 (a)-(i) (continued)

show a clustering of points at the average rate of the decline in brightness.

In explosive phenomena (i.e., supernovae), the increase of brightness will normally be much more rapid than the decrease, since by "explosive" we mean a sudden release of energy. Unless deeply blanketed in some way, or unless the energy is initially released largely in forms which must slowly mutate into visible light, a rapid rise of brightness may be expected, as indeed is observed with nearly all supernovae. Brightness usually fades slowly as the energy of the explosion is radiated away. The observation just quoted thus is inconsistent with a *simple* multiple-explosion hypothesis. However, the argument can be sharpened considerably by studying the relative rates of increase of brightness compared to the rates of decrease.

Such rates were investigated for the QSO's in this sample by simply counting the number of brightness increases and brightness decreases in each of 18 intervals of rate between 0.01 mag/day and 1.0 mag/day; all QSO's were lumped together. The resulting distributions of number versus rate are shown in Fig. 3. The surprising feature is that both distributions (increase as well as decrease) are remarkably similar with no significant differences. The distribution is roughly exponential; the apparent peak at a rate of 0.1 mag/day is due to a change in the plotting interval from 0.01 to 0.1 mag/day.

B. Amplitude Relations

The QSO's in this study showed a range of activity, and they were analysed both for a possible amplitude-

FIG. 2. A sample of QSO rate diagrams, in which the absolute rate of change in brightness is plotted as a function of the time interval of the change. The *dashed line* represents an estimate of the upper envelope (i.e., the characteristic amplitude).

luminosity relation and for a correlation with color. No significant correlation, beyond the effects of emission lines (Strittmatter and Burbidge 1967), was found between the amplitudes of the optical variations and the colors of the QSO's corrected for *K*-effect and galactic reddening (de Vaucouleurs 1961).

Figures 4 and 5 show the optical variations plotted against an "absolute magnitude." In Fig. 4, the standard deviation of the iris photometry results is used as a measure of the amplitude of optical activity, and in Fig. 5 the "upper envelope" (discussed in part 4) is used; both are listed in Table II. Since it was

necessary only to intercompare intrinsic luminosities, pseudoabsolute magnitudes were calculated (Table II). These magnitudes were corrected for galactic absorption (de Vaucouleurs and Malik 1969) and K -effect (Sandage 1966) with distances calculated from $D=c\bar{z}/H_0$, $H_0=75$ (Sandage 1968) assuming cosmological redshift.

There indeed appears to be evidence for an amplitude-luminosity relation. This correlation is qualitatively consistent with a suggestion made informally by J. Wheeler that if the luminosity of QSO's arises from the summation of a number of similar sources active at random times, the intrinsically brighter QSO's should show the smaller amplitudes since the fluctuations should be inversely proportional to the square root of the average number of sources. In fact a least-squares fit yields a slope (Fig. 4) of 0.026 ± 0.01 compared to a predicted slope of 0.035 in the simple Wheeler model. Two things do mitigate against this correlation. In Fig. 5, the correlation is not as good, and if one includes in Fig. 4 the violent variables (3C 279, 3C 345, 3C 446, and 3C 354.3), for which the data are incomplete, the correlation is destroyed. Of course, the presence of such a correlation does not in itself imply a cosmological origin for the redshift. It could be present if the QSO's had been ejected locally (Terrell 1964, and 1967) or even if the redshift arose from gravitational effects.

C. Secular Changes

To determine the secular stability of the QSO's, a straight line was fitted to the light curve of each by the method of least squares, using the relation

$$B(t) - \langle B \rangle = a + b \frac{(t - t_0)}{50 \text{ years}}$$

where $B(t)$ is the magnitude at time t , $\langle B \rangle$ the mean mag, and t_0 , the time of the earliest magnitude measurement for that QSO. The slope, b , is then the rate of change of brightness in units of magnitudes per fifty years.

Results of this test are presented in Table II. There is a wide range in the apparent slopes (from about -0.8 to $+0.5$ mag/50 yr). However, in some cases one would not expect the slope for an individual QSO to be too meaningful due to incomplete photographic coverage. The majority of the plates were taken since 1928, with only a few during the important period 1900 to 1920. This causes the early measurements to receive a high-relative weight in the least-squares solution. For example, in the light curve of TON 256 (Fig. 1) one can see that its large secular slope ($b = -0.79$) is almost entirely caused by two faint earlier measurements—neglect these and the slope would be near zero.

To examine the question of a general tendency for QSO's to brighten or dim systematically during their

TABLE II. Amplitude-magnitude relation.

