PHOTOELECTRIC PHOTOMETRY OF HD 116994*

Kwan-Yu Chen

Department of Physics and Astronomy
University of Florida

and

Cerro Tololo Inter-American Observatory**

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ABSTRACT

From observations on three nights, the period of HD 116994 was found to be 0.1022623 day. Harmonic analyses were made of the light curves and color curves. The observed mean color indices are: B-V = +0.393 and U-B = +0.137. The intrinsic color indices are found to be: $(B-V)_0$ = +0.270 and $(U-B)_0$ = +0.048. Pulsation theory yields $\rho = 0.103\ \rho_\odot$, and $R = 1.4\ R_\odot$. The absolute visual magnitude is estimated to be +2.0, which seems realistic in view of the interstellar reddening and the predictions of the pulsation theory.

I. INTRODUCTION

The star HD 116994 (A5) = SAO 240869, initially chosen as a comparison star for observing BV 513, was found to be a variable at Cerro Tololo Inter-American Observatory on April 26-27, 1966. It was then systematically observed on the following two nights and again on May 2-3 with HD 118014 (A0) = SAO 240975 as the comparison star. The apparent visual magnitude is listed as 8.7 for both stars in the Smithsonian Astrophysical Observatory Star Catalog.

II. OBSERVATIONS AND REDUCTION OF DATA

Observational data in three color-regions, uby, were obtained from a photometer with standard UBV filters attached to the No. 1 16-inch telescope. An integrating amplifier was used, with the integrating time set at 20 sec. Each night, observations of the comparison star yielded the atmospheric extinction coefficients and the variations of colors as linear functions of air mass. These values were applied in the reduction of the observed data. The values of the difference in magnitude between the variable star and the comparison star, Δm = m(var.) - m(comp.), corrected for differential atmospheric extinction, together with the time of variable star observation, are listed in Tables 1, 2, and 3 for y, b, and u respectively.

Van den Bergh (1967) determined the transformation equations to the UBV system for the observational system used in his photometry of globular clusters. These equations,

$$B-V = 0.998\ (b-y) - 0.756 \text{ and}$$

$$U-B = 1.005\ (u-b) - 0.985,$$

were also used in this investigation, since the same observational system was used by both authors. The observed color indices, B-V and U-B, of the variable star, corrected for atmospheric extinction, are listed in Table 4.

III. LIGHT AND COLOR VARIATIONS

The variations of Δm, as well as B-V and U-B, are plotted in Figures 1, 2, and 3, each of which is for a different day. The relation,

$$\Delta m = A_0 + \sum_{n=1}^{2} \left[A_n \sin n(2\pi t/P_1 + \varphi_n) + B_n \sin n(2\pi t/P_2 + \psi_n) \right],$$

was used to analyze each light curve. For convenience, t was chosen to be the heliocentric Julian Date minus 2439243.0. The parameters, including the period, P, were determined by using an iterational least-square method, and the result is listed in Table 5. The variations of the color indices are represented by a truncated Fourier series,

$$\sum_{n=0}^{4} \left[a_n \cos\ (2n\pi t/P) + b_n \sin\ (2n\pi t/P) \right],$$

where P is 0.1022623 day, the average value of P_1. The coefficients a and b and their probable errors are listed in Table 6.

IV. INTERSTELLAR REDDENING

The discrepancy between the observed color index and the Henry Draper spectral type of the star suggests that there is interstellar absorption.

The intrinsic color indices of HD 116994 ($\ell^{II} = 297^{\circ}20'.8$, $b^{II} = 11^{\circ}10'.2$) were obtained from the relation between the color difference, Q, and the color index, $(B-V)_0$, in the UBV system for stars of luminosity class V given by Becker (1963). The relation between the color excesses,

$$E_{(U-B)} = 0.72\, E_{(B-V)} + 0.05\, E^2_{(B-V)},$$

was also used. The values obtained are: $(B-V)_0 = +0.270$ and $(U-B)_0 = +0.048$. This consideration seems to give an upper limit for the color excess, $E_{(B-V)} = 0.12$.

If HD 118014 ($\ell^{II} = 296^{\circ}29'.7$, $b^{II} = 9^{\circ}39'.6$) is considered to be an AO II star, the values $(B-V)_0 = +0.01$, $(U-B)_0 = (-0.06)$, and $Q = (-0.07)$, given by Johnson (1958), can be applied. The observed color indices, B-V = +0.123 and U-B = -0.029, give the calculated value of -0.062 for Q, which agrees with the quoted value. The value of $E_{(B-V)}$ for this star is the same as that for the variable star.

