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GROUND BASED PHOTOMETRY OF POTENTIAL NAVIGATION GUIDE STARS

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ABSTRACT

There is a current need in space astronomy to calibrate accurately the magnitude of the brighter stars used as navigation guide stars in unfiltered tracking systems. In the past, these magnitudes have always been computed from observed narrow-band data, because there have been few direct observations with these systems.

Photoelectric observations of bright stars have been made using the Lunar and Planetary Laboratory 21-inch telescope and a calibrated 1P21 phototube, unfiltered. The magnitude observed is designated [m(S-4)] to indicate that an (S-4) photosurface (1P21 phototube) was used. Calibration curves of [m(S-4) - V] versus (B-V) were derived separately for the supergiant, giant, and subgiant stars, where B and V are the blue and visual photoelectric magnitudes. The curves for the supergiants and giants in the region $+0.1 < (B-V) < +1.2$ are similar and quite linear, while they differ by $\Delta[m(S-4) - V] \simeq 0.15$ mag for $-0.3 < (B-V) < +0.1$. Theoretical investigations show that the (S-4) magnitude of a given star will vary for different 1P21 phototubes. It is concluded that calibration curves must be derived separately for stars of different luminosity classes for each detector system of interest.

A preliminary investigation has confirmed the validity of both the Goddard Space Flight Center m[S-4] computer program and the OAO-A2 guide star list.

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INTRODUCTION

There is a current need in space astronomy for stellar calibration curves for the brighter navigational stars in terms of the detector system. To date a few stars have been observed by using star trackers on Aerobee rocket flights, and on the Mariner, Surveyor, and Orbiter spacecraft. In the past, the calibration curves for broad-band systems, such as an unfiltered 1P21 phototube, have been computed from observational filter-band data. In order to check these theoretical calculations, an observational photometric program was attempted at a high altitude observatory using a calibrated 1P21 phototube. A preliminary report has already been published (Ref. 1). A complete reduction of all the data is given in the present report.

DISCUSSION

Photoelectric observations on stars brighter than 3.0 visual magnitude (V) were obtained using the 21-inch telescope of the Lunar and Planetary Laboratory, University of Arizona, in May and October 1967. Because of the relatively poor observing conditions in May, which were evidenced by large atmospheric extinction values, only the October data is considered here.

Thirty stars were measured on the nights of October 12/13, 14/15, 15/16, and 16/17, 1967, using an unrefrigerated 1P21 photomultiplier tube (HR 145) operated at 700 volts. No filter was used, and the field of view at the telescope focal plane was diaphragmed to one minute of arc. The phototube spectral response was measured with the NBS Photodetector Spectral Response Console at Grumman Aircraft Engineering Corporation on September 18, 1967. This response is presented in Table I and includes the effect of the two aluminum-coated telescope mirrors.

The standard operating procedure was to observe star plus sky for 15 seconds, then sky for 15 seconds, and to repeat the observations at least twice. A calibration lamp was observed for each star observation to monitor the absolute sensitivity of the system, and all data were recorded automatically on punch tape. The time at both the beginning and end of each observation was recorded, as were the amplifier gains. The magnitude observed is designated [m(S-4)] to indicate that an (S-4) photosurface (1P21 phototube) was used. The magnitude for a given star observed through air mass X can be written as:

$$[m(S\text{-}4)]_X = (G_{star} - G_{lamp}) - 2.5 \log_{10} \left[\frac{(I_{star+sky} - I_{sky})}{(I_{lamp} - I_{dark})} \right], \quad (1)$$

where

G_{star}	is the gain used for the star measurement,
G_{lamp}	is the gain used for the calibration lamp measurement,
$I_{star+sky}$	is the measured intensity of the star+sky,
I_{sky}	is the measured intensity of the sky alone,
I_{lamp}	is the measured intensity of the calibration lamp, and
I_{dark}	is the measured intensity of the dark current.

The stellar magnitude at the top of the atmosphere is given by

$$[m(S-4)]_0 = [m(S-4)]_X - k_{(S-4)}X \qquad (2)$$

where $k_{(S-4)}$ is the total atmospheric extinction coefficient. The air mass X is given by

$$X = \sec Z - 0.0018167(\sec Z-1) - 0.002875(\sec Z-1)^2 - 0.0008083(\sec Z-1)^3 \qquad (3)$$

and

$$\sec Z = (\sin \varphi \sin \delta + \cos \varphi \cos \delta \cos h)^{-1} , \qquad (4)$$

where

φ is the latitude of the telescope (32° 25' 0".8 N),

δ is the declination of the star, and

h is the hour angle of the star at the time of observation.

