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THE VARIABILITY OF THE OPTICAL BRIGHTNESS AND POLARIZATION OF THE QUASI-STELLAR RADIO SOURCE 3C 345*

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ABSTRACT

Photometric data obtained from 1965 to 1967 and polarization measurements made in 1967 are given for the variable quasi-stellar radio source 3C 345. An analysis of the observations shows that they are consistent with the optical radiation having three components: *A*, an essentially unpolarized constant component; *B*, a component having about 17 per cent linear polarization which varies both in brightness and position angle with a time scale of months; and *C*, a component which has a high (but undetermined) amount of linear polarization and which has a time-scale of the order of a few days. Component *C* takes the form of outbursts which have a mean period of about 80 days. There is only one chance in several hundred that this periodicity could come from a random distribution. There is also a pattern in the phases of these outbursts in the 80-day period which indicates the existence of a 321.5-day period. There is about one chance in eighty that this longer periodicity could be fortuitous.

It is speculated that the most probable cause of these light variations is the rotation of a single massive body or perhaps the orbital motion of a close binary system in an optically thick envelope It is presumed that the slowly varying component arises from an extended region on the object, while the more rapidly varying component is caused by smaller active regions (which radiate non-isotropically) in transit across the face of the object.

I. INTRODUCTION

It was first shown by Dent (1965) that the quasi-stellar radio source 3C 345 is variable at 8000 Mc. It was later found (Goldsmith and Kinman 1965) that 3C 345 is also an optical variable. More recently it has been shown (Kinman 1967) that the optical radiation of 3C 345 is linearly polarized and that this polarization is variable. The present paper presents the photometric and polarization data which have so far been accumulated, together with a provisional interpretation. There is evidence for variability in both the polarization and optical flux in at least four other quasi-stellar sources (3C 446, 3C 279, 3C 454.3, and 1510-08) and the limited data so far obtained (including those obtained by Appenzeller and Hiltner 1967) suggest that optical variability is accompanied by a higher percentage polarization than is present in non-variable sources. It is hoped to present the observations of these other objects in a later paper.

II. PHOTOMETRIC DATA

The photometric data consist primarily of magnitudes derived from plates taken with the blue-corrected lens of the 20-inch Carnegie Astrograph. These blue-sensitive plates (Kodak 103aO or baked IIaO emulsion) were taken without a filter and the exposure time was normally 45–60 min depending upon the brightness of 3C 345. In addition a few plates were obtained with the Crossley 36-inch reflector and with the 120-inch reflector; for these exposures a filter (Schott GG13, thickness 2 mm) was used to exclude the ultraviolet. All plates were measured with a Sartorius iris diaphragm astrophotometer using the photometric sequence of nearby stars given in Figure 1 of the paper by Goldsmith and Kinman (1965) and four brighter stars shown in Figure 1 (Plate 1) of this paper. The (*BV*) magnitudes on the Johnson system of these stars were determined with the

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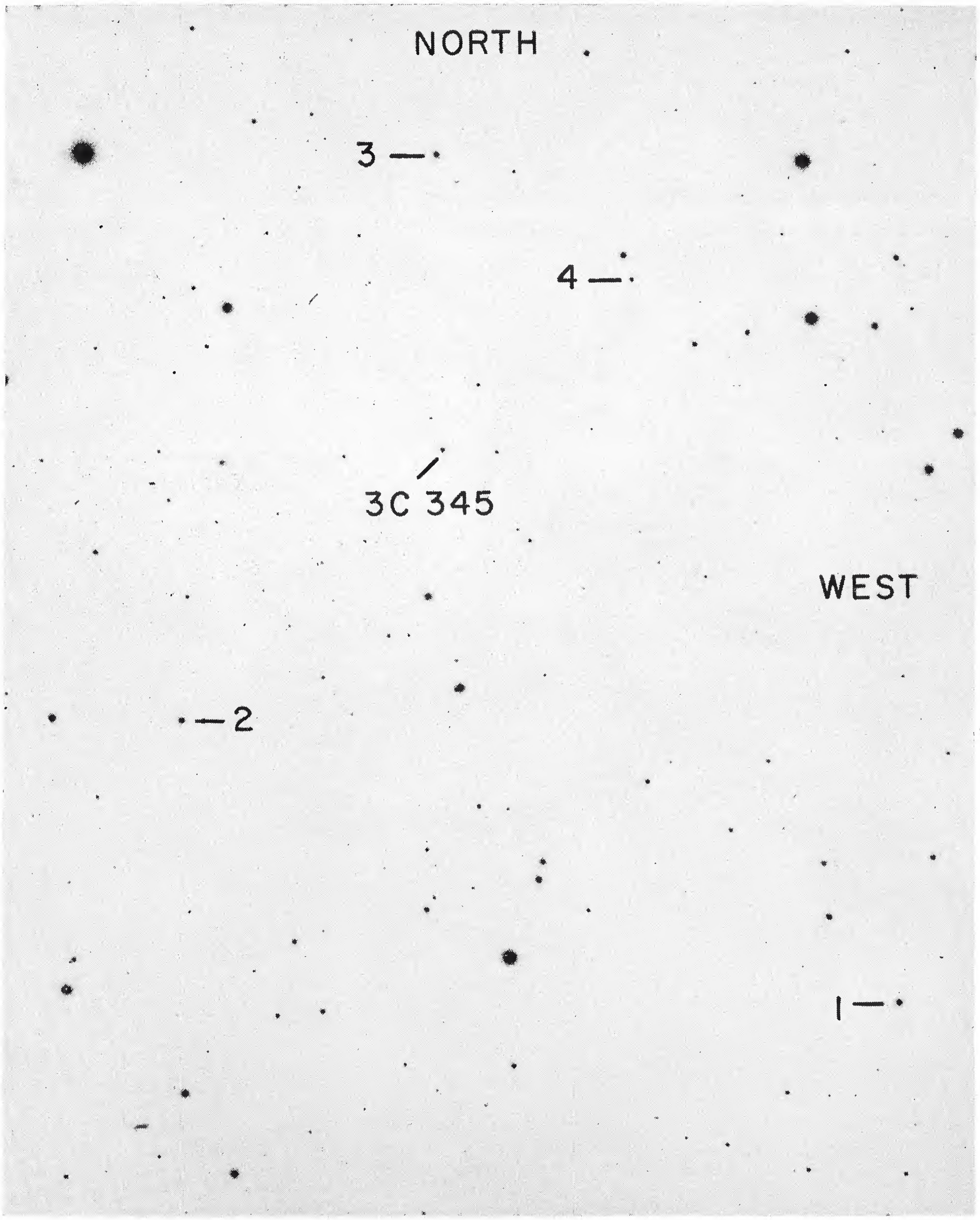

FIG. 1.—Finding chart for the brighter stars in the comparison sequence for 3C 345

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prime-focus photoelectric photometer of the 120-inch reflector and are given in Table 1. It should be noted that some of these photoelectric magnitudes differ by several tenths of a magnitude from those originally published which were derived by a photographic transfer. Star C of the original sequence was not used on account of its redness. The photographic magnitudes (*B*) are listed together with the date of observation (U.T.) and Julian date in Table 2; reflector plates are denoted by asterisks against the magnitude.

A few photoelectric magnitudes are also available and are given in Table 3. They comprise a single observation by Sandage (1966*b*), nine blue magnitudes derived by Wampler (1967) from his scanner observations with the 120-inch reflector, and six *B* magnitudes obtained with the prime-focus photometer of the same telescope.

