CEPHEIDS IN GALACTIC CLUSTERS. VII. S NOR AND NGC 6087*

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ABSTRACT

Photometric observations of the galactic cluster NGC 6087 and the associated 9.8-day cepheid S Nor are presented. A distance of 760 pc ($m-M = 9.4$ mag.) is derived, implying an average absolute magnitude $M_{\dot{V}} = -3.7$ for S Nor. The color excess is found to be constant across the cluster and has a value $E_{B-V} = 0.22$ mag., which gives the cepheid an average intrinsic color index of $(B-V) = 0.75$ mag. The age of the cluster is found to be about $1\text{–}2 \times 10^7$ years. Evidence is presented that the period of the cepheid may be increasing at a rate of about 5 seconds per year, and this is discussed as a possible evolutionary effect.

I. INTRODUCTION

S Nor was the first classical cepheid to be rediscovered in recent years as a member of a galactic cluster. The discovery was made by Irwin (1955), who first realized the importance of this fact for calibration of the period-luminosity relation, although the coincidence of S Nor and NGC 6087 had already been pointed out by ten Bruggencate (1927) and Gaposchkin (1945). In the months immediately following his discovery, Irwin observed both the cepheid and the cluster at the Cape and Radcliffe Observatories, but, because of the unavailability of an aluminized reflector, he was not able to observe the ultraviolet color (on the U, B, V, system) of the cepheid. Aluminized reflectors have since become available in South Africa, and it is principally in order to examine the ultraviolet color-curve of the cepheid that S Nor has been reobserved by the author.

II. THE OBSERVATIONS

The observations of the cepheid and some of the cluster stars were made with the 18-inch aluminized reflector of the Cape Observatory, associated with the usual photoelectric equipment (Cousins 1959). Tie-ins to the U, B, V system were made on two separate nights by observing U, B, V standard stars, and three comparison stars—GC 21837, GC 21876, GC 21894—were used when observing the cepheid. The cepheid results for each night are the means of between three and six observations, and the probable errors of these means are better than 0.01 mag. in all cases. The journal of cepheid observations is shown in Table 1. The phases have been computed from the elements given by Walraven, Müller, and Oosterhoff (1958), viz., Epoch of max.: JD 2434586.39 + 9.75418E. The phases are heliocentric.

The colors and magnitudes for most of the cluster stars were observed with the 24-inch refractor of the Cape Observatory, the photoelectric instrumentation for which has been described by Arp (1958). It is not possible to transform accurately the ultraviolet colors observed with this instrument into those of the U, B, V system, but the Cape observers have defined a refractor color $(U-B)_C$ (*Cape Mimeogram*, No. 5, 1958), which enables one to construct a color-color diagram and deduce E_{B-V} in the usual way. For the benefit of those observers not in possession of this mimeogram, the appropriate relations are listed in Table 2. The reddening line in this color-color plane has a slope $E_{(U-B)C}/E_{B-V} = 0.40$.

For the fainter stars, the photoelectric results have been supplemented by two-color photographic observations. Results are given in Table 3; identifications are given in Figure 1.