The expression for the air mass, Eq. (3), comes from Hardie (Ref. 2). It agrees with the expressions used by Young and Irvine (Ref. 3) and Mitchell (private communication) to within 0.01 for

$X \leq 3.0$ and to within 0.02 for $X \leq 4.0$. A given star is observed at different air masses and a least-squares fit is made to Eq. (2) to derive $k_{(S-4)}$. Figure 1 presents the results for the night of October 12/13, 1967, where the values of $k_{(S-4)}$, determined for 19 stars, are plotted against the (U-B) color (Ref. 4). The (U-B) color was used as the abscissa rather than (B-V) in order to achieve a smoother relation. The quantities U, B, and V are the ultraviolet, blue, and visual photoelectric magnitudes. The curve in Fig. 1 represents the mean extinction for the night, and is used to derive $k_{(S-4)}$ values for those stars either observed only once or with poorly determined extinction values. It can be seen that $k_{(S-4)}$ varies smoothly with stellar color, and reaches a maximum value of 0.32 for stars of earliest spectral class $[(U-B) \sim -1.0]$.

The zero point for the (S-4) magnitude system, $[m(S-4)] = 0$, is defined for α Lyrae (Vega). Values of $[m(S-4)]_0$ are determined separately for each night, and a final mean value, weighted by the number of nightly observations, is calculated. Table II presents the results for the 30 stars observed in October 1967. The stars are listed by their bright star numbers (B.S.) given in Ref. 5. The weighted probable errors (p.e.) are also given, along with the total number of observations (n) for each star. The mean probable error is ± 0.01 mag, with the maximum being ± 0.03 mag. Three stars (B.S. 1017, 2294, and 2491) were observed on only one night, and the p.e. values are estimated as an upper limit. The UBV and spectral classification (Sp) data are from Johnson et al. (Ref. 4).

A color index $[m(S-4) - V]$ is now derived for each star. Figure 2 shows the observed stellar calibration curves for supergiants (Ia, b), giants (II and III), and subgiants (IV and V);

the data was obtained by using an unfiltered 1P21 photomultiplier tube (HR 145). The supergiants and giants follow the same linear curve in the region $+0.1 < (B-V) < +1.2$. This is not surprising since the effective wavelengths of $[m(S-4)]$ and the B magnitude are within 200 Å of each other. The subgiant stars in the region $+0.1 < (B-V) < +0.5$ are brighter in the ultraviolet ($\lambda < 3650$ Å) than the supergiants, and this results in a more negative (bluer) color index $[m(S-4) - V]$, that places the subgiant curve above the supergiant curve. This situation is reversed in the region $-0.3 < (B-V) < +0.1$, where the subgiant and giant stars are fainter than the supergiants in the ultraviolet. This produces a separation between the two curves of $\Delta[m(S-4) - V] \simeq 0.15$ mag for a given $(B-V)$.

It should be mentioned that the data of Fig. 2 have not been corrected for the effect of interstellar reddening. As most supergiants and giants are reddened to some degree, the calibration curves should be considered as only approximate in the region $-0.3 < (B-V) < +0.1$. A highly reddened star with observed $(B-V) = -0.1$ will not have the same $[m(S-4) - V]$ value as an unreddened star with the same value of $(B-V)$. Space reddening has little effect on the stars in the region $+0.1 < (B-V) < +1.2$ as evidenced by linearity of the calibration curve.

The photomultiplier tube used in this study to obtain the stellar data has a "blue shifted" spectral response relative to normal 1P21 phototubes. Calculations made using the measured stellar energy distributions of Kharitonov (Ref. 6) and Kharitonov and Knyazeva (Ref. 7) have indicated that the bluest stars will appear up to 0.15 mag brighter, and the reddest stars 0.20 mag fainter when observed with phototubes with a "normal" response than when observed with the "blue shifted" phototube HR 145. (The zero point for all magnitude systems is normalized to α Lyrae.) These magnitude differences should be considered as only approximate, because extremely "red shifted" or "blue shifted" 1P21 tubes will produce even larger magnitude differences when compared to "normal" 1P21's (L. Draper, private communication).