Color indices of these two stars are plotted in Figure 4.

V. DISCUSSION

The period P_1, determined in Sec. III, may be considered to be the period of basic oscillation. The three values of P_2, independently determined from the three light curves, are very similar, although the coefficients for the terms involving P_2 are small. Hence P_2 is considered to be the period of modulation. The ratio of the first overtone period to the fundamental period is found to be 0.768, using the average values 0.1022623 and 0.33826 for P_1 and P_2, respectively. Comparing this with the short-period variables with two periods given by Christy (1966), the pulsation constant of the

fundamental mode, Q_0, has a value of 0.0328. This establishes the value of the mean density, ρ, of HD 116994 as 0.103 $\rho_\odot$. Using the formula

$$Q_0 \cong 0.022 \ (R/R_\odot)^{1/4}(M_\odot/M)^{1/4}$$

of Christy, the radius, R, is found to be 1.4 $R_\odot$, and the mass, M, then would be 0.28 $M_\odot$, giving a surface gravity, g, of 0.14 $g_\odot$. Also, from Christy's instability strip in the log g-log T_e plane, the boundary values for the effective temperature, T_e, are found to be approximately 6500 and 8060 at log g = 3.59. Together with the radius, the higher temperature gives M_{bol} = +2.4, while the lower temperature gives M_{bol} = +3.4.

McNamara (1965) gave the relation

$$(B-V)_{median} = +0.23 \log P + 0.473$$

for dwarf Cepheids, from which a value of 0.245 was obtained with the observed P_1. The value of $(B-V)_0$, obtained in Sec. IV, agrees with this computed $(B-V)_{med.}$. If this variable is considered to be dwarf Cepheid, the absolute visual magnitude, M_v, can be determined to be 3.4 from the relation,

$$M_v = -3.33 \log P + 2.96 \ (B-V) - 1.66 \log (M/M_\odot) + 3.33 \log Q + 3.34,$$

also given by McNamara. However, this absolute magnitude, combined with the apparent magnitude and the interstellar absorption, $A_V = 3 \ E_{(B-V)}$, gives a distance of the order of 100 parsecs. It is difficult to believe that there would be this amount of interstellar absorption within such a distance. Unless there is very little reddening of this star, it is most probable that M_V = +2.0 which would place the star at a distance of 185 parsecs.

The situation regarding reddening might be realistic in this case if it is compared with the region of the Coalsack ($\ell^{II} = 304^{o}$, $b^{II} = 0^{o}$), in which the photographic absorption ranges from 0.7 to 2.4 at a distance of 174 parsecs (Rodgers 1960). Besides the above problem with the absolute magnitude and reddening if this star is considered to be a dwarf Cepheid, it is also pointed out in the literature that the amplitudes of the light variations in dwarf Cepheids are normally of the order of 0.5 mag and larger, as compared with only 0.2 mag for this star.

On the other hand, Danziger and Dickens (1967) gave data for sixteen δ Scuti stars, of which three are listed as spectral type A with values of B-V of 0.25, 0.30, and 0.20. The analysis of the light curves of HD 116994 can also be compared with those for five δ Scuti stars represented by Leung and Wehlau (1967) in the form,

$$\Delta m = \Sigma_i \, a_i \cos (\omega_i t + \varphi_i) \, .$$

Two points of difference can be noted from the comparison of the coefficients in the two investigations: (1) the amplitudes of the variations corresponding to the period of basic oscillation are larger for HD 116994; and (2), the amplitudes corresponding to the period of modulation are much larger for the δ Scuti stars.

Finally, a comparison with ρ Pup (F6 II), a δ Scuti variable with a period of 0.141 day, can be made. Ponsen (1963) investigated ρ Pup and found a near-sinusoidal blue light curve with an amplitude of 0.127 mag, and a (B-V) curve with an amplitude of 0.03 mag which is similar in shape to that of HD 116994. No secondary period was found for ρ Pup, although Ponsen found that its individual light curves seem to show small systematic deviations from the mean curve. Danziger and Kuhi (1966) found the amplitude

of light variation (4566 Å) to be 0.15 mag. A linear relation between θ_e and (B-V) is not apparent from the comparison of their θ_e curve with Ponsen's (B-V) curve.