The accuracy of the magnitudes derived from Astrograph plates is discussed by Kinman, Lamla, and Wirtanen (1966) in connection with similar observations of 3C 446. For these observations, the systematic errors did not exceed more than a few hundredths of a magnitude and the rms. deviation of the magnitude derived from a single plate was estimated to be ±0.05 mag. In the present observations the difference between the magnitudes derived from photoelectric and photographic observations on the same night (Table 3, 4th col.) has an rms. value of ±0.06 mag. The rms. deviation of a magnitude derived from a single plate obtained from a comparison of plates taken on the same night is ±0.07 mag. The scatter of the magnitudes in determining the calibration curve for each plate also suggests an rms. precision of about the same size, but this type of estimate tends to give too low a value for the precision because of the arbitrary way in which the calibration curve is drawn through the points. As a test to see if a substantial color equation were present, the four bluest stars within about 1° of 3C 345 were measured photoelectrically and also included in the astrophotometer measurements. No large systematic differences between the photographic and photoelectric magnitudes appeared even at observations made at large zenith distances.

TABLE 1

PHOTOELECTRIC MAGNITUDES OF COMPARISON SEQUENCE

Star*	*B*	*B*−*V*	No of Observations
1 .	14 18	+0.74	1
2	14 58	+ 91	2
3	14 45	+ 62	1
4	15 60	+ 64	1
A	16 08	+ 81	3
B	16 33	+ 64	1
D	16 53	+ .78	1
E	17 10	+ 57	3
F	17 31	+ 63	1
G	17 30	+ 53	1
H	17 44	+ 65	2
I.	17 89	+0 59	1

* Finding charts for stars 1–4 are given in Fig 1 of this paper and for stars A–I in Fig 1 of Goldsmith and Kinman (1965) In the latter finding chart the direction labeled "West" should read "East."

It was noticed, however, that on a number of plates the magnitudes of 3C 345 were different from those on adjacent nights by amounts which seemed improbably large for a normal distribution of errors. Remeasurement and closer examination of these plates showed that these discrepant magnitudes resulted from fluctuations in the plate background around the image of 3C 345 on the plate. Such fluctuations were not easy to

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TABLE 2

PHOTOGRAPHIC MAGNITUDES OF 3C 345

Date (U T)	J D 2430000+	*B*	Date (U T)	J D 2430000+	*B*
1965:			Apr. 1	9217 0	16 89
June 24	8935 8	17 06	13	9228 8	16 92
July 1	8942 8	17 08	14	9229 9	17 02
20	8961 8	16 67	15	9230 9	16 97
21	8962 8	16 72	16	9231 9	17 04
29	8970 7	16 80	17	9232 9	16 96
Aug. 1	8973 8	16 92	19	9234 9	17.00
17	8989 7	16 94	20	9235 9	17 04
23	8995 7	16 95	21	9236 9	17 05
23	8995 7	16 89	22	9237 9	17 00
24	8996 7	16 94	26	9241 9	17 05
27	8999 7	17 01	28	9243 9	17 06
31	9003 7	17 09	May 11	9256 8	17 09
Sept 14	9017 7	17 06	12	9257 8	17 04
15	9018 7	16 97	13	9258 8	17 09
16	9019 7	16 88	15	9260 8	17 17
17	9020 7	16 89	16	9261 8	17 07
18	9021 7	16 87	17	9262 9	17 22
19	9022 7	16 98	18	9263 8	17 18*
19	9022 7	16 84*	18	9263 8	17 12
20	9023 7	17 01	19	9264 8	17 20
21	9024.7	16 94*	20	9265 8	17 05
21	9024 7	16 88	21	9266 8	17 02*
22	9025 7	16 90	23	9268 8	17 01
23	9026 7	16 96	24	9269 8	17 16
24	9027 7	16 85	25	9270 8	17 15
24	9027 7	16 92*	26	9271 9	17 03
25	9028 7	16 94	June 10	9286 8	17 12
Oct. 4	9037 7	16 72	11	9287 9	17 15
17	9050 6	16 66*	13	9289 8	17 21
20	9053 6	16 46	14	9290 7	17 28
23	9056 6	16 86	14	9290 8	17 11
24	9057 6	16 94	15	9291 8	17 18
25	9058 6	16 93†	17	9293 8	17 13
26	9059 6	17 04	18	9294 9	17 19
27	9060 6	16 96	19	9295 8	17 22
29	9062 6	17 11	20	9296 8	17 22
1966:			24	9300 8	17 20
Jan. 17	9143 1	16 86†	July 6	9312 7	17 20
18	9144 1	16 96†	10	9316 8	17 10
21	9147 1	16 87	12	9318 7	17 18
28	9154 1	17 06	13	9319 7	17 09
Feb. 14	9171 0	17 15	14	9320 7	17 07
15	9172 1	17 11	15	9321 7	17 18
16	9173 0	17 16	16	9322 7	17 08
17	9174 0	17 19	17	9323 7	17 19
20	9176 9	17 10	17	9323 8	17 18
27	9183 9	17 14	17	9323 8	17 07
28	9185 0	17 19*	19	9325 7	17 16
Mar. 3	9188 0	17.27	20	9326 7	17 22
21	9205 9	17 00	20	9326 7	17 12
23	9208 0	17 03	20	9326 7	17 18
24	9209 0	16 88	21	9327 7	17 16
25	9210 1	17 05	21	9327 8	17 23
26	9211 0	17 02*	21	9327 8	17 21
26	9211 0	17 00	22	9328 7	17 09
28	9212 9	16 88	24	9330 7	17 14
29	9213 9	16 88	Aug. 5	9342 7	17 13
30	9214 9	16 95	6	9343 7	17 16
31	9216 0	16 89	7	9344 7	17 15

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TABLE 2—*Continued*

Date (U T)	J D 2430000+	*B*
1966—*Continued*		
Aug 8	9345 7	17 23
9	9346 7	17 20
10	9347 7	17 20
11	9348 7	17 19
12	9349 7	17 20
13	9350 7	17 22
13	9350 8	17 07
14	9351 7	17.16
15	9352 7	17 18
16	9353 7	17 19
18	9355 7	17.08
19	9356 7	17 14
20	9357 7	17 08
21	9358 7	17 18
22	9359 7	17 11
23	9360 7	17 06
Sept. 3	9371 7	16 38
5.	9373 7	16 27
6	9374 7	16 58
7	9375 7	16 79
8	9376 7	16 76
9	9377 7	16 93
10	9378 7	17 01
11	9379 7	17 08
12	9380 7	17 06
14	9382 7	17 08
15	9383 7	17 00
16	9384 7	17 13
17	9385 7	17 08
19	9387 7	17 14
21	9389 7	17 01
22	9390 7	17 13
23	9391 7	17 10
24	9392 7	16 98
26	9394 7	17 03
Oct. 6	9404 6	16 86
7	9405 6	16 75
9	9407 6	16 76
10	9408 6	16 84
11	9409 6	16 80
12	9410 6	16 82
13	9411 6	16 79
15	9413 6	16 75
16	9414 6	16 64
17	9415 6	16 70
18	9416 6	16 66
1967:		
Jan. 16	9507 1	16 07
17	9508 1	16 20
18	9509 1	16 06
Feb. 4	9526 1	15 96
6	9528 1	15 95
7	9529 1	16 11
8	9530 1	16 05
9	9531 1	16 13
10	9532 0	16 06
11	9533 0	16 12
15	9537 0	15 79
16	9538 0	15 64
18	9540 0	15 56
Feb. 19	9541 0	15 41
20 ..	9542 0	15 56
21	9543 0	15 70
Mar 3	9553 0	16 00
5	9555 0	15 98
6	9556 0	15 93
7	9557 0	16 00
8	9558 0	15 91
9	9559 0	15 84
Apr. 9	9589 9	15 86
May 1	9611 8	16 29
2	9612 8	16 31
3	9613 8	16 34
5	9615 8	16 31
6	9616 8	16 38
7	9617 8	16 27
8	9618 8	16 33
13	9623 8	16 18
15	9625 8	16 31
16	9626 8	16 10
17	9627 8	16 25
18	9628 8	16 23
19	9629 8	16 27
20	9630 8	16 33
26	9636 8	16 22
27.	9637 8	16 08
30	9640 8	16 05
June 4	9645 8	16 05
6	9647 8	15 96
8	9649 8	16 10
9	9650 8	16 14
10	9651 8	16 09
11	9652 8	16 07
12	9653 8	16 05
13	9654 8	16 01
14	9655 8	16 11
15	9656 8	16 17
17	9658 8	16 09
27	9668 8	15 97
28	9669 8	16 16
29	9670 8	16 13
30	9671 8	16 13
July 1	9672 7	16 14
2	9673 7	16 23
3	9674 7	16 14
4	9675 7	16 13
6	9677 7	15 91
7	9678 7	15 98
8	9679 7	16 00
9	9680 7	15 81
10	9681 7	15 80
11	9682 7	15 84
12	9683 7	15 77
14	9685 7	15 61
15	9686 7	15 50
16	9687 7	15 69
17	9688 7	15 49
25	9696 7	15 63
26	9697 7	15 63
27	9698 7	15 83