A preliminary investigation, using the observed data in the present report and Kharitonov's measured stellar curves, has shown that all of the stars in the OAO-A2 guide star list are indeed brighter than 2.0 mag [m(S-4)] for every OAO star tracker. This is the specified guide star limiting magnitude. While this does not preclude the addition of a few more stars, it does confirm the validity of the Goddard Space Flight Center [m(S-4)] computer program.

CONCLUSIONS

It is concluded that the conversion between magnitude systems such as the UBV and [m(S-4] systems must be handled with care. The calibration must be obtained either by direct observation or from theoretical considerations for each detector system of interest. The differences between the spectral responses in a given generic family of phototubes can produce magnitude differences of up to several tenths for a given star. A calibration curve must be derived separately for the supergiant, giant, and subgiant stars, as differences of up to 0.15 mag can exist between these stars for a given (B-V).

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Table I

SPECTRAL RESPONSE DATA FOR

PROGRAM 1P21 PHOTOTUBE (HR 145)

λ(Å)	R†	λ(Å)	R†
3000	0	56	58.7
31	5.9	57	51.1
32	19.6	58	43.6
33	32.5	59	31.1
34	44.7	6000	17.7
35	56.1	61	9.2
36	66.4	62	4.8
37	75.4	63	2.8
38	82.2	64	1.6
39	88.3	65	1.1
4000	93.1	66	0.7
41	96.8	67	0.4
42	98.2	68	0.2
43	99.2	69	0.2
44	100.0	7000	0.1
45	99.9	71	0.1
46	99.4	72	0
47	98.4	73	0
48	97.0	74	0
49	95.4	75	0
5000	94.2		
51	91.8		
52	87.5		
53	81.2		
54	73.8		
55	66.2		

†Response includes effect of two aluminum-coated telescope mirrors.

Table II

[m(S-4)] OBSERVATIONS OF BRIGHT STARS

B.S.	Name	[m(S-4)]	p.e.	n	V	(B-V)	(U-B)	Sp	
15	ALF AND	1.85	0.03	5	2.06	-0.11	-0.47	B9p	(III)
911	ALF CET	3.50	.01	3	2.53	1.64	1.93	M2	III
1017	ALF PER	2.11	(.02)†	1	1.79	0.48	0.39	F5	Ib
1231	GAM ERI	3.93	.01	4	2.94	1.60	1.98	MO	III
1457	ALF TAU	1.83	.01	5	0.86	1.54	1.92	K5	III
1708	ALF AUR	0.54	.03	5	0.08	0.80	0.45	G8	III + F
1713	BET ORI	-0.06	.01	5	0.13	-0.03	-0.65	B8	Ia
1790	GAM ORI	1.17	.01	5	1.64	-0.22	-0.88	B2	III
1791	BET TAU	1.44	.01	5	1.65	-0.13	-0.49	B7	III
1829	BET LEP	3.40	.01	5	2.84	0.82	0.47	G5	III
2004	KAP ORI	1.61	.03	5	2.05	-0.18	-1.02	BO.5	Ia
2294	BET CMA	1.48	(.02)†	1	1.97	-0.24	-0.96	B1	II-III
2421	GAM GEM	1.89	.01	5	1.92	0.00	0.05	AO	IV
2491	ALF CMA	-1.53	(.02)†	2	-1.46	0.00	-0.05	A1	V
2890	ALF GEM	1.54	.01	6	1.58	0.04	0.01	A1	V + Am
2943	ALF CMI	0.58	.01	2	0.37	0.42	0.03	F5	IV-V
6603	BET OPH	3.55	.01	3	2.77	1.17	1.24	K2	III
6705	GAM DRA	3.21	0.01	3	2.22	1.52	1.88	K5	III

†probable error estimated as an upper limit

Table II (Cont.)