Object	$M(q_0=1)$	s.d. Amplitude	Envelope Amplitude	b	Error
3C 120	-21.4	0.23	...		
TON 1542	22.1	0.20	0.63	-0.04	0.11
TON 730	21.9	0.21	0.4	-0.10	0.07
TON 256	23.2	0.31	0.8	-0.79	0.11
3C 273	26.5	0.21	...	0.04	0.02
2135-14	23.6	0.22	0.5	0.29	0.05
3C 323.1	24.1	0.28	1.0	0.49	0.24
2251+11	24.7	0.18	0.6	0.06	0.14
3C 48	25.2	0.15	...	-0.03	0.14
3C 351	25.5	0.25	1.0	0.08	0.12
PHL 658	25.4	0.16	0.5	0.02	0.08
2128-12	26.2	0.22	0.6	-0.17	0.09
3C 232	25.7	0.27	0.8	0.40	0.08
3C 334	25.7	0.22	0.8	-0.48	0.17
0405-12	26.8	0.18	0.5	-0.52	0.05
3C 345	25.1	0.55	1.3	0.04	0.29
3C 263	26.1	0.25	0.8	-0.39	0.28
0159-11	25.7	0.22	0.6	0.28	0.10
2344+09	26.0	0.19	0.5	-0.07	0.18
1354+19	26.5	0.18	0.3	0.18	0.16
3C 454.3	26.4	0.62	1.0	-0.78	0.23
0350-07	26.6	0.13	0.5	0.02	0.14
0237-23	28.0	0.13	0.4	-0.32	0.06

active periods, the fifty-year slopes were averaged yielding a mean slope of -0.05 mag/50 yr. In view of the difficulty in determining the slope, the data suggest an upper limit on the secular change of about 0.1 mag/

FIG. 3. Histogram of the distribution of rates of change in brightness, showing the similarity of the rates for increase and decrease in brightness.

FIG. 4. Amplitude-luminosity diagram ($q_0=1$). The *solid line* is the least-squares fit, and the *dashed line* is the slope predicted by the Wheeler hypothesis. The circle-plus-dot is 3C 120, and the *open circles* are the probably non-QSO's TON 730 and TON 1542.

century. In a few individual cases where both the slope and the number of plates are large, there may be a real secular variation with a time-scale of 50 yr. An example of this is 0405-12 with 289 plates and a slope of -0.52 ± 0.05 mag/50 yr. In the averaging process 3C 454.3 was not included because its apparent slope is entirely due to a two magnitude flare-up in 1952. In addition, to increase the time span of the data recent photoelectric measurements were included.

D. Relationship and Variability to Models

The various models and energy generating mechanisms have been reviewed elsewhere (Burbidge and Burbidge 1967; Smith 1966; Schmidt 1969). The information gained so far from the study of optical variability is insufficient to allow the selection of a QSO model. One of the difficulties in assessing the models with respect to variability is that most of the models make no specific prediction concerning the nature of variability, and so the purpose here is merely to point out the constraints that variability now places on some of the proposed models. In addition, the important but complex topic of possible periodicities will be dealt with in a future publication. Some preliminary results on QSO periodicities from this data have been published (Angione and Smith 1972).

An attractive subgroup of random models is that based on supernovae explosions; attractive in that it

is not necessary to invoke new and often speculative mechanisms. Such models, as proposed by Field (1964) and Colgate (1967) among others, can be made compatible with the observed rapid luminosity changes. Supernovae light curves do show rapid changes, but in general they do not show decreases in brightness as rapid as the QSO's (see Shklovskii 1968); this is of course inconsistent with the equality of rates (Fig. 3). If one is dealing with ordinary supernovae, as in Field's model, one needs about 50 Type II's per year (for the cosmological case) and an interstellar density about 10^8 times normal for changes in time scales of several days. These constraints can be alleviated somewhat if one uses extraordinary supernovae, Colgate's model, in which case we have 50 solar-mass stars becoming supernovae at the rate of 5-10 per year. In this model, Colgate could get a change of 4×10^{45} ergs/sec in 10^6 sec (12 days). We can compare this to the observed rates found here of about 10^{45} to 10^{46} ergs/sec in one day—a factor of ten faster.

The supernovae models of course predict random variations. Strict periodicity, which would rule out this type of model, has not been established. However, there are at least trends with time scales of about ten years evident in some of the light curves (the objects in class V). In addition, some objects (e.g., 0405-12) showed trends on a fifty-year time scale. In the random models, the optical fluctuations should have a constant mean brightness, but apparent trends over short-time scales would be expected. A simple calculation will show a difficulty in accounting for the trend observed in 0405-12 (0.52 mag/50 yr). Let us assume a standard deviation of 1 mag about the mean brightness, five

FIG. 5. Amplitude-luminosity diagram ($q_0=1$) using the "envelope amplitude" from the rate diagrams (Fig. 2). The *open circles* are the Seyfert-like objects TON 730 and TON 5542; the *triangles* are the violent variables 3C 345 and 3C 454.3.

explosions per year, a time scale of 50 yr (250 explosions), and for simplicity assume that the explosions are uniformly distributed in time. The apparent trend, obtained from the standard deviation of the slope through these 250 events, is 0.2 mag/50 yr, which is 2.5 standard deviations less than that observed. In the case of ordinary supernovae (about 50 per year), the situation is much worse.