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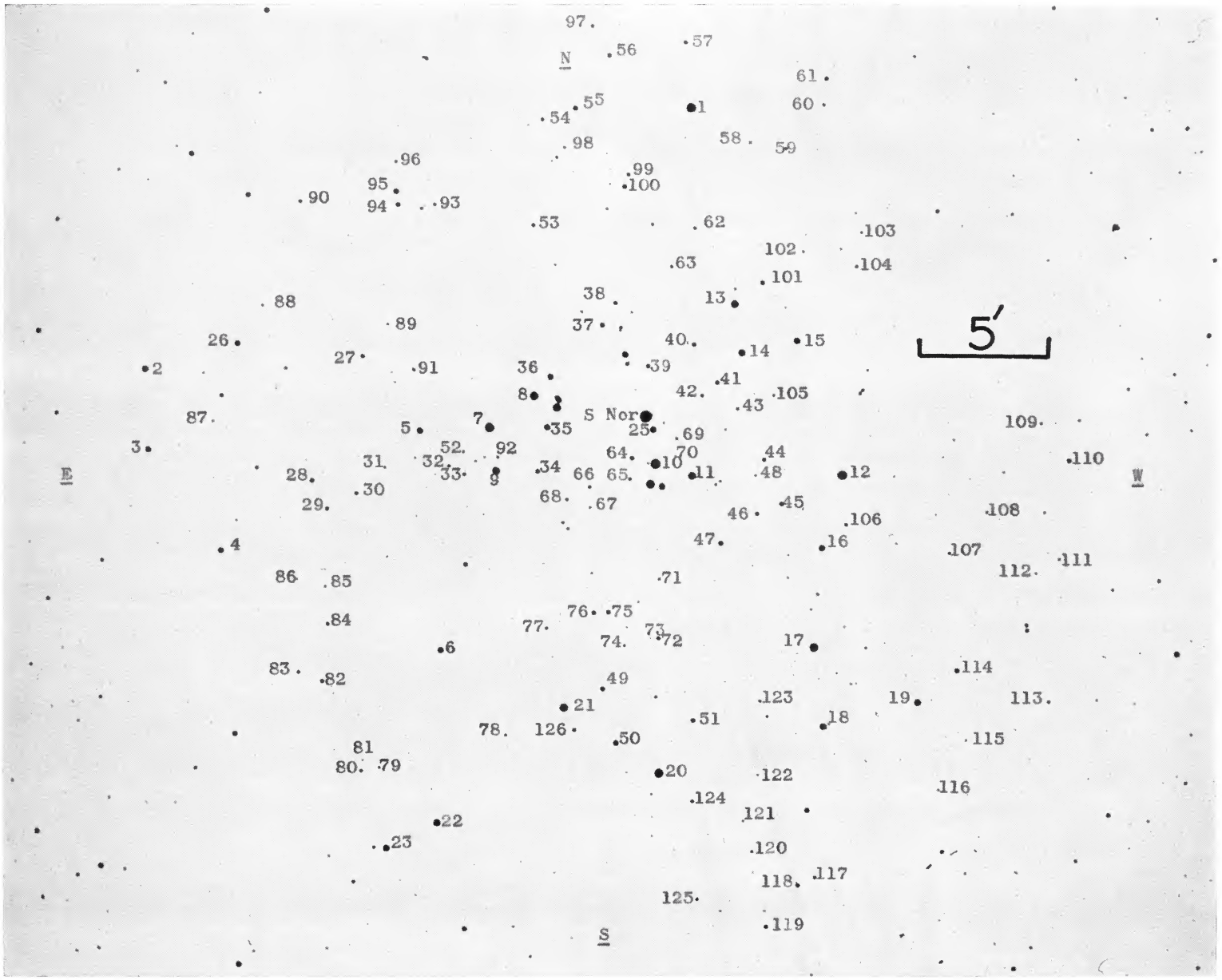

FIG. 1.—The galactic cluster NGC 6087. The original plate is blue-sensitive with a limiting magnitude of about 15.5. All numbered stars were measured either photoelectrically or photographically, but results are given only for those which are probable members of the cluster.

TABLE 1

JD 2436000+	Phase	V	$B-V$	$U-B$
806 405	0 596	6 73	1 10	0 80
807 405	699	6 50	0 98	57
812 304	201	6 27	0 94	58
813 322	306	6 45	1 07	76
816 269	608	6 71	1 11	78
818 240	810	6 30	0 88	52
819 244	.913	6 27	0 87	50
834 250	451	6 68	1 17	89
835.269	556	6 74	1 13	86
840 264	067	6 14	0 86	50
848 258	887	6 30	0 87	48
849.266	0.990	6 11	0 82	0 46