TABLE 2—*Continued*

Date (U T)	J D 2430000+	*B*	Date (U T)	J D 2430000+	*B*
1967—*Continued*			Aug 30	9732 7	16 16
July 29	9700 7	16 02	31	9733 7	16 22
30	9701 7	16 05	Sept. 1	9734 7	16 10
31	9702 7	15 98	2	9735 7	16 11
Aug. 1	9703 7	16 06	6	9739 7	16 40
2	9704 7	16 10	7	9740 7	16 42
3	9705 7	16 04	8	9741 7	16 46
4	9706 7	15 97	10	9743 7	16 48
5	9707 7	16 03	24	9757 7	16 47
6	9708 7	16 10	25	9758 7	16 65
7	9709 7	16 02	26	9759 7	16 58
9	9711 7	16 19	27	9760 7	16 65
10	9712 7	16 15	28	9761 7	16 66
11	9713 7	16 20	30	9763 7	16 56
12	9714 7	16 06	Oct. 1	9764 7	16 59
13	9715 7	16 20	4	9767 7	16 50
26	9728 7	16 30	6	9769 7	16 57
27	9729 7	16 22	7	9770 7	16 50
28	9730 7	16 24	26	9789 6	15 86‡
29	9731 7	16 20	29	9792 6	16.10‡

* Crossley reflector.

† 120-inch reflector

‡ These late observations were not included in the statistical discussion They are however plotted in Figs 2, 3, 6, and 8 and confirm the marked brightening of 3C 345 between Oct 7, 1967, and Oct 26, 1967

TABLE 3

PHOTOELECTRIC MAGNITUDES OF 3C 345

Date (U T)	J D 2430000+	*B* (mag)	pe-pg (mag)	Reference*
1965:				
May 25	8905 8	17 03		(1)
June 28	8939 8	17 14		(1)
July 22	8963 7	16 60		(1)
July 23	8964 7	16 67		(1)
Sept. 4	9007 7	16 94		(1)
Oct. 3	9036 6	16 78		(1)
Oct. 19	9052 6	16 25		(2)
Oct. 22	9055 6	16 79		(1)
Oct. 30	9063 6	17 21		(1)
1966:				
May 21	9266 8	17 06	+0 04	(1)
June 14	9290 8	17 20	− 08; +0 09	
July 15	9321 7	17 14	− 04	
July 17	9323 7	17 17	+ .04; +0 01; +0 10	
Aug. 18	9355 7	17 09	+ 01	
Aug. 20	9357 7	17 10	+ 02	
1967:				
May 3	9613 8	16 36	+0 02	

* *References:* (1) Wampler (1967); (2) Sandage (1966*b*).

detect visually and any apparently discrepant plates were remeasured with a view to detecting such effects. In view of the existence of such effects, it is felt that no single photographic observation by itself can be taken as sufficient evidence for a change in brightness of the object. Changes in brightness should therefore only be established by a trend in several observations. The time resolution of the present observations is therefore a function of the amplitude of the brightness fluctuations being considered: it may be only a day or two for the largest fluctuations but is perhaps of the order of a week to ten days for fluctuations with an amplitude of the order of 0.1 mag.

TABLE 4

OPTICAL POLARIZATION MEASUREMENTS OF 3C 345

Date (U T) 1967	J D 2439000+	p (per cent)	θ	I_2/I_1
Feb. 7	529 0	8 4±1 5	75°5± 5°3	−0 06
8	530 0	7 8±1 2	82 8± 4 5	−0 03
16	538 0	7 1±1 1	44 7± 4 4	+0 78
Mar. 5	555 0	6 8±0 7	93 1± 3 0	+0 10
May 3	613 9	7 6±2 2	99 2± 8 4	−0 40
5	615 9	8 4±1 2	97 3± 4 1	−0 37
June 8	649 7	9 0±1 2	99 9± 3 9	−0 06
9	650 7	10 0±0 6	98 6± 1 8	−0 11
14	655 7	10.5±0 9	90 5± 2 5	−0 06
July 7	678 7	7 8±0 9	110 3± 3 2	+0 20
14	685 7	4 8±1 4	131 3± 8 3	+1 03
Aug. 4	706 7	8 7±0 9	59 3± 2 8	+0 36
5	707 7	6 3±0 4	57 7± 1 9	+0 25
12	714 7	10 9±0 6	71 8± 1 6	+0 24
Sept. 1	734 7	3 2±0 3	32 2± 3 1	+0 41
2	735 7	7 0±1 4	40 1± 5 8	+0 39
8	741 7	10 0±0 8	53 3± 2 3	−0 20
10*	743 7	5 9±1 8	49 5± 8 7	−0 21
28*	761 7	2 4±1 2	91 2±13 8	−0 31
Oct. 4*	767 7	3 3±0 8	147 6± 7 1	+0 19

* HN-32 Polaroid analyzer was used

III. POLARIZATION DATA

The polarization observations were made at the prime focus of the 120-inch reflector with the single-beam polarimeter described by Kinman, Lamla, and Wirtanen (1966). The observed position angle (θ) and percentage polarization (p) is given as a function of the date (U.T.) and Julian date in Table 4. The observations were all made with an RCA IP21 photomultiplier without a filter (approximate waveband λλ3000–6500). The instrumental correction was derived (and checked during most observing runs) by observing stars of known polarization (Hiltner 1956). This instrumental effect is apparently produced by a small error in the centering of the Ahren's analyzing prism. In September, 1967, an HN-32 Polaroid sheet analyzer became available: this analyzer (according to observations of three of Hiltner's stars) does not produce any instrumental effects greater than a few tenths of 1 per cent in the measured polarization. The transmission of this analyzer is 1.1, 21.5, and 33.4 per cent for the U, B, and V band passes, respectively, for a star with UBV colors similar to that of 3C 345. This Polaroid analyzer was used for a few of the later observations (as indicated in Table 4). No significant dependence of p or θ upon color was found in observations of 3C 446 (Kinman *et al.* 1966) but this matter merits a more thorough investigation. It happens that the percentage polarization (p) was low on the nights when the Polaroid analyzer was used. No reduction in p was found in similar measurements of 3C 446, so that it is considered unlikely that in the case of 3C 345 the reduction in p was due to the use of the Polaroid analyzer.

It is not thought, therefore, that the use of analyzers with different color transmissions has materially affected the homogeneity of the present observations.

The polarizations reported here are relatively large compared with those normally found for stars. The main uncertainties are therefore not so much caused by the small instrumental errors which can strongly effect stellar polarization measures, but by factors such as fluctuating sky brightness, guiding and scintillation errors. The quoted rms. errors for polarization measurements will tend to be somewhat smaller than the true errors (Hall and Serkowski 1963), but the agreement between the polarization elements derived from observations on consecutive nights (Fig. 9) indicates that these errors are substantially correct.