B.S.	Name	[m(S-4)]	p.e.	n	V	(B-V)	(U-B)	Sp	
7001	ALF LYR	0.00	0.00	11	0.03	0.00	0.00	AO	V
7121	SIG SGR	1.76	.01	4	2.03	-0.22	-0.75	B2	V
7525	GAM AQL	3.67	.01	5	2.72	1.52	1.68	K3	II
7528	DEL CYG	2.82	.01	8	2.87	-0.02	-0.10	B9.5	III
7557	ALF AQL	0.89	0.00	10	0.76	0.22	0.09	A7	IV, V
7796	GAM CYG	2.69	.01	4	2.23	0.67	0.54	F8	Ib
7924	ALF CYG	1.32	.01	10	1.25	0.09	-0.23	A2	Ia
7949	EPS CYG	3.16	.02	5	2.46	1.03	0.87	KO	III
8162	ALF CEP	2.59	.03	4	2.45	0.22	0.11	A7	IV, V
8232	BET AQR	3.44	.01	3	2.87	0.84	0.57	GO	Ib
8414	ALF AQR	3.59	.02	3	2.93	0.97	0.77	G2	Ib
8728	ALF PSA	1.24	0.01	5	1.16	0.09	0.06	A3	V

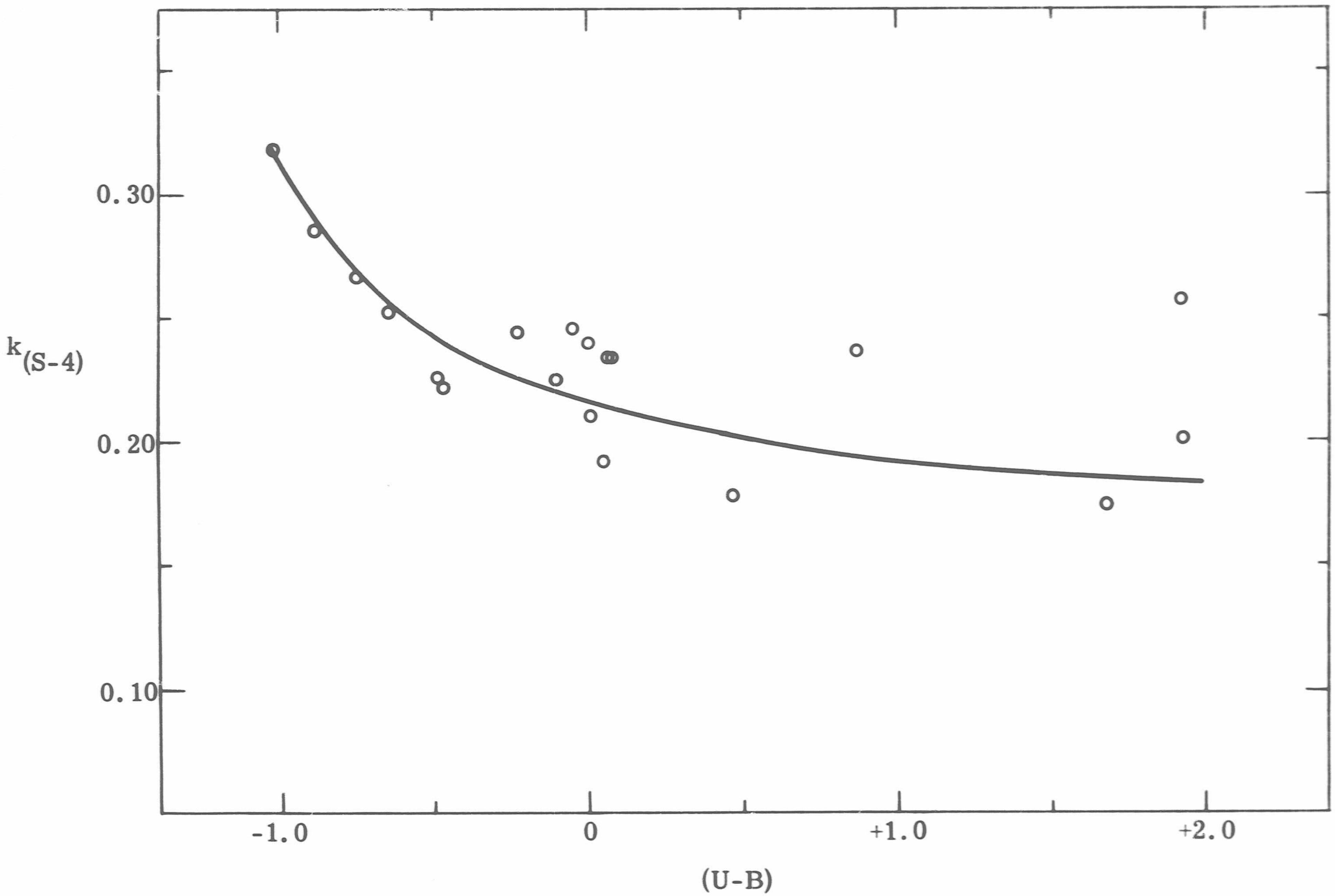

Fig. 1 Dependence of Extinction Coefficient $k_{(S-4)}$ On Stellar Color (U-B) for the Night of Oct 12/13, 1967