TABLE 2

$(B-V)$	$(U-B)_C$	$(B-V)$	$(U-B)_C$
−0 30	+1 07	+0 50	+1 62
− .20	+1 16	+0 60	+1 70
− .10	+1 31	+0 70	+1 80
00	+1.47	+0 80	+1 90
+ .10	+1 56	+0 90	+2 01
+ .20	+1 59	+1.00	+2 11
+ .30	+1 59	+1.10	+2 20
+0 40	+1 58	+1 20	+2 29

TABLE 3

Star	V	$(B-V)$	$(U-B)$ or $(U-B)_C$	Star	V	$(B-V)$	$(U-B)$ or $(U-B)_C$
1	8 34	0 06	+1 32	61	11 54	0 19	1 47
2	10 03	.07	+1 33	62	12 06	.30	1 55
4	10 47	09	+1 41	63	12 05	32	
5	10 29	.00	−0 35	64	11 39	18	1 43
6	10 39	05	+1 36	65	11 96	26	1 59
7	8 28	10	−0 35	66	11 98	.32	
8	8 97	06	−0 35	67	12 55	30	
9	9 41	09	−0 29	68	11 97	31	1 54
10	7 93	09	+1 34	69	12 08	35	1 56
11	9 40	08	+1.34	71	12 35	35	1 66
13	9 31	07	−0.40	74	12 16	32	
14	9 64	12	+1 39	75	11 24	18	
15	10 14	10	+1 36	77	12 30	36	
17	8 78	11	−0 28	79	12 39	.36	
18	9 90	19	+1 38	82	11 55	23	
19	9 88	11	+1 39	83	11 89	32	
20	8 45	08	−0 39	87	12 44	34	
22	9 69	10	+1 32	89	12 60	46	
23	9 82	05	+1 37	92	12 37	38	
25	9 69	15	−0 21	96	12 36	28	
28	11 30	13	+1 43	97	11 84	27	
29	11 49	21	+1 50	99	11 66	29	
32	12 06	31		103	12 30	37	
33	11 96	.28	+1 59	106	11 74	34	
38	11 40	.24	+1 56	109	11 29	19	
41	11.34	14	+1 47	111	12 43	39	
42	11 83	31	+1 60	115	12 72	.38	
46	11.39	31	+1 53	118	11.33	21	
57	11 59	0.19	+1 49	123	12 20	0 45	

Ultraviolet indices with values less than unity are on the U, B, V system; those with values greater than unity are on the Cape refractor system. Those stars for which no ultraviolet color is given have been observed only photographically in B and V. Results are given only for those stars which are probable members of NGC 6087 (as judged by their position on the color-magnitude array).

There seems no evidence for differential reddening in the cluster, and the following absorption corrections are deduced: $E_{B-V} = 0.22$, $A_V = 0.67$, $E_{U-B} = 0.16$ ($= 0.73E_{B-V}$), which agrees well with Irwin's (unpublished) determination of $E_{B-V} = 0.21$. These corrections are applicable to the cepheid, since it is situated near the optical center of the cluster and its physical membership in the cluster has been confirmed by the radial-velocity measurements of Feast (1957).

The color-magnitude diagram, corrected for effects of absorption, is shown in Figure 2. In it, Sandage's (1957) age-zero main sequence is shown displaced by 9.36 mag. I take the distance modulus to be 9.4 $\pm$ 0.1 mag., which again is consistent with Irwin's (unpublished) value of 9.5 mag. Furthermore, it is seen from this diagram that NGC 6087 is in a stage of evolution similar to, although perhaps slightly less advanced than, the Pleiades. Its age is therefore probably about 1–2 $\times$ 10^7 years (Mitchell and Johnson 1957).