IV. ANALYSIS OF THE OBSERVATIONS

a) Photometry

The observed magnitudes (B) of 3C 345 are shown plotted against the Julian date in Figure 2. Photographic observations are shown by filled circles and photoelectric observations are shown by crosses. The figure is drawn for convenience in three overlapping

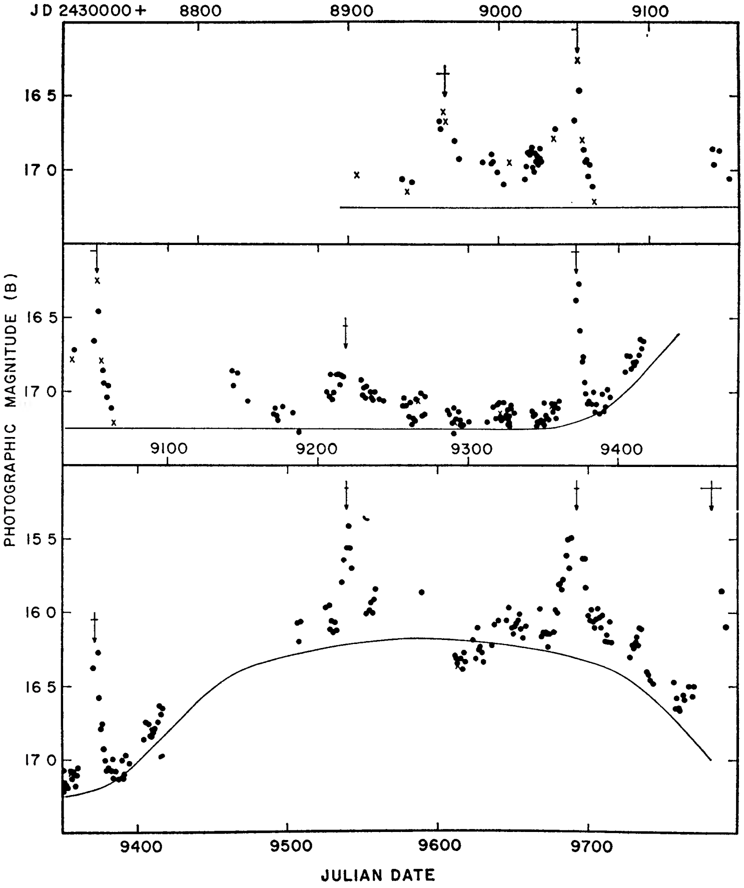

FIG. 2.—B magnitudes for 3C 345 as a function of the Julian date. Photographic observations are shown by filled circles and photoelectric observations by crosses. The panels show three overlapping intervals of 450^d arranged so that observations are 320^d apart from those in the same vertical line in adjacent panels. The full line shows the first approximation to the slowly varying component.

sections so that a given time in the middle section is 320 days later than the corresponding time vertically above it in the first section, and 320 days earlier than that vertically beneath it in the last section.

It is seen that variations in brightness (with amplitudes many times the observational precision) are present with time scales that range from several days to several hundred days. This range in the observed time scales results presumably from our inability to detect rapid fluctuations because of the limited time resolution (discussed in § II) and the impossibility of detecting variations with time scales much longer than the duration of the observations. Evidently, fluctuations with a time scale comparable to the length of the observations are present, and it is because of this and because of the lack of continuity in the observations that we have not attempted a power spectrum analysis in a provisional analysis. We therefore have chosen to start our analysis of the observations on the assumption that the light from 3C 345 has two components: one which is constant in brightness ($B = 17.25$ mag) before J.D. 2439357 and is thereafter given by the smooth curve, and another which consists of the remaining light. We call the amplitude of this second component ΔB (in magnitudes) or ΔI if it is expressed as an intensity on a scale in which 17.25 mag equals unit intensity. Inspection of Figure 2 shows that the light curve has features which tend to repeat after 320 days and that major features are present at intervals of about 80 days. As a test of the reality of this impression, Figure 3 shows a plot of ΔB as a function of phase ϕ for a period of 80.37 days for observations (*a*) before J.D. 2439357 and (*b*) after J.D. 2439357. In the same figure the corresponding plots for ΔI are shown in (*c*) and (*d*), respectively. It is seen that the scatter in ΔB (and also ΔI) shows a maximum close to $\phi = 0.0$ and a minimum close to $\phi = 0.5$ for observa-

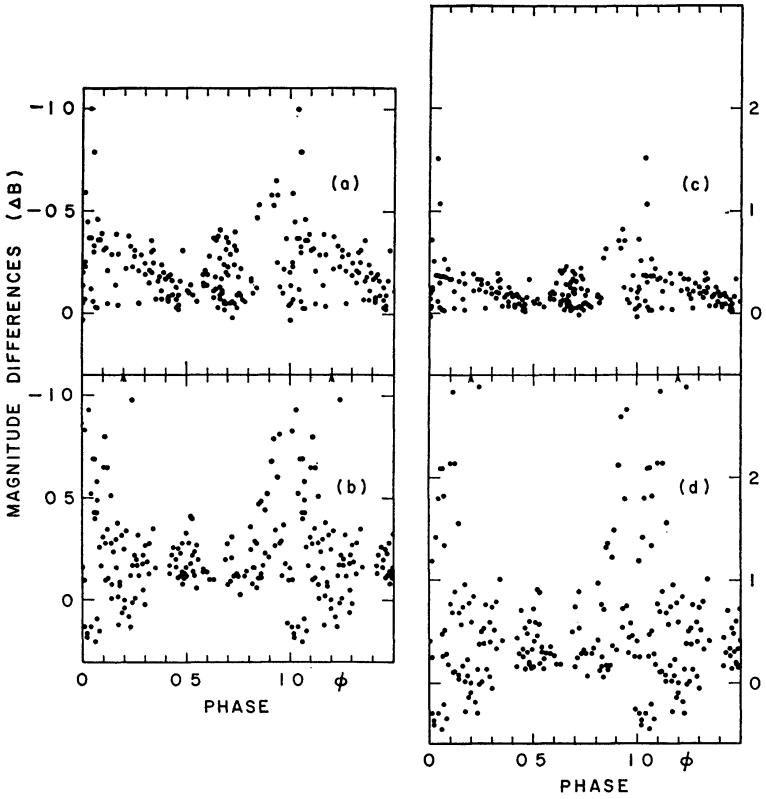

FIG. 3.—Magnitude differences ΔB of 3C 345 as a function of phase ϕ for an 80 37-day period for (*a*) observations before J.D. 2439357 and (*b*) observations after this date. The corresponding plots for the intensity differences ΔI are shown in (*c*) and (*d*) respectively.

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tions both before and after J.D. 2439357. The similarity between plots (*a*) and (*b*) suggests that our method of separating out the effects of long time scale changes in brightness has some validity. Thus in Table 5 we see that the standard deviation of ΔB from its mean value $\langle \Delta B \rangle$ and also the value of $\langle \Delta B \rangle$ *for a given phase interval* is similar for observations before and after J.D. 2439357. We also see that there is a significant difference between the mean values ($\langle \Delta B \rangle$ and $\langle \Delta I \rangle$) for the phase range $0.30 < \phi < 0.70$ and for the range $0.80 < \phi < 0.20$. To test the reality of this periodicity further we have taken the *mean* values of ΔB in *each* 80-day cycle for the observations for which (*a*) $0.30 < \phi < 0.70$ and (*b*) $0.80 < \phi < 0.20$, and these are shown plotted against the cycle number by open circles and filled circles, respectively, in Figure 4. The difference in the scatter between the two sets of observations is obvious: the rms. dispersion is only ±0.069 mag for the group with $0.30 < \phi < 0.70$ and is ±0.196 mag for the group with $0.80 < \phi < 0.20$. The square of the ratio of these dispersions is 8.11 with 9 and 8 degrees of freedom, respectively. The probability that these observations could come by chance from the same parent population is only 0.0022 by interpolating from the percentage points of the F-distribution (Lindley and Miller 1953). In other words there is only about one chance in 450 that a random distribution of fluctuations could give rise to this 80-day periodicity. We may note that the dispersion of the observations in the phase range $0.30 < \phi < 0.70$ is scarcely larger than the observational precision; this suggests that

TABLE 5

THE MEAN VALUES OF THE MAGNITUDE AND INTENSITY DIFFERENCES ΔB AND ΔI AND THEIR DISPERSION AS A FUNCTION OF PHASE ϕ IN AN 80-DAY PERIOD

Phase Interval	Mean Value $\langle \Delta B \rangle$ (mag)	No of Observations	Dispersion* in ΔB (mag)	Mean Value $\langle \Delta B \rangle$	Dispersion* in ΔI
0 30<ϕ<0 70 ..	−0 17±0 01	71	±0 10	0 17±0 01	±0 11 } Before J.D. 2439357
80<ϕ< .20 .	− .29± 03	48	± .22	34± .04	± .30
30<ϕ< 70 .	− 19± 01	45	± 09	.40± 04	± 24 } After J D. 2439357
0 80<ϕ<0 20 ..	−0 28±0 03	73	±0 27	0 69±0 09	±0 80

* Calculated from $[\Sigma_n(\Delta B - \langle \Delta B \rangle)/(n-1)]^{1/2}$ and similarly for the intensity differences.