In view of the lack of accurate spectroscopic work on HD 116994, the question of whether this star is a δ Scuti variable or a dwarf Cepheid cannot be answered definitely at this time. However, from the similarity of this star and ρ Pup, it is suggested that HD 116994 could be a counterpart of ρ Pup but of earlier spectral type. In this case, the absolute magnitude of HD 116994 might well be of the order of +0.5, which gives a distance of 370 parsecs. This would probably account successfully for the reddening, but, like ρ Pup, it would not fit neatly in the picture of present pulsation theory.

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TABLE 5

PARAMETERS FOR Δm

	A_0	P_1 (day)	A_1	φ_1 (rad)	A_2	φ_2 (rad)	P_2 (day)	B_1	ψ_1 (rad)	B_2	ψ_2 (rad)	Standard Error
y	0.1071	0.1022698	- 0.0851	5.6449	- 0.0202	5.3185	0.33653	- 0.0065	2.4951	0.0019	5.0263	0.0184
b	0.3776	0.1022667	- 0.1106	5.7058	0.0286	- 2.6137	0.34264	- 0.0018	3.8078	0.0052	- 2.3525	0.0208
u	0.5451	0.1022505	- 0.1001	5.7075	0.0248	- 2.4944	0.33562	- 0.0066	- 3.6265	- 0.0019	- 4.3053	0.0242

TABLE 6

FOURIER COEFFICIENTS FOR COLOR INDICES

	a_0	a_1	a_2	a_3	a_4	b_1	b_2	b_3	b_4
B-V	0.3934	0.0091	0.0043	- 0.0001	0.0007	- 0.0232	0.0047	0.0011	- 0.0006
	±.0008	±.0011	±.0011	±.0011	±.0012	±.0011	±.0011	±.0011	±.0011
U-B	0.1367	- 0.0125	- 0.0010	0.0000	- 0.0007	0.0064	- 0.0062	- 0.0005	- 0.0028
	±.0011	±.0015	±.0015	±.0016	±.0015	±.0015	±.0015	±.0015	±.0015

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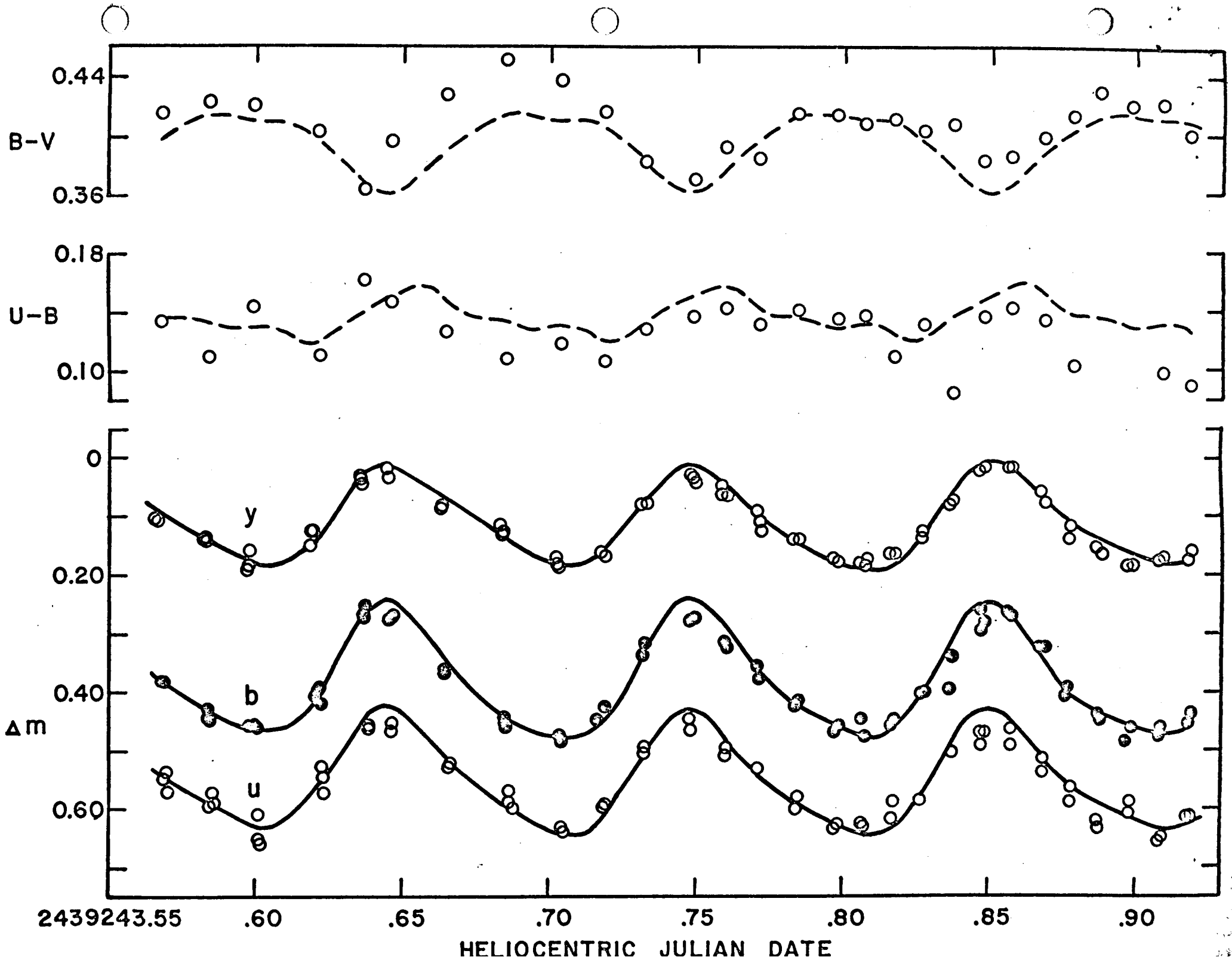
FIGURE LEGENDS