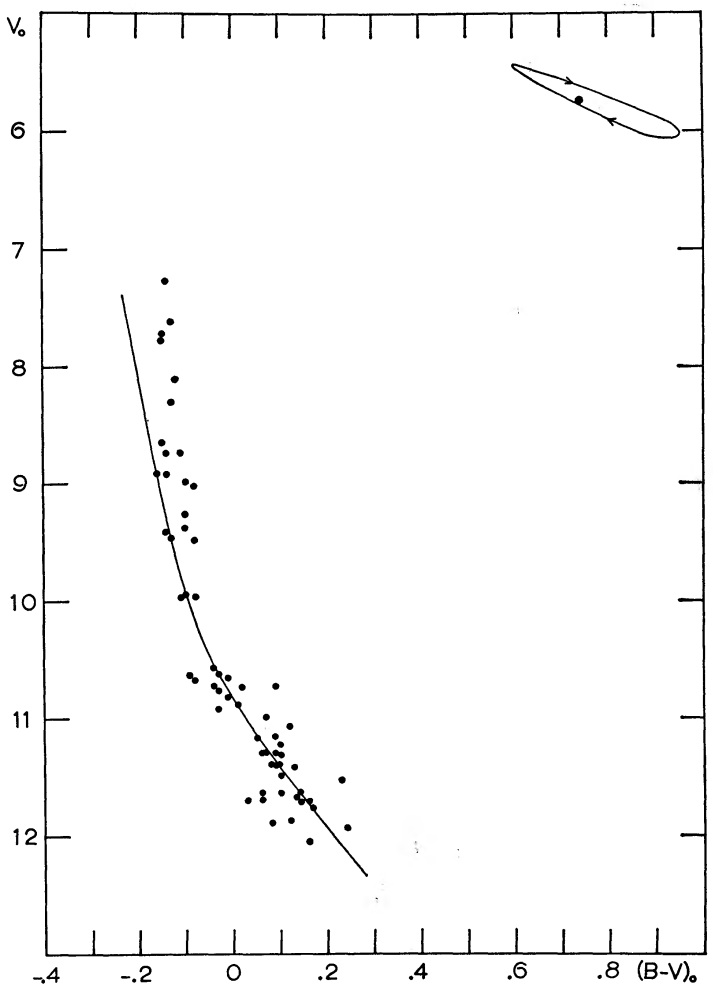

FIG. 2.—The color-magnitude diagram for NGC 6087, corrected for effects of interstellar absorption. The loop shows the cyclic variation of S Nor and the filled circle within the loop the average position of S Nor. The age-zero main sequence is shown displaced by 9.4 mag.

III. DISCUSSION

The light- and color-curves of the cepheid are shown in Figure 3. The shape of the light-curve is approximately what one would expect for a cepheid of this period, although it is perhaps even more typical of cepheids of slightly shorter period. The Eggen type (Eggen, Gascoigne, and Burr 1957) is C, since maximum follows minimum by $0^{p}44$.

It seemed that maximum light for the present series of observations did not fall exactly at the predicted times, indicating that the period quoted above was not quite correct. A new derivation, using the epoch of maximum given by Walraven, Müller, and