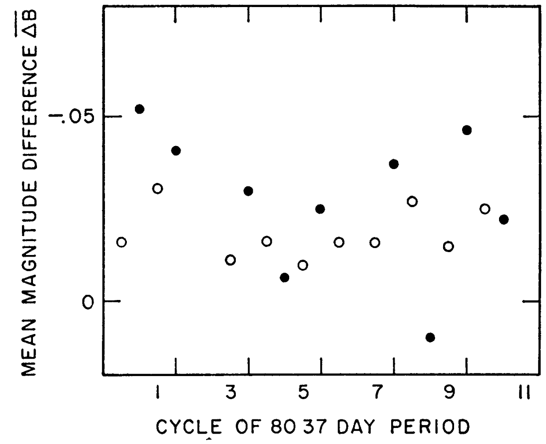

FIG. 4.—Mean magnitude difference $\langle \Delta B \rangle$ for the observations in each cycle of the 80.37-day period as a function of the cycle number. Filled circles are for observations in the phase range $0\ 80 < \phi < 0.20$ and open circles are for $0.30 < \phi < 0.70$.

the brightness changes of our second component are largely confined to the phase range $0.80 < \phi < 0.20$.

We now attempt to identify the fluctuations which are responsible for the dispersion in ΔB around $\phi = 0.0$. Examination of Figure 2 shows that the six brightest "maxima" in the light curve (indicated by arrows) occur in the range $0.92 < \phi < 0.10$; five of these have $\Delta B > 0.72$ mag and the sixth is uncertain but certainly has $\Delta B > 0.40$ mag. There is also good evidence for a seventh maximum ($\Delta B > 1.0$ mag), but its phase is uncertain although in the range $0.97 < \phi < 0.20$. Only one other "maximum" can be identified with any certainty, and this has an uncertain ΔB of less than 0.40 mag and $\phi \approx 0.59$. Table 6 gives details of the six brightest "maxima" and estimates of their computed

TABLE 6

OBSERVED FEATURES

a) $0\ 80 < \phi < 0.20$*

Cycle	J D. 2430000+	Phase in 80 37-Day Period†	Phase in 321 5-Day Period†	Amplitude ΔB (mag)	Type
1	8966 0 *8963 0* 8958 0	0 958 *0 921* 0 858	0 240 *0 230* 0 215	≈0.7	Maximum
2. . .	*9052 5* 9048 5	*2 034* 1 984	*0 508* 0 496	≈1 0	Maximum
3‡	....	...	. ...		Maximum?
4.........	9220 0 *9218 0* 9216 0	4 118 *4 093* 4 069	1 030 *1 023* 1 017	>0 4	Maximum
5‡	. .... .	. ...	. .. .		Maximum?
6...... .	9373 5 *9371 5* 9368 5	6 028 *6 003* 5 966	1 507 *1 501* 1 492	≈0 9	Maximum
7‡... ...	. ... .	.....	. ...	.	?
8.	9541 0 *9540 0* 9539 0	8 112 *8 100* 8 087	2 028 *2 025* 2 022	≈0 7	Maximum
9‡.....	.. . .. .	.. ..	. .. .		Minimum?
10.	9694 0 *9692 5* 9691 0	10 016 *9 997* 9 978	2 504 *2 499* 2 495	≈0 9	Maximum
11‡. .	. . .			..	Maxmium

b) $0\ 20 < \phi < 0.80$

A weak maximum ($\Delta B \approx 0\ 4$) occurred at $\phi = 10.59$ (80-day period)
No maxima with $\Delta B > 0.4$ occurred in this phase range

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* Preferred values of the epochs and phases are shown in italics; other values indicate the range of uncertainty.

† Assuming epoch for $\phi = 0$ is J D. 2438889 0.

‡ See notes to Table 6.

NOTES TO TABLE 6

Cycle 3: Insufficient observations; a maximum probably occurred before $\phi = 3.16$.
Cycle 5: Insufficient observations; a weak maximum possibly occurred in the interval $4.76 < \phi < 4.93$.
Cycle 7: No observations.
Cycle 9: Insufficient observations; minimum observed at $\phi < 8\ 99$.
Cycle 11: Insufficient observations; a strong maximum ($\Delta B > 1\ 0$ mag) occurred in interval $10.97 < \phi < 11.20$ and most probably in interval $11.10 < \phi < 11.20$.

phases. Details are also given of the behavior of the light curve for $0.80 < \phi < 0.20$ in the 80-day cycle for the five cycles not represented by the six observed "maxima." In two of these cycles there are no observations. In the remaining three cycles there are insufficient observations, but in the case of two there is some indication that a maximum may have occurred, while the third indicates a minimum. It therefore appears that the variation of the dispersion in ΔB with phase in an 80-day cycle is primarily due to all the large maxima having phases in the range $0.92 < \phi < 0.10$.

Let us consider this class of well-observed maxima with $\Delta B > 0.4$ mag. Two of the six observed were used in effect to define the period from which the phases were calculated. The chance that the remaining four should fall in a phase range $\Delta\phi$ is $(\Delta\phi)^4$ if the observations are evenly distributed in time and the distribution of the maxima is random. It follows that there is one chance in 952 that the observed distribution arose by chance from a random distribution of maxima. In fact 23.5 per cent of the observations were made in the phase range $0.92 < \phi < 0.10$, rather than the 18 per cent for a uniform distribution of observations with time. If we assume that the chance of observing a maximum is proportional to the number of observations, then the chance that we observe four maxima in the stated phase interval is one in 328 if the distribution of maxima is random. If we also consider the seventh maximum which occurred in the range $0.97 < \phi < 0.20$, the observed phase range in which seven maxima occurred is <0.28. There is less than one chance in 580 that this could be due to a random distribution of these large maxima with time. Thus, either from a consideration of the phases of the large maxima or from a consideration of the differences in the variances of $\langle\Delta B\rangle$ in two phase intervals we conclude that there is only one chance in several hundred that the 80-day period could be due to large fluctuations which are randomly distributed in time.

The amplitudes and phases of the features occurring near zero phase in the 80.37-day period are shown as a function of cycle number in Figure 5. There is evidence that a pattern exists which repeats after four cycles or a period of 321.5 days. Thus the maxima of the second, sixth, and tenth cycles have a spread of only 0.037 in phase, and there is a phase difference of only 0.007 between the fourth and eighth maxima. The probability that this pattern could arise by chance within a phase interval of 0.18 is only one in 84 if the observations are evenly distributed with time. There is also an indication that the amplitudes also show some regularity in the same 321.5-day period. This evidence, although far from complete, seems adequate to make a prima facie case for the existence of this long period. A plot of the magnitude differences (ΔB) as a function of phase in the 321.5-day period (taking zero phase at JD 2439049.7) is shown in Figure 6.

b) *Polarization Measurements*

Inspection of Table 4 shows that both the polarization position angle (θ) and the percentage polarization (p) of 3C 345 showed significant variations in 1967. It may be noted that Aller and Haddock (1967) found variations in both p and θ for 3C 345 at 8000 Mc between 1963 and 1966. The optical polarization measurements (which could only be made with a large reflector) span an interval of 238 days and because of the poor weather in the spring months of 1967 have a very non-uniform distribution.