Fig. 1 Light and color variations of HD 116994 on April 27-28, 1966, with computed curves.

Fig. 2 Light and color variations of HD 116994 on April 28-29, 1966, with computed curves.

Fig. 3 Light and color variations of HD 116994 on May 2-3, 1966, with computed curves.

Fig. 4 Plot of observed color indices of HD 116994 and HD 118014; dashed lines indicate the reddening lines, and the dotted curve is the computed path of the variations of color indices for the variable star.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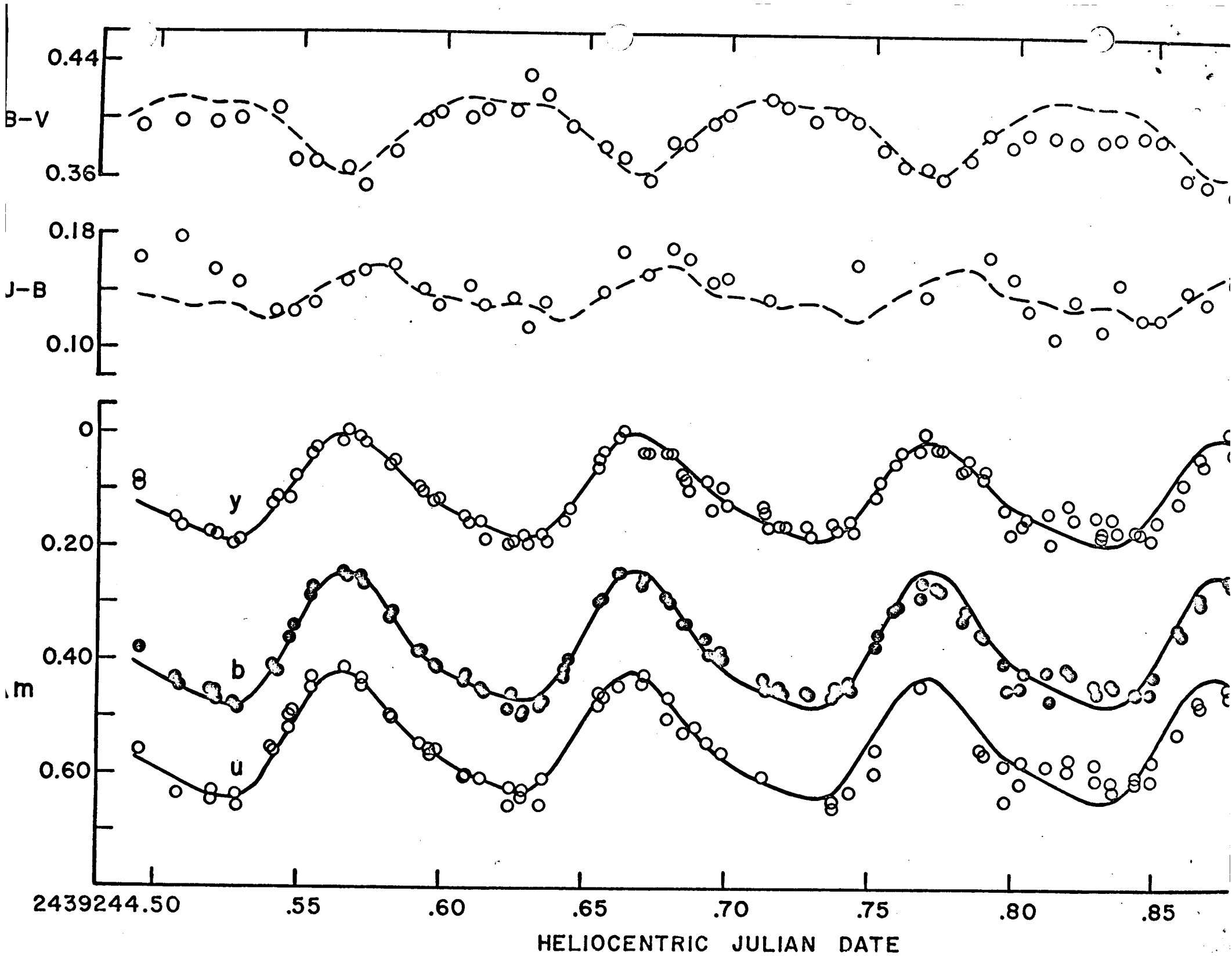
