MODELING VISUAL PHOTOMETRY I: PRELIMINARY DETERMINATION OF VISUAL BANDPASS

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Abstract

This paper addresses the issue of spectral sensitivity as part of the overall visual model. A mathematical theory and observational method are presented for the determination of color coefficient with error term for an individual observer.

1. Introduction

The AAVSO currently has a dynamic database of over 9 million visual observations of variable stars. Visual work can be done rapidly, using minimal equipment and effort for mathematical reduction, with reasonable reliability and repeatability. Visual work is of sufficient historical importance that photographic (m_{pv}) and photoelectric (Johnson V) magnitude systems were created to emulate the spectral response of the eye. The scatter in visual light curves—0.5 magnitude or more—is often taken to be random. However, a body of experience among observers has come to suggest a network of systematic influences on visual observation. Although most of these effects are documented, not much quantitative modeling or testing has been undertaken. Table 1 is a partial list of such effects with a minimal bibliography.

The purpose of this study is to put visual observing on a more quantitative basis. It is informational in nature only, and will not suggest changes to observing procedures. No claim is made that visual observations can be corrected or improved. Readers are

Table 1. Influences on visual magnitude estimation.

Effect	*Max. Likely Amplitude*	*Bibliography*
1.1 Visual Bandpass	1.0 mag.	Kaiser *et al.* 1993; Stanton 1981
1.2 Field Orientation	0.5 mag.	Williams 1987
1.3 Atmospheric Extinction	0.3 mag.	Liller 1992; Guinan 1986
1.4 Brightness Response (Non-Log.)	0.2	Young 1990
1.5 Sky Background	?	Levy 1989
1.6 Purkinje Effect	0.3? mag.	Sterken 1992
1.7 Brightness Level	?	
1.8 Aberrations and Focus	?	
1.9 Atmospheric Scintillation	0.2 mag.	

Effects tend to be interrelated—note groupings (1.3, 1.5, 1.9) and (1.1, 1.6, 1.7). Most vary with observer.

NOTES
1.1 1.0 mag. is specifically *vis* – *V* for reddest stars.
1.3 Mostly a differential effect when stars are low.
1.4 Increases as magnitude spread of comparison grows.
1.5 Mostly a differential effect when stars are low or near Moon.
1.7 Stars best estimated 2–4 magnitudes above visual limit.
1.8 Also includes field illumination and vignetting problems.
1.9 Significant when star is low—eliminate by averaging.

urged not to make changes to their routine variable star work based on considerations discussed herein. Changes should not be prescribed until the visual model is complete, since many of the effects in Table 1 are interrelated and of similar amplitude.

The current plan of this study is to follow the list in Table 1, studying each effect in isolation. Isolation of effects is difficult, and so the early publication of the first paper in the series is acknowledged to be risky. The author states his initial bias—that better accuracy can be gotten from visual work and that benefits to astronomy will come from trying.

2. True visual bandpass

All photometric systems, including those of the Johnson UBV magnitudes, correspond to spectral passbands. The apparent magnitude of a star in system **x** can be calculated from the integrated flux $\phi(\lambda)$ of the star across the passband:

$$m_x = -2.5 log \left(\int_\lambda \phi(\lambda) R_x(\lambda) d\lambda\right) + m_{0,x} \qquad (1)$$

The passband response $R_x(\lambda)$ is characterized by range and peak wavelength. The zero point magnitude $m_{0,x}$ may be assigned arbitrarily and absorbs the scale factor implicit in the units of $\phi(\lambda)$. Since the dark-adapted eye peaks 25 nm blueward of the Johnson V passband response function (Liller 1992), we would expect

$$vis = V + A_k + \beta \ , \qquad (2)$$

where *vis* denotes a visual magnitude, β is a zero-point magnitude, and A_k is a term for the particular star (spectrum) *k*, depending on stellar flux distribution and the response functions for *vis* and *V*:

$$A_k = -2.5 log \left(\frac{\int_\lambda \phi_k(\lambda) R_{vis}(\lambda) d\lambda}{\int_\lambda \phi_k(\lambda) R_V(\lambda) d\lambda}\right) . \qquad (3)$$

A linear approximation can be made for *vis* (Stanton 1981):

$$vis = V + \alpha(B - V) + \beta \qquad (4)$$

where $(B - V)$ is the star's Johnson-Morgan color index. Stanton finds a mean

$$\alpha = 0.182 \ , \quad \beta = -0.15 \qquad (5)$$

based on B,V photometry and visual photometric magnitudes from the Revised Harvard Photometry.

It is conventional wisdom that some AAVSO observers have unusual color sensitivity, and see red stars as particularly bright or dim. Color sensitivity probably varies over time, as the cornea is known to yellow with age. Brightness level and focus will also change the eye's color response according to the Purkinje effect.

As a matter of nomenclature, *vis* (after Kaiser *et al.* 1993) shall be the photometric system of a particular eye under particular conditions. M_v (per Stanton) is the visual magnitude scale of the Revised Harvard Photometry—any *future* standard magnitude system for visual observers might be called *Vis*. The *visual spectroscopic correction* is the value (from equations (2)–(4)) of

$$s_k = A_k - \alpha(B - V) \ , \qquad (6)$$

corresponding to a particular spectrum or spectral class. It is the deviation of the actual *vis* magnitude from the linear equation (4), with adopted values of α and β.