As we noted in the Introduction, existing evidence points to large percentage polarizations being present when optically variable quasi-stellar sources are bright. This suggests a simple model in which we divide the observed light into three components:

a) A constant unpolarized component equal in intensity to the mean observed for 3C 345 for phases $0.30 < \phi < 0.70$ (80-day cycle) before J.D. 2439357.

b) A slowly varying component with percentage polarization p_1, and of intensity I_1, obtained by drawing a smooth curve through the observed intensities for phases $0.30 < \phi < 0.70$ (80-day cycle) after J.D. 2439357 and subtracting the intensity of component (*a*). This component is assumed to be absent before J.D. 2439357.

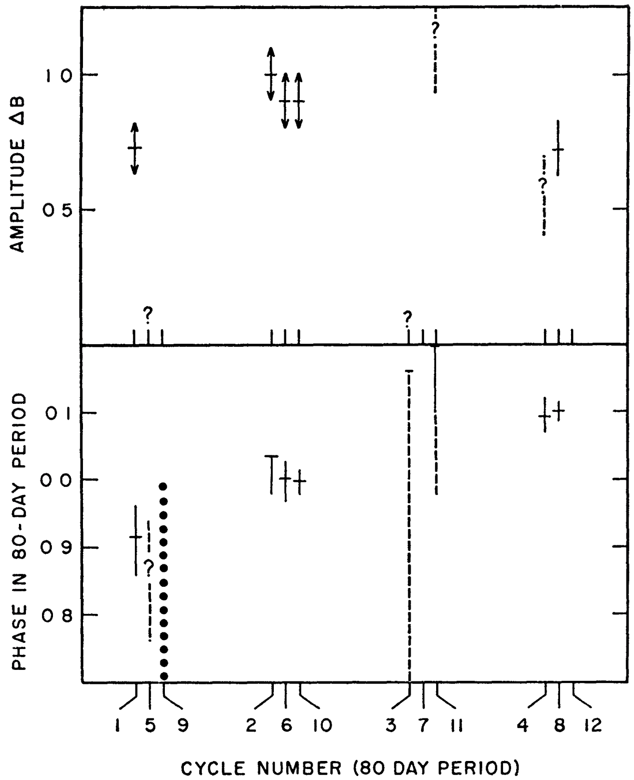

FIG. 5.—Amplitude ΔB in magnitudes and the phase ϕ (in the 80-day period) of the major fluctuations in the light curve of 3C 345 as a function of the cycle number of the 80-day period. All fluctuations except one are maxima: the single minimum is shown by filled circles. The most probable amplitudes and phases of the most completely observed maxima are shown by short horizontal lines and their uncertainties by vertical lines. Incompletely observed features are shown by dashed lines and a question mark is added if the estimate is quite uncertain.

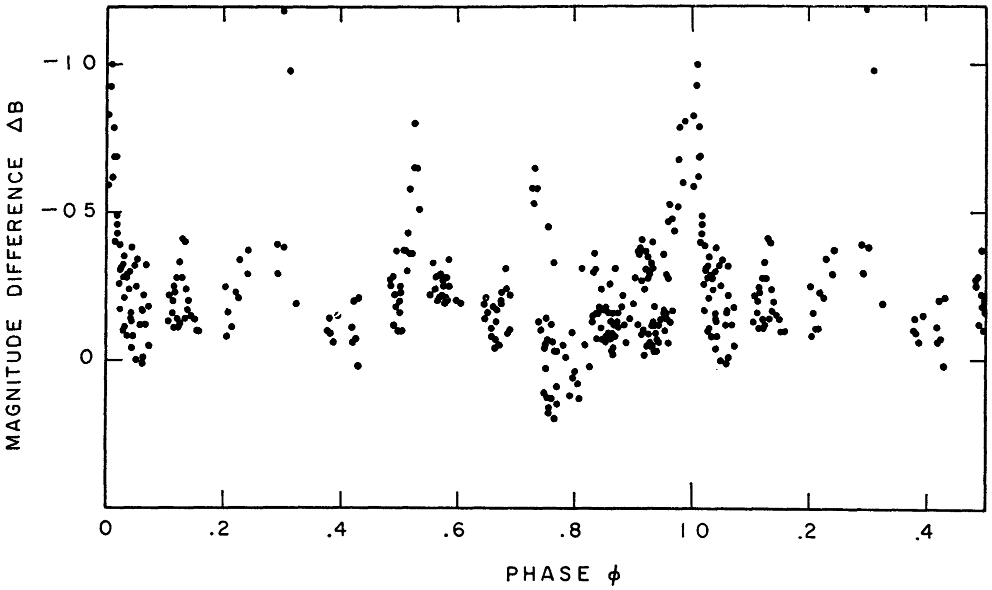

FIG. 6—Magnitude residuals ΔB of 3C 345 as a function of phase ϕ assuming a period of $321^{d}.5$ and taking $\phi = 0.0$ at J.D. 2439049.7.

c) A residual component of percentage polarization p_2 and intensity I_2 obtained by subtracting the intensities of components (*a*) and (*b*) from the observed intensity I. It should be noted that according to this definition I_2 may be negative.

The intensities of the components are in units such that the constant component (*a*) equals unity:

$$I = I_1 + I_2 + 1 . \tag{1}$$

If we define the percentage polarization which is observed and those percentages which are due to components (*b*) and (*c*), respectively, by p, p_1, and p_2, we have

$$p \frac{I}{I_1} = p_1 + \frac{I_2}{I_1} p_2 . \tag{2}$$

We may expect to find a linear relationship between $(I/I_1)\,p$ and I_2/I_1 if our model is valid and if there is a strong positive correlation between the position angles of the planes of polarization of the polarizations p_1 and p_2. The actual plot is shown in Figure 7 and if we take all twenty points on the plot we see that there is no significant relationship (correlation coefficient $r = 0.29$). If, however, we only take the ten observations with negative I_2/I_1 we find a correlation between $p(I/I_1)$ and I_2/I_1 ($r = 0.620$) which is probably significant; for ten observations, r equals 0.632 at the 5 per cent significance level and 0.765 at the 1 per cent level (Quenouille 1959). Assuming then that a linear relation exists between $p(I/I_1)$ and I_2/I_1 for negative values of I_2 we can derive p_1 from the slope of this relation and p_2 from its intercept with the I_2/I_1 axis. This gives $p_1 \approx p_2 \approx 17$ per cent. We find no correlation for the points with positive I_2.

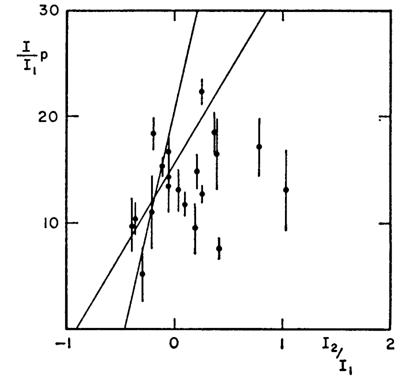

FIG. 7.—The intensity of the linearly polarized component Ip as a function of the intensity of the rapidly fluctuating component I_2—both expressed in units of the slowly varying component I_1. A correlation is found for the negative but not the positive values of I_2.

This result is consistent with our model if we redefine component (*b*) so that it has the intensity I_1 (as previously defined) plus that of the component of I_2 (as previously defined) when I_2 is negative. We call this component B and its intensity is I_B and its percentage polarization is about 17 per cent. Our new component C (to replace *c*) has an intensity I_C which is equal to I_2 when this is positive and is otherwise zero. If our interpretation is correct, component C must be strongly polarized but with a position angle that does not correlate positively with that of component B. It follows that when I_2 is positive our observed polarization elements should correspond to the resultant polarization from two sources (B and C) but when it is negative they are only due to component B. Figure 8 shows a plot of the polarization position angle θ as a function of Julian date. The observations made when I_2 was negative are shown by filled circles while those when I_2 was positive by open circles. It is seen that the filled circles lie on a relatively smooth

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curve (shown by the dashed line)—in other words these observations which according to our model refer to only the slowly varying single source *B* show only a smooth, slow variation in the position angle. In the lower half of Figure 8 we show the light curve in intensity units (constant unpolarized component *A* equals unity); the curve in this diagram is our estimate of the contribution of component *B*. It is seen that both the position angle (θ) of the plane of polarization of component *B* and its total intensity appear to change with a very similar time scale: this gives some measure of support for our interpretation.