There are, however, ways in which to obtain trends in the supernovae model. Burbidge (1961) has suggested the idea of a chain reaction of supernovae with one explosion triggering succeeding ones. For a ten-year trend this would involve 50 or 500 supernovae depending on whether or not ordinary supernovae are employed. Another possibility is to imagine the expanding cloud encountering a shell of high-density interstellar matter. Since the conversion of the gas kinetic energy is proportional to the density of the interstellar matter (Field 1964), this encounter would cause an increase in the luminosity, and the variation would appear to have come from an object with the diameter of this shell. The problem is that this ten-year trend would be the result of only one event; on the order of 10^{55} ergs would be required per event—nearly two orders of magnitude greater than in the Colgate model.

The optical variability can be accounted for in some detail in a radically different model. This is the gravitational lens model recently discussed by Barnothy (see in particular Barnothy and Barnothy 1968a and 1968b). The following discussion will be confined strictly to the predictions regarding optical variability. In this model, the QSO is simply the gravitationally focused nucleus of a distant Seyfert galaxy. Optical amplification is inversely proportional to the distance of the optical axis from the center of the deflector. Optical variability results from scanning motion of the optical axis due to the proper motion of deflector galaxy and object galaxy, plus solar motion in our galaxy. As the axis scans across the deflector galaxy, it passes very close to individual stars with resulting rapid changes in the focused image and consequently increases and decreases in the apparent brightness of the background Seyfert galaxy.

An attractive feature of this model is its clearest prediction of the result shown in Fig. 3 that the average rates of increase and decrease in brightness should be exactly equal—the brightness changes must be statistically symmetrical. Barnothy calculates that the typical time scale for a brightness change, assuming a transverse velocity of 100 km/sec, would be about ten years, but there would also be flashes of several weeks duration resulting from the chance alignment of stars very close to the optical axis. The model runs into some difficulty in accounting for the very rapid (one day) variations. He suggests that a nova exploding within 10^{-3} pc of the optical axis would account for this. However, from the historical light curves there is at

least one such event per year. In addition, these brightness changes do not have the appearance of a nova (see the discussion of 3C 446 by Sandage *et al.* 1966; Oke 1967; and Wampler 1967).

The gravitational lens model appears also to be consistent with the large spread of intrinsic brightness. The spread of about 4–5 mag in the Hubble diagram (Burbidge and Burbidge 1967) would result simply from different amounts of amplification. One can also see an explanation for the individual systematic trends. The average trend should be zero, which it is. Individual trends would result from the optical axis scanning in towards the center of the nucleus, or scanning away from the nucleus. Finally, this model is consistent with the possible amplitude–luminosity relation. In the case of the optical axis passing across the nucleus, the total number of stars encountered along the line of sight will be large, the amplified brightness large, but the percentage change in brightness will be small. In the opposite case when the optical axis passes near the edge of the nucleus, the amplified brightness will be small (fewer stars), but the percentage change in brightness will be large. This is just the result of Figs. 4 and 5—the brightest QSO's show the smallest fluctuations. Qualitatively the optical variability evidence is compatible with this model, and the gravitational lens is certainly a serious contender, provided the probability of its occurrence is firmly established.

Another area in which optical variability can act as a discriminant is with the question of single versus multiple source. The variations manifested in both the historical light curves and recent observations also point towards a multiple-source model. First is the problem of the very short-time-scale (less than one day) variations. If the QSO is a single object, then we must confine a total energy of as much as 10^{60} to 10^{62} ergs in a dimension of about one light-day; if instead the QSO is an assemblage, then the size limit of one day would apply only to one source, whereas the total QSO is composed of many, thus relaxing the confinement of the total energy (down to perhaps 10^{52} to 10^{54} ergs). Then there is the Wheeler hypothesis (supported by Figs. 4 and 5) calling for each QSO to be composed of a number of sources.

However, the 3C 273 class of objects shows a degree of coherence and concentration of power in a narrow part of the frequency power spectrum, as well as a rather uniform envelope bounding the optical variations, all of which is inconsistent with a simple random process. Even in the multiple source models at any given time, one is still dealing with presumably a single very tiny, very energetic, and probably coherent core. While all QSO's may be multiple source objects on a time scale of a million years, some may be single sources on a time scale of decades. Thus for those 3C 273-like objects, showing quasiperiodicity, we may still be dealing with a single, coherent, massive object as we see it today.

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