In this paper we address the practical determination of the α constant in equation (4) through visual observations. The visual spectroscopic correction s_k is assumed 0 for all stars in this discussion. The author made 36 observations of non-variable stars with binoculars and with the naked eye, and obtained a personal weighted $\alpha = 0.23 \pm 0.03$. Most observations were made with the left eye only; observations of red variable stars suggest the author's eyes have similar color sensitivity. Triplets of stars with precise V and $B - V$ values were observed using the fractional method. Precautions were taken to minimize other Table 1 effects. The stars used were several degrees apart and observed centered in separate fields. This was somewhat awkward, and different from most variable star observing, but obviates field orientation effects. Observations were corrected for atmospheric extinction using nominal coefficients. The accuracy of the result was diminished by non-optimal selection of stellar triplets.

A theory for observations of α is given in Section 3, which shows the necessity of plotting potential triplets on a V versus $B - V$ diagram. Section 4 explains procedures and reductions for the observations. Section 5 describes a parallel reduction using Tycho magnitudes from the *Hipparcos Catalogue* in place of B and V. Section 6 discusses all reduced results, and Section 7 gives suggestions for future work.

3. Determination of α (V versus *vis*)

The fractional method for variable star magnitude estimation is well known (Levy 1989). Denoting the perceived brightness of a brighter comparison as 1.0, and that of a fainter as 0.0, that of the variable is perceived as f:

$$m_{var} = (1 - f)m_1 + fm_3, \quad 0.0 \leq f \leq 1.0 \ , \tag{7}$$

where m_1 and m_3 are the (Pogson) magnitudes of the fainter and brighter comparisons, respectively. This presumes a logarithmic response to intensity. Young (1990) suggests the visual response follows a power law that causes the m_{var} in equation (7) to be systematically too faint. The deviation increases with $m_1 - m_3$; for a 2-magnitude bracket, it is stated to be 0.2 magnitude. This effect is not considered here.

Equation (7) will hold for any group of 3 stars of magnitudes m_1, m_2, and m_3, where

$$m_1 \geq m_2 \geq m_3 \ . \tag{8}$$

Rearranging equation (7) and denoting the *vis* band

$$f = \frac{(m_{vis1} - m_{vis2})}{(m_{vis1} - m_{vis3})} \ . \tag{9}$$

Using equation (4) and including extinction

$$m_{visi} = vis_i + ext_{visi} = V_i + \alpha(B_i - V_i) + \beta + ext_{visi} \ , \tag{10}$$

where ext_{visi} is the extinction in the *vis* bandpass. The value of β is taken to be zero. It will be seen below that β cancels in differences.

We will approximate *vis* band extinction bysubstituting in equation (4) values of V and ($B - V$) corrected for extinction. After Guinan *et al.* (1986), we have for air mass X

$$\begin{aligned} & ext_V = \kappa_V X = (\kappa_V' + \kappa_V''(B - V))X \\ \text{and} \quad & ext_{B-V} = \kappa_{BV} X = (\kappa_{BV}' + \kappa_{BV}''(B - V))X \ , \end{aligned} \tag{11}$$

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where principal and color-dependent coefficients are introduced for both V and $B-V$. It can be seen

$$\kappa_{BV}' = \kappa_B' - \kappa_V' \quad \text{and} \quad \kappa_{BV}'' = \kappa_B'' - \kappa_V'' \ . \tag{12}$$

Guinan gives nominal values for stations at elevations less than 1000 feet:

$$\kappa_B \,\tilde{}\, 0.38^{\mathrm{m}},\ \kappa_V \,\tilde{}\, 0.22^{\mathrm{m}},\ \kappa_B'' \,\tilde{}\, {-0.035}^{\mathrm{m}},\ \kappa_V'' \,\tilde{}\, {-0.01}^{\mathrm{m}}\ , \tag{13}$$

so figuring a mean $\overline{B-V}$ of 1.0, and using (11) and (12),

$$\kappa_B' \,\tilde{}\, 0.42^{\mathrm{m}},\ \kappa_V' \,\tilde{}\, 0.23^{\mathrm{m}},\ \kappa_{BV}' \,\tilde{}\, 0.19^{\mathrm{m}},\ \kappa_{BV}'' \,\tilde{}\, {-0.025}^{\mathrm{m}}\ . \tag{14}$$

From (9),

$$f = \frac{\hat{V}_1 + \alpha(\hat{B}_1 - \hat{V}_1) - (\hat{V}_2 + \alpha(\hat{B}_2 - \hat{V}_2))}{\hat{V}_1 + \alpha(\hat{B}_1 - \hat{V}_1) - (\hat{V}_3 + \alpha(\hat{B}_3 - \hat{V}_3))}\ , \tag{15}$$

and so

$$\alpha = -\frac{e}{d} = -\left\{\frac{(1-f)\,\hat{V}_1 + f\hat{V}_3 - \hat{V}_2}{(1-f)\,(\hat{B}_1 - \hat{V}_1) + f(\hat{B}_3 - \hat{V}_3) - (\hat{B}_2 - \hat{V}_2)}\right\}, \tag{16}$$

where the photometry corrected for extinction is

$$\text{and} \quad \begin{aligned} \hat{V}_i &= V_i + (\kappa_V' + \kappa_V''(B_i - V_i))X_i \\ \hat{B}_i - \hat{V}_i &= (B_i - V_i) + (\kappa_{BV}' + \kappa_{BV}''(B_i - V_i))X_i\ . \end{aligned} \tag{17}$$

Note that in subsequent equations "d" and "e" introduced in equation (16) are used in place of the expressions they represent. The V_i and $(B_i - V_i)$ are in the absence of extinction. The κ_V'' and κ_{BV}'' terms affect the value of α even when all stars are viewed at the same air mass ($X_1 = X_2 = X_3$). They compensate for the slight redness of the atmospheric filter.