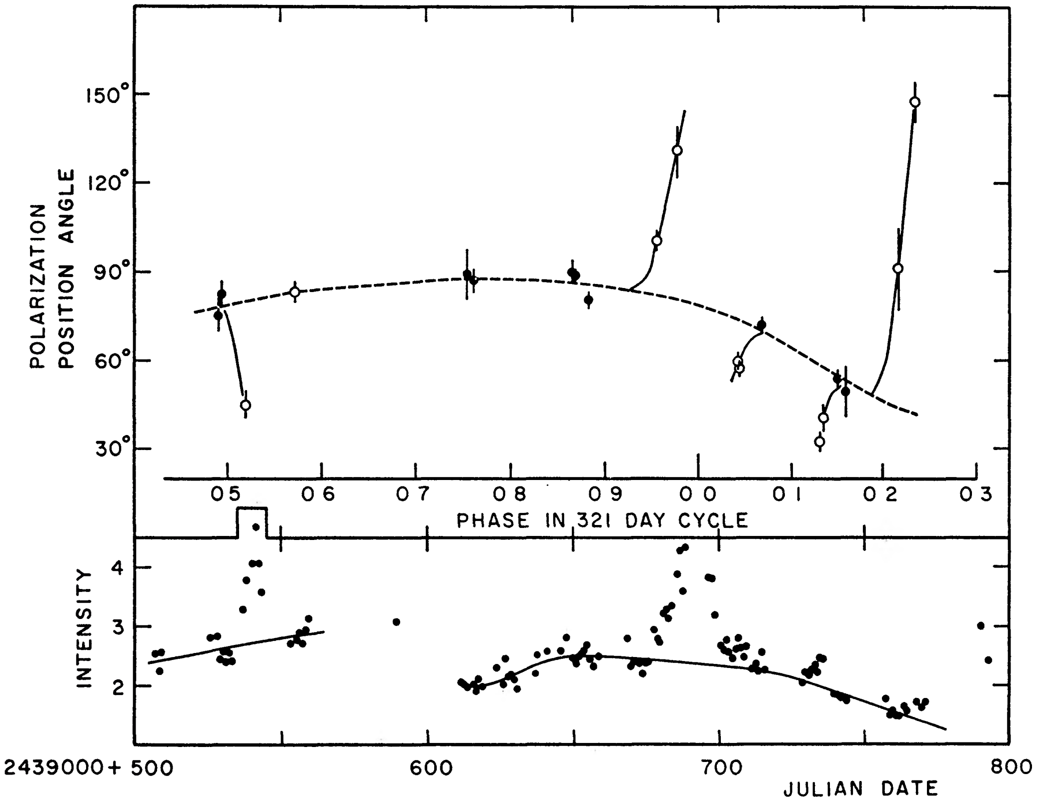

Fig. 8.—The upper diagram shows the variation with Julian date of the polarization position angle θ of 3C 345. Filled and open circles refer to observations made when I_2 is zero or negative and when I_2 is positive, respectively. On the three-component model the dashed curve (through the filled circles) shows the trend of θ for the slowly varying component I_1. The lower diagram shows the observed intensities of 3C 345 in units of the constant component of the three-component model. The full curve is an estimate of the contribution of the slowly varying component I_1.

We see that when I_2 is positive (i.e., the observed light curve lies above the smooth curve) and therefore there is a contribution from component *C* that the measured position angles of the polarization (θ) depart strongly from the smooth curve which defines θ for component *B* alone. At the times when θ was measured, component *C* was generally no brighter than component *B*, and yet there are large departures from the predicted polarization for *B* alone; we conclude that component *C* probably has at least as high a percentage polarization as component *B* and that the position angle of its polarization must be sharply inclined to that of *B*. It is unlikely that component *C* is unpolarized and that its effect is simply to dilute light of component *B* or disorganize its polarization mechanism, since this would lead to only a diminution of *p* as I_2 increases, and this is not observed.

Any measure of a position angle is ambiguous by an integral multiple of 180°. It is therefore a matter of concern as to whether corrections of ±180° should be applied to the observed values of θ. We may calculate $d\theta/dt$ (the rate of change of θ in degrees per day) from consecutive measurements of θ on the assumption that no 180° correction need be applied. These values of $d\theta/dt$ are shown as a function of the time interval in days between the consecutive observations (ΔT) by the filled circles in Figure 9. If we assume that a correction of ±180° has occurred between consecutive observations, we get the values of $d\theta/dt$ shown by crosses; this correction has not been applied to the pairs of observations with small ΔT since it seems clearly inapplicable in these cases. We see that, when $\Delta T > 15$ days, the values of θ obtained by applying a correction are not so large that we can exclude the possibility that such a correction should be applied to at least some of the observations. It might well be, therefore, that following each excursion in θ represented by the open circles in Figure 8, the curve through the filled circles is displaced by 180°. There seems to be no way to resolve this ambiguity with the present observations. Furthermore it will be difficult to resolve it in any future observations, since these are likely to be restricted (like the present ones) to relatively short observing periods near the dark of the Moon.

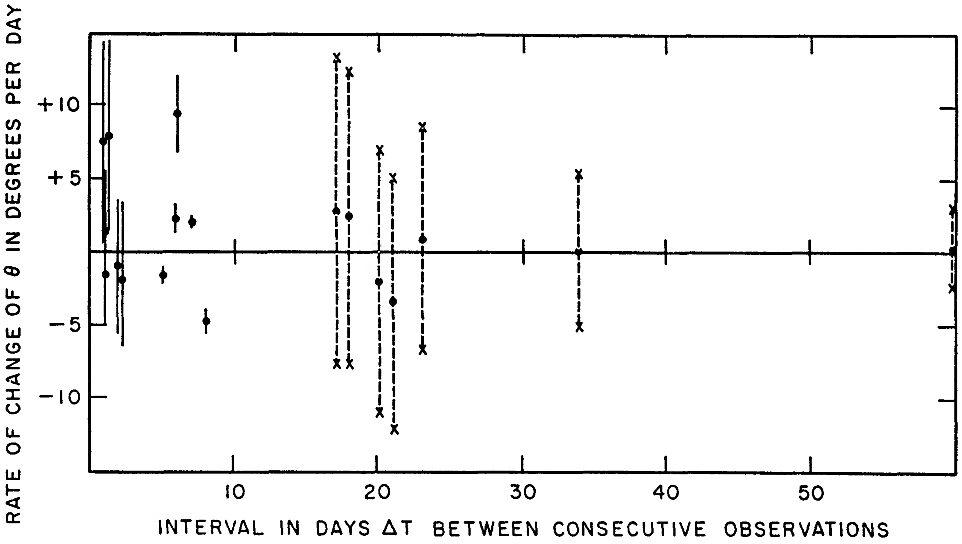

FIG. 9.—The rate of change of the polarization position angle θ (in degrees per day) between consecutive observations as a function of the time interval ΔT between these observations. Filled circles dentoe rates calculated directly from the observed position angles, and solid vertical lines are their estimated rms. errors. The crosses are the rates calculated when either ±180° is added to the position angle of the second observation.