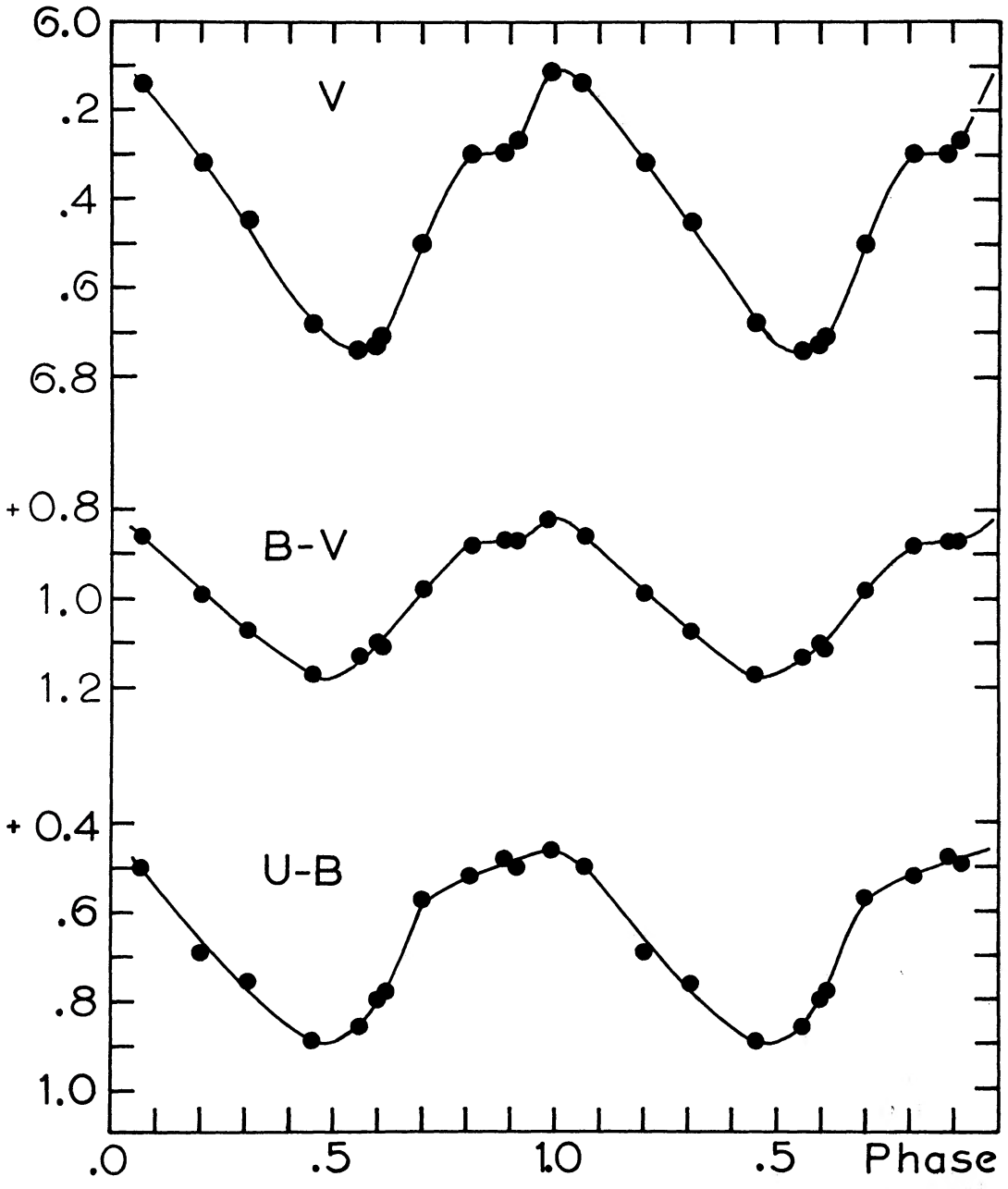

FIG 3.—Light- and color-curves for S Nor, uncorrected for reddening

Oosterhoff (1958) and a present epoch of maximum at JD 2436849.51 gave the value $P = 9^d75483 \pm 0^d00022$. It is interesting to note that there is slight evidence that the period of S Nor is steadily increasing. Previous determinations of the period are listed in Table 4. Ten Bruggencate's determination has been ignored here, partly because he employed an unusual method and partly because the result shows such a large discrepancy with the other determinations. Of course, all these determinations have fairly large probable errors, but, taken at their face values, they do show a linear trend (shown in Fig. 4), implying a rate of increase in the period of about 5 seconds per year. We return to this later.