We need to compute the nominal error for each α value determined from a stellar triplet. The error value is used to compute weights for a weighted mean $\overline{\alpha}$. The conventional treatment requires the partial derivatives of α with respect to all inputs: the V_i, $(B_i - V_i)$, extinction parameters, air masses, and the observed f value. The error is taken to be the square root of the sum of the squared product of the uncertainty in each input and the corresponding derivative.

The Δf term alone is presented here, since that is usually the overwhelming contributor. We have

$$\frac{\partial\alpha}{\partial f} = \frac{e((\hat{B}_3 - \hat{V}_3) - (\hat{B}_1 - \hat{V}_1)) - d(\hat{V}_3 - \hat{V}_1)}{d^2} \ \text{and}\ (\Delta\alpha)^2 = \left(\frac{\partial\alpha}{\partial f}\Delta f\right)^2, \tag{18}$$

where e and d are as per equation (16).

The $\Delta\alpha$ listed in Table 4 includes the errors contributed by the other inputs.

Most of the error derivatives, as well as α, are singular where $d = 0$. This corresponds to the condition

$$f = \frac{(\hat{B}_2 - \hat{V}_2) - (\hat{B}_1 - \hat{V}_1)}{(\hat{B}_3 - \hat{V}_3) - (\hat{B}_1 - \hat{V}_1)}\ . \tag{19}$$

Using equation (15), and ignoring extinction:

$$\frac{(B_2-V_2)-(B_1-V_1)}{(B_3-V_3)-(B_1-V_1)} = \frac{V_1+\alpha(B_1-V_1)-(V_2+\alpha(B_2-V_2))}{V_1+\alpha(B_1-V_1)-(V_3+\alpha(B_3-V_3))}, \qquad (20)$$

which can be reduced to:

$$\frac{V_1-V_3}{V_1-V_2} = \frac{(B_1-V_1)-(B_3-V_3)}{(B_1-V_1)-(B_2-V_2)}, \qquad (21)$$

which is the condition that the 3 stars are collinear on a plot of V versus B–V. This shows the need to make such plots prior to selecting stars to observe. Triplets must appear as triangles of reasonable dimension in the color magnitude diagram.

The singularity at $d = 0$ (equation (21)) can be interpreted geometrically. On a plot of $(-V)$ versus $(B-V)$, lines of constant *vis* are of slope α :

$$-V = \alpha(B-V) - vis \qquad (22)$$

A fractional estimate (equation (9)) is represented as the projection of a triplet S_1, S_2, S_3 onto a line perpendicular to the lines of constant *vis*, where f is the ratio of the projected line segments P_1P_2 and P_1P_3 (Figure 1). If the triplet is collinear in any orientation, it can be seen that this ratio is independent of the value of α, which rotates the line of projection (Figure 2). Collinear triplets are degenerate and furnish no information on the value of α.

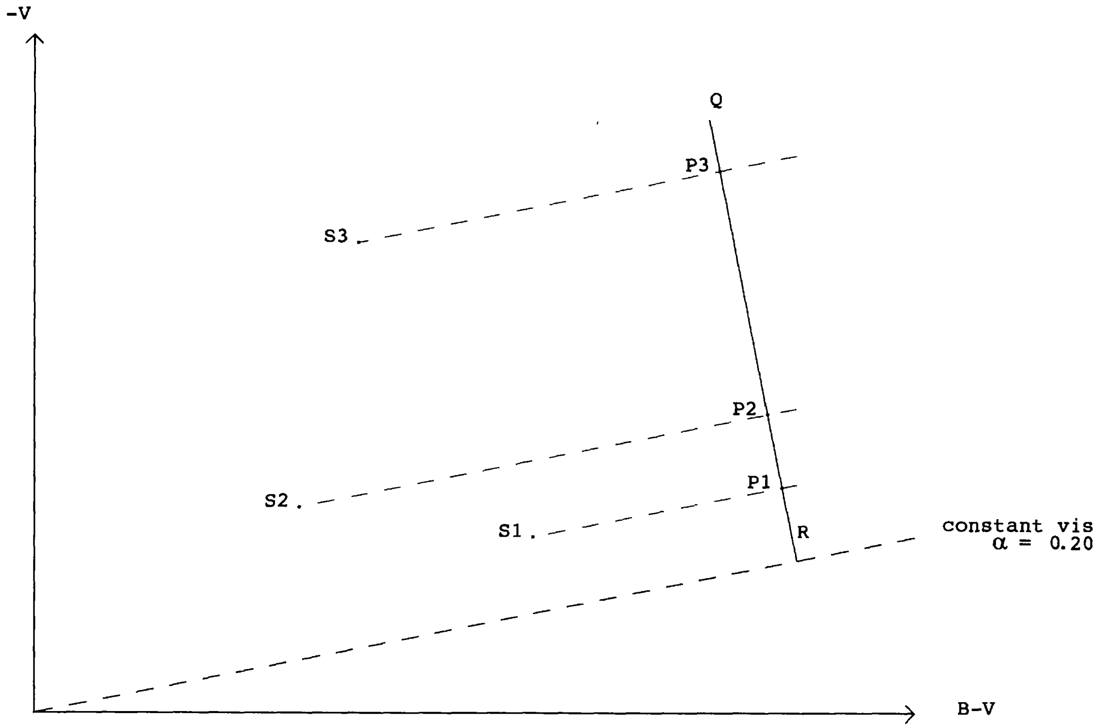

Figure 1. Geometric construction of fractional magnitude estimate. The f value is the ratio P_1P_2/P_1P_3 for S_1, S_2, S_3.