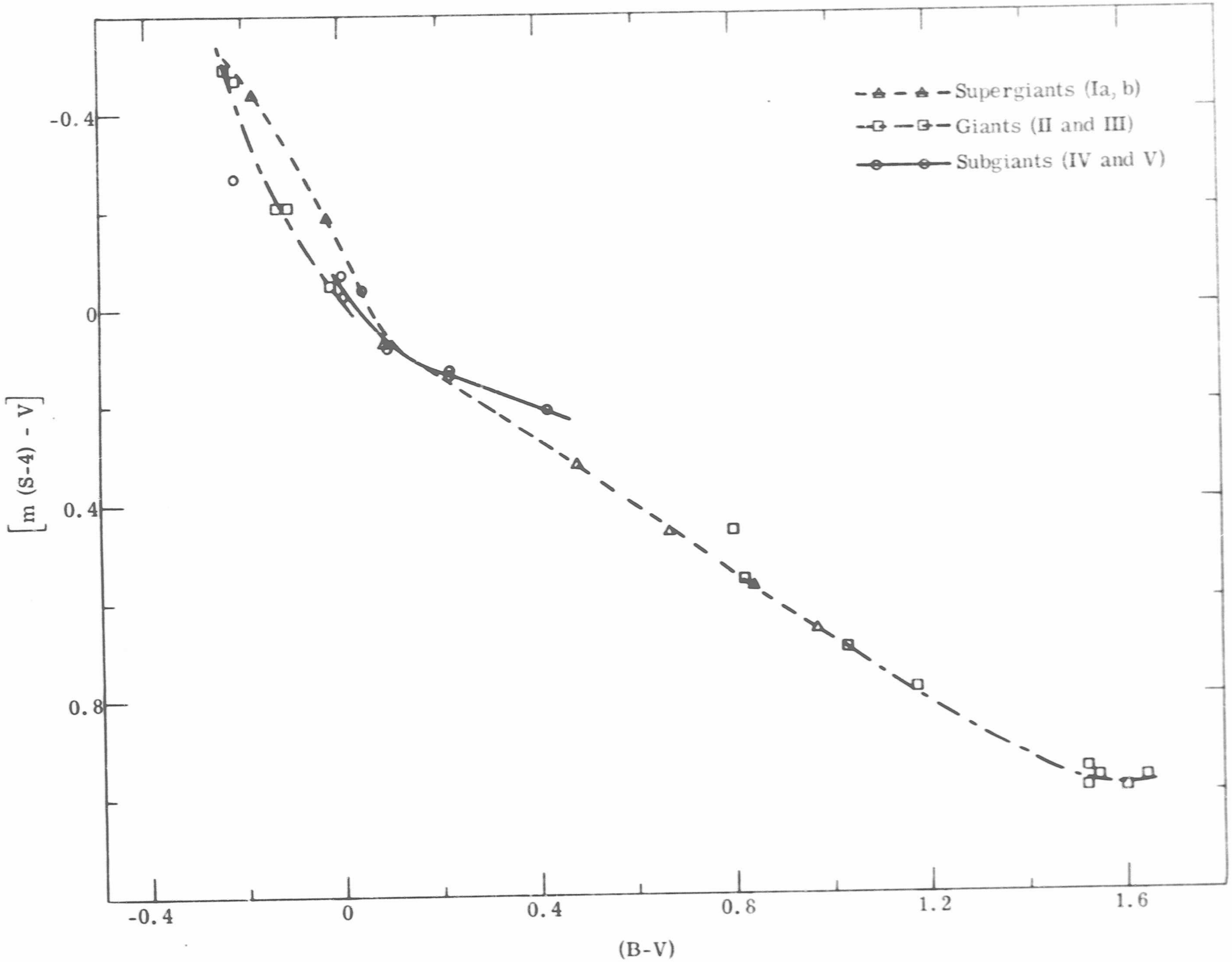

Fig. 2 Observed Stellar Calibration Curves for Unfiltered 1P21 Photomultiplier Tube - HR 145