TABLE 4

Observer	Period	Approx. Epoch	Reference
Roberts	9d7525	1915::	Ten Bruggencate (1927)
Ten Bruggencate	98 (?)	1926	Ten Bruggencate (1927)
Shapley	296	1927::	Shapley (1930)
Walraven, Müller, and Oosterhoff	418	1953	Walraven, Müller, and Oosterhoff (1958)
Fernie	483	1956	

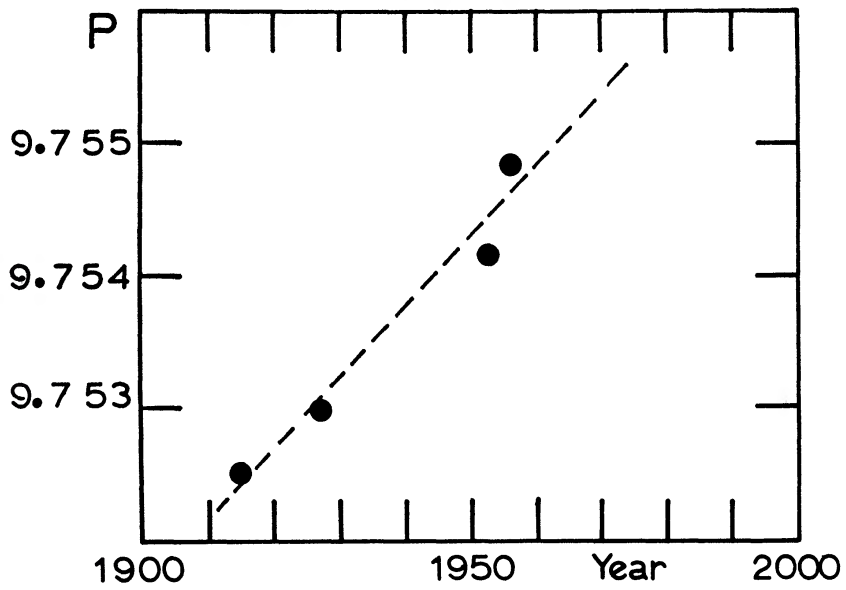

FIG. 4.—Possible variation in the period of S Nor

With the colors corrected for reddening, the motion of the cepheid on the color-color plot is shown in Figure 5. The dotted lines illustrate the position of the dwarf and supergiant sequences (Johnson and Morgan 1953) in this diagram. It is interesting to note that, as the cepheid approaches minimum light, its colors are very nearly those of normal supergiants (indeed, considering the uncertainty in the colors of the latter, S Nor may have exactly the colors of a normal supergiant), while near maximum light the colors are quite abnormal compared with the stable supergiants. This is to be expected, since the spectra of cepheids are most normal near minimum light and become increasingly abnormal toward maximum light. But it is perhaps unexpected that the cepheid should imitate the colors of dwarf stars in its postminimum phases.

With a distance modulus of 9.4 mag., the average absolute magnitude (obtained by planimetering the light-curve expressed in intensity units) of S Nor is

$$M_V = -3.7\,, \qquad M_B = -3.0\,.$$

If the apparent increase in the period of S Nor is real, it may be an evolutionary effect. Consider an equation due to Sandage (1958):

$$\log P - 1.051\,(B - V) + 0.239\,M_V = \text{Const}\,.$$

If the star evolves horizontally across the color-magnitude array, we may rewrite this as

$$\log P = 1.051\,(B - V) = \text{Const}\,.$$

Differentiating with respect to time, we get

$$\frac{1}{P}\frac{dP}{dt} = 1.051\,\frac{d}{dt}(B - V)\,.$$

Substituting the period and rate of change of period found earlier, we find

$$\frac{d}{dt}(B - V) \sim 6 \times 10^{-6}\ \text{mag/year}\,.$$

From its present position in the cepheid instability strip on the H-R diagram (Sandage 1958), S Nor appears to have covered about 0.13 mag. in $(B - V)$ since entering the strip. If it is assumed that the above rate is constant across the strip, then S Nor has been