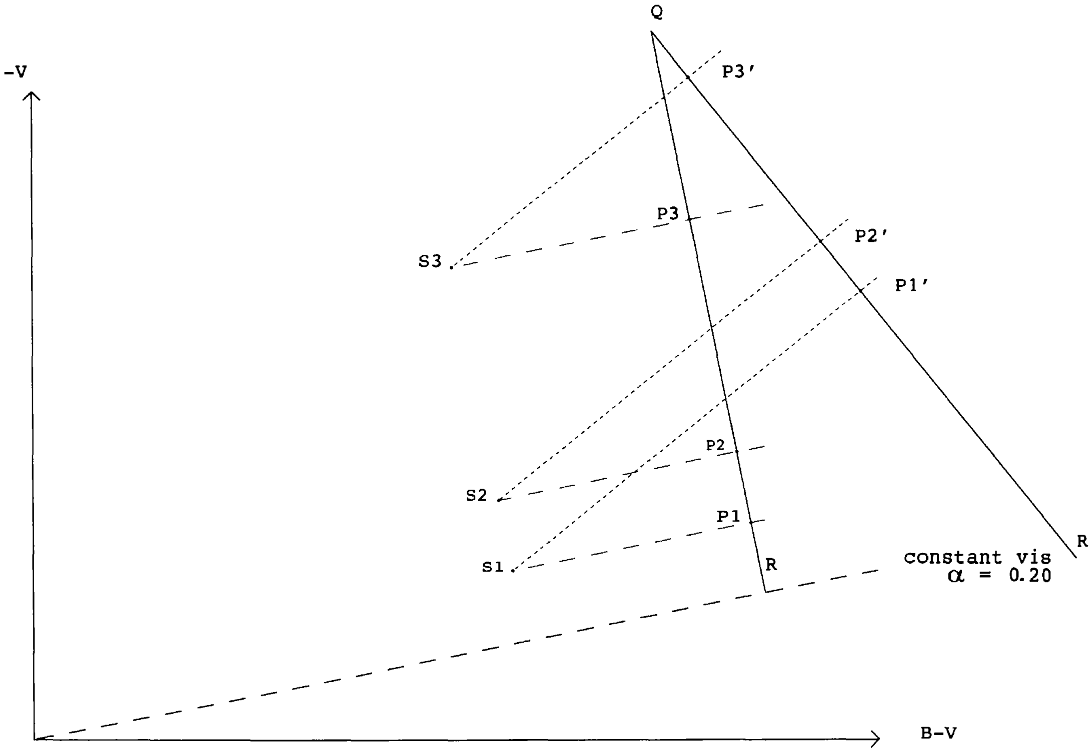

Figure 2. If S_1,S_2,S_3 are collinear, the projection line segment ratio is invariant under rotation; thus α does not affect *f* value. QR' corresponds to an α value of 0.8.

4. Setup and reduction of observations

The observations listed in Table 4 were made in 1994–1995. The first 9 were of naked-eye stars. The remainder were made with 10 x 50 binoculars (6° field) of selected areas near Pegasus, Leo, and Corona Borealis. After selecting an area, *Sky Catalogue 2000.0* (Hirshfeld *et al.* 1991) was searched. We wanted non-variable stars with photoelectric magnitudes. A star atlas was used to eliminate stars within several degrees of brighter stars. Triplets were selected according to the following criteria:

a. Reasonable triangle described on a V versus $B-V$ diagram.
b. $B-V$ range > 0.50 magnitude and *vis* magnitude range < 0.50 magnitude.
c. Angular separation enough for separate centering in field.

Some of these criteria were discovered in the course of the work, and not all triplets complied. The *vis* range in particular was often too large.

Observations were made without moon, with stars high (elevation > 40°). Usually only the left eye was used, with stars slightly defocused and separately centered. The 3 stars were repeatedly checked over 2–3 minutes, and a fractional estimate *f* was taken. A short tube for centering the left eye was used for most naked-eye observations. The binoculars were stopped down to 30mm for the brighter stars. The goal was to use stars 2– 4 magnitudes above the instrument limiting magnitude. The aperture stop also reduces the effect of sky background.

Attempts were made to measure visual extinction coefficients, but they were not carried out consistently. We thus use the nominal values in equations (13) and (14).

The author has myopia poorly corrected by spectacles, so the naked-eye observations were slightly defocused. All of the observations were made at Scottsdale, Arizona (111.8 W, 33.6 N, elevation = 335m), about 24 km from downtown Phoenix.

Significant light pollution exists, especially towards the southwest. Some observations suffered additional local lighting.