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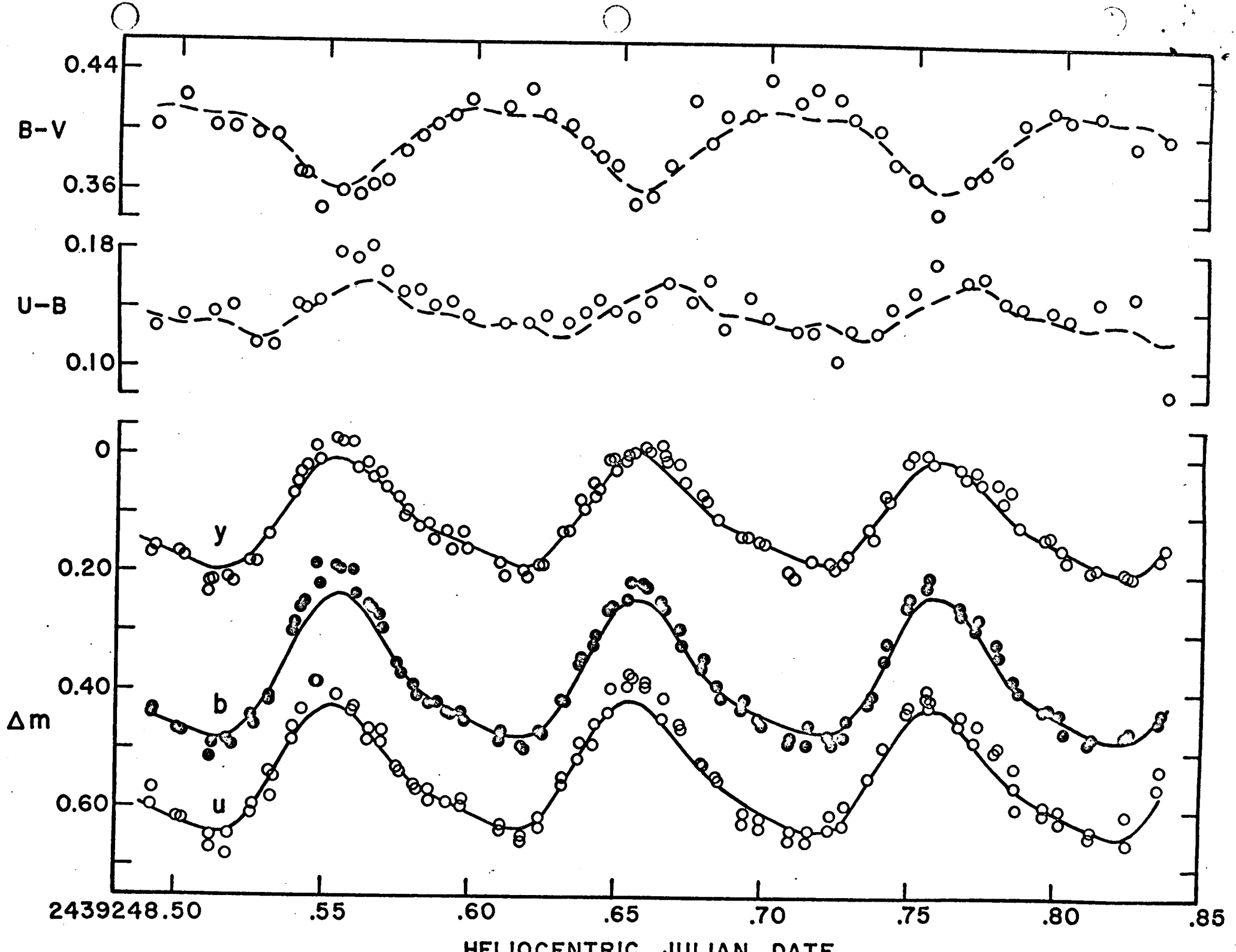
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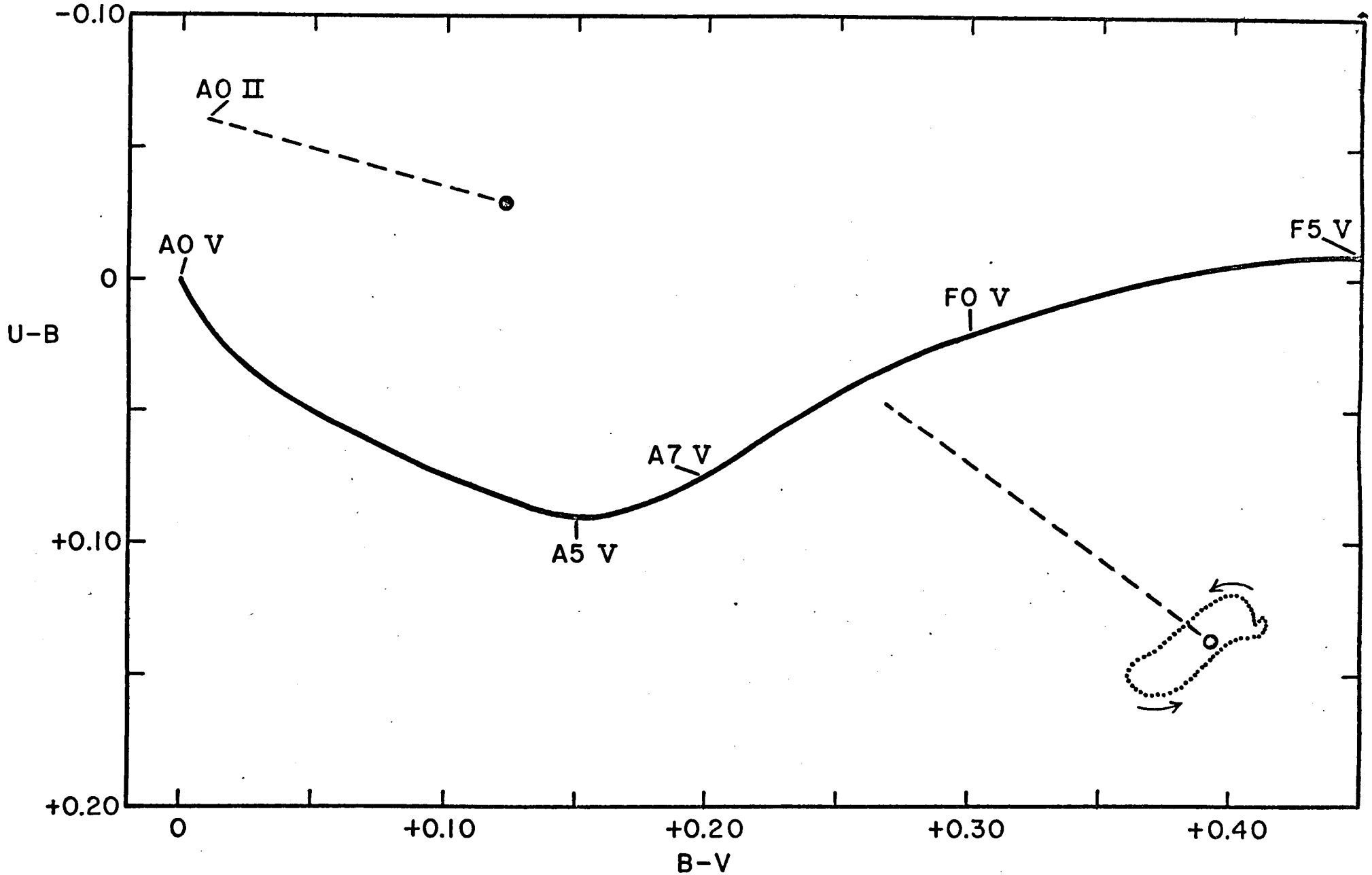
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