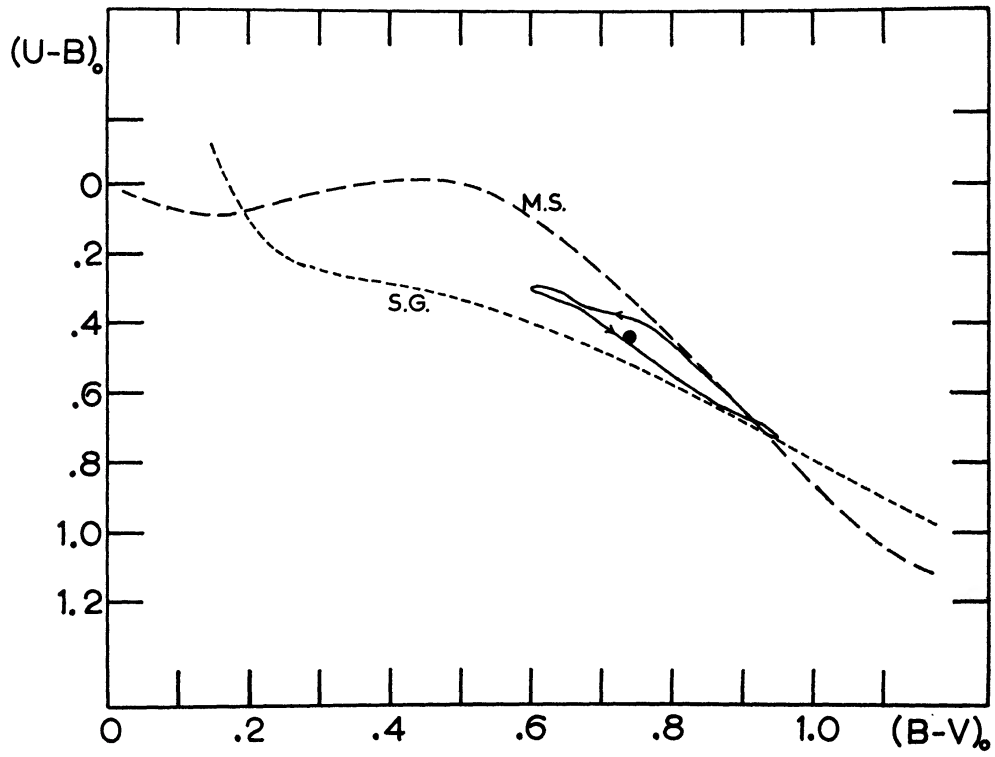

FIG. 5.—Position of S Nor on the intrinsic color-color plot. The solid line shows the variation of S Nor, and the two dotted lines show the dwarf and supergiant sequences. The filled circle indicates the average colors of S Nor.

a cepheid for some 2×10^4 years, or about 10^{-3} of its present age, indicating the rapidity with which stars traverse the Hertzsprung gap. However, it must be emphasized that the magnitude of the period increase is uncertain and could conceivably be zero, while the interpretation of the effect as an evolutionary one is purely an assumption.

IV. SUMMARY

S Nor:

	Max.	Min	Median	Average	Amplitude
V_0 ..	5 44	6 07	5 76	5 74	0 63
$(B-V)_0$	+0 61	+0 96	+0 79	+0 75*	35
$(U-B)_0$	+0 30	+0 74	+0.52	+0 45†	0 44

*In the sense $(\bar{B}_0 - \bar{V}_0)$
†In the sense $(\bar{U}_0 - \bar{B}_0)$

$$A_V = 0.67\,, \qquad E_{B-V} = 0.22\,, \qquad E_{U-B} = 0.16\,.$$

$$\text{Distance} = 760\ \text{pc}, \qquad (m - M) = 9.4 \pm 0.1\,.$$

$$M_{\dot{V}} = -3.7\,, \qquad M_{\dot{B}} = -3.0\,.$$

$$(\text{Phase})_{\max} - (\text{Phase})_{\min} = 0.44\,.$$

Eggen type: C (1957 scheme).

Revised elements:

$$\text{Max. visual light; JD } 2436849.51 + 9.75494E\ (+0.0000015E^2)$$

I am indebted to Her Majesty's Astronomer for permission to use the instruments of the Cape Observatory and also to certain of his staff for making some of the observations and measurements for me. I am also indebted to Dr. John B. Irwin for permission to quote his unpublished results on NGC 6087.

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