Table 3 provides stellar data, including V and $B\text{–}V$ values from *Sky Catalogue 2000.0*, as well as V_T and $B_T - V_T$ from the *Hipparcos and Tycho Catalogues* (ESA 1997). Table 4 lists the observations, as well as derived α and error quantities. As detailed in Section 5, an equivalent analysis to that of Section 3 was performed on the observations, using Tycho V_T and $(B_T - V_T)$ as the photometric color-magnitude pair. The resulting α_T is also given in Table 4. The Tycho extinctions and error terms are not given, but are similar to the values for the Johnson photometry. The stars used in Table 4 are keyed to Table 3 through index ordinals, and are in ascending brightness order as per equation (8). The time, date, and f value for each observation are given. The air masses are taken as the secant of the zenith distance, and the extinctions are in V, following equation (11).

The error term $\Delta\alpha$ depends on partial derivatives (such as in equation (18)) and on uncertainties in input quantities. The most significant error is due to Δf, which is about 0.20. That value is based in part on indoor experiments with projected light spots in 1996–97. Δf is semi-systematic due to power-law response, but is taken here as random. A larger value is presumed for binocular observations due to greater field-centering time. Errors in photometry are assumed nominal (typically 0.04 magnitude), as are errors in extinction coefficients and air masses. Errors in Hipparcos photometry are taken from the catalog, as corrected for indications of variability.

5. Reduction to Hipparcos photometry

The Hipparcos mission of the European Space Agency generated a large body of precise photometry incidental to its principal astrometry product. The brighter stars were typically observed scores of times. This resulted in accurate photometry, and revealed many small-amplitude variables. Photometry in two bands yielded the "Tycho" magnitudes V_T and B_T. The nominal transformations to B and V are

$$V = V_T - 0.090(B_T - V_T) \tag{23}$$

and

$$B - V = 0.850(B_T - V_T) \; . \tag{24}$$

A relationship similar to equation (4) holds between *vis* and the set V_T and $B_T - V_T$:

$$vis = V_T + \alpha_T(B_T - V_T) + \beta \, , \tag{25}$$

and by equations (23) and (24):

$$\alpha = \frac{(\alpha_T + 0.090)}{0.850} \; . \tag{26}$$

The accuracy of equation (26) is limited by the approximations implicit in equations (4), (23), and (24).

The treatment in Section 3 can be repeated exactly by replacing V and $(B-V)$ with V_T and $B_T - V_T$. Extinction can be approximated by substituting coefficients for the corresponding magnitudes and colors in equations (23) and (24), yielding

$$\kappa_{VT}' = \kappa_V' + 0.1059\kappa_{BV}', \; \kappa_{VT}'' = 0.850(\kappa_V'' + 0.1059\kappa_{BV}'') \tag{27}$$

and

$$\kappa_{BVT}' = 1.176\kappa_{BV}', \; \kappa_{BVT}'' = \kappa_{BV}'' \; . \tag{28}$$

The resultant α_T values can be weighted and averaged as described in Section 6. They are directly useful in converting Hipparcos magnitudes to a visual scale.

One disconcerting result of the Hipparcos reduction was the discovery that some of the stars used are variables! They are indicated with an asterisk in Table 3. The indicated amplitudes in the Hipparcos catalogue are 0.05 magnitude or less except for ψ Peg and SAO 81730, which are slightly larger. Hipparcos variability indications should be examined carefully in future selections.

Hipparcos variability indications and indicated range modulated the photometric error used in generating the nominal error term for each α_T. The normal error term provided in the Hipparcos catalogue was replaced by the "95%" range in H_p, divided by 2, for the photometric error of stars with variability indicators. Note that H_p is the main Hipparcos magnitude and is different from either of the Tycho magnitudes (van Leeuwen 1995).

6. Discussion of results

A glance at Table 4 shows considerable scatter in the α values determined from the individual observations. A total of 38 observations were evaluated.

Two types of averages were taken. The normal arithmetic mean and standard deviation were computed. Because of the large variation in nominal error, weighted averages (Taylor 1997) were also taken. The weights used were the reciprocal of the nominal error squared. Standard deviations of the weighted and unweighted means were also obtained.

Table 2 gives these means and deviations for the indicated observation groupings. Note that two very wild binocular observations ({24, 26, 25} and {27, 23, 26} on 28 November 1994) were not included in any of the averages. These share the problematic star SAO 107786, located very near a brighter neighbor. Thus, the overall values are based on 36 observations.

The α_T values in parentheses are based on the Tycho photometry from the Hipparcos catalogue. Two naked-eye observations of γ Psc were removed since Tycho magnitudes are not available for that star. The value of α_T is smaller than that of α, reflecting the fact that V_T is intermediate in color between V and *vis*.

Table 4 shows that the deviation of the mean for the weighted α_T values is actually a little worse than that for the unweighted mean, and that this arises primarily out of the naked-eye set. Further checking spotlights two observations, {3, 9, 10} on 11 September 1994 and {16, 12, 17} on 10 October 1994, the weights of which increased due to the smaller Hipparcos photometric error. The first of these indicates observational problems (nearby, fairly bright stars), and the second is nearly collinear on the color diagram. Removing these two observations has rather little effect on the overall α statistics. On the α_T side, removing them creates the proper relationship between weighted and unweighted deviations (0.03 versus 0.04), and changes the overall $\overline{\alpha_T}$ to 0.072. This is an object lesson on tightening up the selection process for triplets.

Table 2. Observation set statistics (Tycho values parenthesized).