V. DISCUSSION

Our analysis of the photometric observations showed that there is only one chance in several hundred that the 80.37-day periodicity which we ascribe to component C could arise from a random distribution of events. The chance that the secondary period of 321 days arises from a random distribution is one in eighty. If we were dealing with a star (even one of unknown type) we should probably accept these observations as fairly definite evidence that a periodicity really exists. This is because periodic phenomena are common in stars. Quasi-stellar objects are almost certainly extragalactic according to present evidence, and we have no other evidence of an isolated extragalactic object (discounting stars in external galaxies) showing periodic behavior. It is therefore not unreasonable that the evidence should be quite strong before the existence of periodic phenomena in quasi-stellar objects should be regarded as proved. We feel that the present evidence is strong enough to accept both the 80- and 321-day periods as good working hypotheses (to be strengthened or weakened by further observation) and that the theoretical consequences of these periodicities merit serious consideration.

Although the photometric and polarization data are consistent with the optical radiation having three components, this does not necessarily imply that there are just three physically distinct sources. We cannot distinguish between many randomly oriented sources of polarized radiation and a single source which has unpolarized radiation. The only restriction that we can put on the constant source A is that its polarization is small compared with that of the other components—say less than 3 per cent. It is not certain to what extent the variable sources B and C should be regarded as physically distinct. As Gudzenko, Ozernoy, and Chertoprud (1967) have pointed out, regular variability of this type implies that the sources must be part of a single body rather than some assemblage of bodies. The rapidly variable source C was present in 1965 and 1966 before the slowly varying source B became apparent. This may suggest that source C is not simply a perturbation of source B and that source C might produce B but not vice versa. A relationship between the two sources is suspected since a minimum was observed in source B at a time when a maximum was expected in source C. This minimum occurred when source B was at its peak brightness; however, at other times source C was generally brighter (in intensity units) when source B was present than before this source appeared.

The most obvious causes of periodic phenomena are pulsation, rotation, and orbital motion. The presence of more than one period might suggest (by analogy with some variable stars) that we are observing some pulsation phenomenon. Fowler (1965) proposed that relaxation oscillations of a non-rotating star of mass $2 \times 10^5 M_\odot$ could account for a period of 13 years in the optical variations of 3C 273 which was inferred by Smith (1965). The 80-day period of 3C 345 (50 days in the rest frame of the object) together with a luminosity of 10^{46} ergs sec^{-1} (assuming that the redshift has a cosmological origin) leads to a mass of $\approx 3 \times 10^4 M_\odot$ according to Fowler's model. This mass is small compared with that deduced for the hydrogen emission regions alone for 3C 273 and 3C 48 (Greenstein and Schmidt 1964) and also with current estimates of the mass required to satisfy the energy needs of the object ($\approx 10^8 M_\odot$) if its redshift has a cosmological origin. Chandrasekhar (1964) showed that dynamical instability would result if a body of $10^8 M_\odot$ contracted to a radius of 4.7×10^{17} cm (0.5 light-years) because of general relativistic effects. The optical variations seem to imply even smaller dimensions ($\lesssim 0.01$ light-years), at least for the variable part of the source.

It has been suggested by Fowler (1966) and Roxburgh (1965) that sufficient rotational energy could stabilize such compact massive bodies at radii small enough to allow high enough central temperatures for nuclear reactions to occur. According to Fowler (1966) such bodies with radii of the order of 10^{15} cm would have fundamental radial pulsation periods of the order of 10 to 100 days. It is not obvious, however, that oscillations of the type considered by Fowler could account for the present observations; more needs to be known about the mechanisms of energy transport and loss from the atmosphere of such a body which will govern the damping of such oscillations. It has been suggested that magnetoturbulence may also provide a stabilizing energy source in large compact masses. The time scale over which such magnetoturbulence can be maintained is uncertain; Bardeen and Anand (1966) following a suggestion of Layzer (1965) consider that it may be generated from rotational energy. They point out that the evolutionary contraction of a magnetoturbulent star must involve the loss of a significant amount of angular momentum if the rotational energy is not to exceed that of the magnetoturbulence. They are thus led to picture a magnetoturbulent star as "a distorted $n = 3$ polytrope rotating uniformly with the critical angular velocity of equatorial stability." Ozernoy (1966) has also considered the role of magnetoturbulence. In his "magnetoid" model he calculates a circulation time for an inhomogeneity in the magnetic field which is 5 years in 3C 273 and identifies this with the time scale of optical variations. He identifies the time scale of more rapid fluctuations with the characteristic time for magnetohydrodynamic waves to traverse the object, but these fluctuations are considered to be random phenomena.

In spiral galaxies (where rotation is easily observable), the angular momentum per unit mass is several orders of magnitude larger than that implied by these rotating models. If these compact massive objects can be formed, it does not seem unlikely that they will possess the angular momentum close to the limit set by stability considerations. It is therefore suggested that we should consider rotation as the most likely cause of the observed periodicities. Together with rotation one must also consider the possibility that the observed effects could be caused by the orbital motion of a close binary. We must also consider the problem of why the variable radiation alone is strongly polarized. Evidently there must be some ordering process which is at work on the magnetic field at such times. Perhaps the most likely process is a very strong local mass motion which presumably occurs in a direction which is radially outward from the center of the body.

On a rotational hypothesis, the long period (321 days) must presumably be identified with the rotation period of the body. The short-period fluctuations (component *C*) are then identified with the transit of bright regions across the face of the body. The relatively short time of rise and decay of these fluctuations suggests that this radiation is not emitted isotropically but in a beam with a half-width of the order of perhaps 20°. Such a beaming effect may result if the electrons travel outward from the object at small angles to the field lines (cf. Woltjer 1966). On this hypothesis, the symmetry in positions of the active regions suggests that there must be some underlying symmetry in the nucleus of the body. In this connection it may be noted that a close binary has two orthogonal symmetry planes which are perpendicular to its equatorial plane. Viewed from its equatorial plane, however, such a binary would be expected to show a characteristic sinusoidal light variation unless it was immersed in an optically thick spheroidal envelope. On either a rotational or orbital hypothesis, the slowly varying component *B* presumably arises from an extended region—perhaps an equatorial belt which is produced as a result of emission from the active regions.

The present observations in themselves are inadequate to establish any model. It is hoped, however, that these speculations may focus attention on physical mechanisms which may be relevant. We do not know how many quasi-stellar objects are variable since no proper surveys have been made. Some type of variability has been established in about a dozen of these objects. In most cases this variability has a small amplitude and was detected photoelectrically (Sandage 1966*a*); such small amplitude variability may well be quite common. Large variations ($\Delta B > 1.0$ mag) seem less common, but fluctuations of the component *C* type could easily be missed unless a thorough survey were made. On a rotational hypothesis, we might expect that these large-amplitude fluctuations would only be seen if the equatorial plane of the object makes an angle of less than 10° or 20° with the line of sight. The only other objects known to us for which some kind of light curve is available are 3C 279 and 3C 446. The light curve of 3C 446 (the more complete of the two) is clearly more complex than that of 3C 345. It seems to us that these complexities are likely to be more readily interpreted on a rotational than a pulsational model.

The problem of the existence of periodicities in the radiation from quasi-stellar sources is important enough for a theoretical understanding of these objects to make it very worthwhile to continue these observations. Clearly, nightly observations covering several years are needed if one is to obtain useful light curves. The most practical way to achieve this is to use a photographic telescope (of say 24 to 40-inches aperture) in a good observing site and use it wholly for this purpose. In observatories where the climate is adequate, the demand on the observing time of even small existing telescopes is such that adequate coverage cannot be obtained with them; a special-purpose telescope is needed. The only alternative to this is to try to piece together observations from a number of instruments. The problem of obtaining adequate homogeneity both in the observation and reduction and of organizing a co-operative program is as yet unsolved.

The Carnegie Astrograph (with which most of the present observations were made and which was designed specifically for astrometric work) will shortly be devoted to taking second-epoch plates for the Lick proper-motion program. It will therefore not be possible to continue the present program with this instrument. If support is forthcoming, a limited continuation of the present work may be possible with the Lick 12-inch refractor.

We have been fortunate in the past years to have had unrestricted use of the Astrograph and we would like to thank Dr. S. Vasilevskis for this courtesy and for his general help. Our thanks are also due to Mr. J. Vollertsen for assistance in observing.

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