	Count	*Average*	*Standard Deviation*	*Weighted Average*	*Dev. of mean*	*Weighted Dev. of mean*
naked-eye	9	0.236	0.259	0.270	0.092	0.052
	(7)	(0.060)	(0.298)	(0.177)	(0.122)	(0.134)
10x50	27	0.311	0.382	0.206	0.075	0.040
	(27)	(0.117)	(0.236)	(0.051)	(0.046)	(0.026)
all	36	0.293	0.357	**0.230**	0.060	0.033
	(34)	(0.105)	(0.251)	**(0.091)**	(0.044)	(0.049)

Table 3. Stellar data.

Star	*SAO*	*HD*	*Hip*	*V*	*B–V*	V_T	B_T-V_T	*Spec*	*Name/SAO No.*
1	36699	4727	H3881	4.52	-0.15	4.510	-0.158	B5V	ν And
2	54281	5448	H4436	3.87	0.13	3.881*	0.157	A5V	μ And
3	74996	11443	H8796	3.41	0.49	3.476*	0.526	F6IV	α Tri
4	30429	159181	H85670	2.79	0.98	2.901*	1.116	G2II	β Dra
5	46872	160762	H86414	3.80	-0.18	3.777*	-0.186	B3V	ι Her
6	30653	164058	H87833	2.23	1.52	2.413*	1.843	K5III	γ Dra
7	18222	180711	H94376	3.07	1.00	3.188	1.174	G9III	δ Dra
8	54058	3627	H3092	3.28	1.28	3.419	1.526	K3III	δ And
9	110707	16970	H12706	3.47	0.09	3.460	0.138	A3V	γ Cet
10	23789	18925	H14328	2.90	0.73	3.018	0.789	G5III+A2V	γ Per
11	54471	6860	H5447	2.06	1.58	2.264*	1.903	M0IIIvar	β And
12	108638	221115	H115919	4.55	0.94	4.647	1.086	G8III	70 Peg
13	128513	224617	H118268	4.00	0.43	4.076	0.439	F4IV	ω Psc
14	128085	219615	H114971	3.69	0.92			G7III	γ Psc
15	127934	217891	H113889	4.53	-0.12	4.474*	-0.129	B6Ve	β Psc
16	91611	224427	H118131	4.66	1.59	4.837*	1.844	M3III	ψ Peg
17	91253	220657	H115623	4.40	0.61	4.495	0.665	F8IV	υ Peg
18	128336	222603	H116928	4.50	0.20	4.521	0.223	A7V	λ Psc
19	30631	163588	H87585	3.75	1.18	3.867	1.397	K2III	ξ Dra
20	90206	209665	H108966	7.21	0.07	7.226	0.061	A0	90206 (Peg)
21	90329	210944	H109700	7.20	0.48	7.298	0.498	F5V	90329 (Peg)
22	90409	211732	H110152	7.71	0.22	7.743	0.231	A3	90409 (Peg)
23	90423	211884	H110247	7.29	1.59	7.500	1.910	K5III	90423 (Peg)
24	107650	209725	H109030	7.47	1.26	7.582	1.520	K2	107650 (Peg)
25	107796	211500	H110038	7.10	0.94	7.190	1.148	K0III	107796 (Peg)
26	107786	211420	H109991	7.50	0.99	7.577	1.170	K0	107786 (Peg)
27	107825	211775	H110189	7.77	1.56	7.901*	1.929	K5	107825 (Peg)
28	107935	212989	H110900	7.08	0.90	7.235	1.050	K0V	107935 (Peg)
29	127490	212291	H110508	7.92	0.68	7.986	0.783	G5	127490 (Peg)
30	81615	95242	H53766	7.06	1.12	7.412	1.293	K0	81615 (Leo)
31	99403	95486	H53881	7.66	0.93	7.742	1.087	K0	99403 (Leo)
32	118628	95651	H53977	7.24	0.11	7.227	0.118	A0	118628 (Leo)
33	81648	95804	H54063	6.98	0.26	6.998	0.295	A5	81648 (LMi)
34	99444	96372	H54319	6.39	1.59	6.581*	1.871	K5	99444 (Leo)
35	81681	96528	H54388	6.46	0.16	6.503	0.194	A5m	81681 (Leo)
36	81692	96738	H54487	5.68	0.06	5.701	0.082	A3IV	81692 (Leo)
37	81730	97658	H54906	7.76	0.84	7.861*	0.950	K1V	81730 (Leo)
38	81755	98154	H55166	7.40	0.13	7.390	0.148	A3V	81755 (Leo)
39	81756	98153	H55170	6.94	0.20	6.988	0.226	A2	81756 (Leo)
40	83616	132879	H73464	6.38	1.10	6.414	1.395	K0	83616 (Boo)
41	83624	133124	H73568	4.81	1.50	4.965*	1.802	K4III	ω Boo
42	83723	135263	H74505	6.30	0.06	6.311	0.071	A2V	83723 (Ser)
43	83729	135502	H74596	5.26	0.03	5.287	0.069	A2V	χ Boo
44	83755	136138	H74896	5.70	0.97	5.795	1.126	G5IV	83755 (Ser)
45	83778	136643	H75125	6.39	1.23	6.496	1.494	K0	83778 (Ser)
46	83830	137853	H75674	6.02	1.62	6.205*	1.952	M1III	83830 (Ser)
47	64769	138749	H76127	4.14	-0.13	4.141	-0.138	B6Vnn	θ CrB
48	64808	139389	H76456	6.52	0.35	6.508	0.444	F5V:	64808 (CrB)
49	101682	140159	H76852	4.52	0.04	4.515	0.069	A1V	ι Ser
50	81865	100128	H56207	7.81	0.21	7.855	0.245	A3	81865 (Leo)
51	99662	100447	H56383	7.01	1.28	7.135	1.499	K2	99662 (Leo)
52	99577	99824	H55533	7.03	1.06	7.121	1.276	K1III	99577 (Leo)
53	0	0	Hxxx	3.50	0.00	5.021	0.023		fictitious

V_T marked with asterisk denotes Hipparcos variability flag.

Table 4. Author's observations to determine α.

Stars	*1994*	*U.T.*	*f*	*am1*	*am2*	*am3*	*ex1*	*ex2*	*ex3*	α	α_T	*err* (Δα)	*notes*
1,2,3	09/08	07:05	0.60	1.11	1.12	1.30	0.26	0.26	0.29	-0.051	-0.286	1.443	*1,4,7*
7,4,6	09/09	04:05	0.35	1.21	1.17	1.12	0.27	0.26	0.24	0.067	-0.054	0.657	*1,4,8*
19,5,4	09/09	04:05	0.30	1.16	1.13	1.17	0.25	0.26	0.26	0.272	0.143	0.124	*1,4*
1,2,8	09/11	06:52	0.75	1.11	1.12	1.10	0.26	0.26	0.24	0.383	0.224	0.152	*1,4*
3,9,10	09/11	07:50	0.33	1.13	1.62	1.31	0.25	0.37	0.29	0.860	0.672	0.297	*1,4,8*
18,15,53	10/10	06:20	0.00	1.18	1.20	1.10	0.27	0.28	0.25	0.118	-0.117	0.525	*1,9*
12,13,14	10/10	06:20	0.80	1.08	1.12	1.19	0.24	0.25	0.26	0.274		0.271	*1,4,17*
12,15,14	10/10	06:20	0.25	1.08	1.20	1.19	0.24	0.28	0.26	0.225		0.131	*1,4,17*
16,12,17	10/10	06:20	0.33	1.01	1.08	1.03	0.22	0.24	0.23	-0.021	-0.166	0.191	*1,6*
24,26,25	11/28	04:20	0.40	1.49	1.45	1.42	0.32	0.32	0.31	1.284	0.779	1.759	*2,4,10,15*
29,24,28	11/28	04:20	0.25	1.47	1.49	1.40	0.33	0.32	0.31	0.468	0.334	0.346	*2,4,15*
27,23,26	11/28	04:45	0.40	1.50	1.41	1.61	0.32	0.30	0.35	1.782	1.233	1.535	*2,4,10,15*
22,20,21	11/30	03:48	0.80	1.22	1.27	1.23	0.28	0.29	0.28	-0.231	-0.402	0.591	*2,4,11,15*

Stars	*1995*	*U.T.*	*f*	*am1*	*am2*	*am3*	*ex1*	*ex2*	*ex3*	α	α_T	*err* (Δα)	*notes*
30,34,35	05/24	05:30	0.40	1.36	1.38	1.32	0.30	0.29	0.30	0.523	0.480	0.283	*2,4,15*
37,30,33	05/24	05:50	0.25	1.35	1.47	1.41	0.30	0.32	0.32	1.148	0.428	0.727	*2,4,12,15*
34,35,36	05/24	06:00	0.30	1.54	1.46	1.44	0.33	0.33	0.33	0.304	0.174	0.262	*2,4,15*
30,38,39	05/26	05:32	0.15	1.41	1.30	1.29	0.31	0.30	0.29	0.416	0.035	0.163	*2,4,13,15*
31,30,33	05/26	05:42	0.30	1.56	1.46	1.40	0.34	0.32	0.32	1.116	0.298	0.863	*2,4,13,15*
31,30,38	05/26	05:55	0.40	1.65	1.54	1.40	0.36	0.34	0.32	1.030	0.358	0.528	*2,4,13,15*
50,32,51	05/31	05:25	0.80	1.32	1.68	1.34	0.30	0.39	0.29	0.190	0.051	0.172	*2,4,8,15*
52,34,35	05/31	05:30	0.50	1.44	1.53	1.45	0.32	0.33	0.33	0.367	0.207	0.244	*2,4,15*
45,42,43	06/27	03:45	0.20	1.03	1.03	1.01	0.22	0.24	0.23	0.162	0.064	0.303	*3,4,14,16*
40,42,43	06/27	03:45	0.15	1.03	1.03	1.01	0.22	0.24	0.23	0.114	0.073	0.303	*3,4,14,16*
40,46,44	06/29	07:06	0.30	1.35	1.23	1.29	0.30	0.26	0.28	0.355	0.095	0.323	*3,4,13,15*
45,46,44	06/29	07:08	0.35	1.26	1.23	1.30	0.27	0.26	0.29	0.310	0.111	0.371	*3,4,13,15*
44,41,49	06/29	07:17	0.40	1.34	1.37	1.26	0.29	0.29	0.29	0.471	0.296	0.379	*3,4,13,15*
48,45,44	07/04	07:08	0.15	1.24	1.33	1.38	0.28	0.29	0.31	0.002	-0.106	0.230	*3,4,15*
48,40,44	07/04	07:20	0.25	1.28	1.53	1.45	0.29	0.34	0.32	-0.169	-0.154	0.322	*3,4,15*
43,41,47	07/04	07:25	0.20	1.41	1.52	1.31	0.32	0.33	0.30	0.149	0.051	0.168	*3,4,15*
43,41,49	07/04	07:30	0.30	1.43	1.55	1.39	0.33	0.33	0.32	0.154	0.051	0.142	*3,4,14,15*
40,42,43	07/23	06:15	0.20	1.60	1.50	1.43	0.35	0.34	0.33	0.177	0.121	0.345	*3,5,14,15*
45,42,43	07/23	06:15	0.15	1.44	1.50	1.43	0.31	0.34	0.33	0.116	0.027	0.279	*3,5,15*
48,40,44	07/24	05:53	0.25	1.25	1.48	1.40	0.28	0.32	0.31	-0.163	-0.149	0.323	*3,4,15*
48,40,44	07/24	05:53	0.20	1.25	1.48	1.40	0.28	0.32	0.31	-0.093	-0.102	0.295	*3,5,15*
48,45,44	07/24	05:56	0.20	1.26	1.36	1.42	0.29	0.30	0.31	-0.052	-0.149	0.247	*3,4,15*
48,45,44	07/24	05:56	0.20	1.26	1.36	1.42	0.29	0.30	0.31	-0.052	-0.149	0.247	*3,5,15*
44,41,49	07/24	06:18	0.30	1.55	1.60	1.42	0.34	0.34	0.33	0.668	0.455	0.473	*3,4,15*
44,41,49	07/24	06:18	0.20	1.55	1.60	1.42	0.34	0.34	0.33	0.926	0.659	0.608	*3,5,15*

NOTES

(1) naked-eye
(2) 10 X 50 binoculars
(3) 10 X 50 binoculars, stopped to 30mm
(4) left eye
(5) right eye
(6) both eyes
(7) not centered
(8) differential extinction or light pollution
(9) two stars exactly equal
(10) α wild, not used for average
(11) too near ι Peg
(12) possible misidentification
(13) possible cirrus low
(14) some bias
(15) made from somewhat illuminated balcony
(16) slight twilight
(17) Hipparcos magnitudes unavailable

Converting the weighted mean α_T of all observations to α using equation (26) gives a value of 0.213, which is reasonably compatible with that based on Johnson photometry. Values of α_T may be directly usable with the large Hipparcos data set.

It appears that the author's α value is about 0.230, to an accuracy of 10–20%. This indicates a more blue-sensitive eye than that implied by the Stanton (1981) value of 0.182. It is of interest to see if blue or red sensitivity is seen in the author's observations of red variable stars. An observer with deviant α should show magnitude deviations on the order of $\Delta\alpha\Delta\overline{(B-V)}$, where the term $\Delta\overline{(B-V)}$ represents the mean color difference between the variable star and its comparisons. Several caveats apply:

a. Table 4 includes no gross variables. The spectroscopic corrections for late-type variables are unknown.
b. The colors of variables often vary, and are not usually available.
c. It is not certain that the observers who provided data for the Revised Harvard Photometry used in Stanton's determination of $\bar{\alpha}$ had the same mean color sensitivity as that of AAVSO observers.
d. All of the Table 1 effects are at play in real-world light curves.

Unevaluated AAVSO visual light curves (Mattei 1994) were examined for 0231+33 R Tri and 2016+47 U Cyg during the interval JD 2449000–2450000. Eighteen personal observations for R Tri, and 30 for U Cyg, were examined, having been made in various phases except very near minimum, using primarily 10x50 binoculars for R Tri, and a 10-cm f/4.5 Newtonian for U Cyg. Fairly scrupulous defocusing was employed, especially with U Cyg. The left eye was dominant, but both were often used with binoculars. The author averaged 0.06 magnitude fainter than the mean curve for R Tri, and 0.35 magnitude fainter for U Cyg. For U Cyg, the deviation increased towards minimum light, while that for R Tri appeared uncorrelated with phase. The author seemed to be fairly close to the bottom of the scatter band for U Cyg on many of the observations. The nominal B–V values given in the Hipparcos catalogue for R Tri and U Cyg are 1.3 and 3.3, respectively.

The R Tri and U Cyg deviations both indicate a bluer eye than the + 0.05 personal deviation from the Stanton $\bar{\alpha}$. In particular, the U Cyg observational deviation, combined with the nominal $B-V$ of the variable and a reasonable $B-V$ of 0.5 for the comparisons, imply a personal α of about 0.30! One suspects additional factors are at work here. A more detailed analysis is needed, which must await determination of spectroscopic corrections and other Table 1 effects.

7. Future work

The $\bar{\alpha}$ determined here will be used in further photometric studies. Considerable labor was required to obtain the current semi-accurate value. In retrospect, more effort seems needed in triplet selection to reduce the anticipated scatter. This means using relatively small spreads in *vis* for a given spread in color. A computerized star catalogue search could be used to produce a list of well-optimized triplets. A visual photometer would be a useful instrument for measuring α, since the Δf error term would be greatly reduced. With a photometer, a reliable method of measuring extinction and sky background becomes important.

A disadvantage of triplet work is that a discrepant value cannot be linked to an individual star. It is probably impractical to produce spectroscopic corrections using triplets. The derivation of $\bar{\alpha}$ by Stanton (1981) suggests another approach. A small number of standard stars are selected, spaced perhaps 0.5 magnitude apart. These stars have nearly identical $(B-V)$ values. Other stars of various colors are compared against them. This will create a true *vis* magnitude scale, with some 0-point (β) value. Plotting

$vis - V$ against $B - V$ will then yield a scatter band oriented at slope α. A least-squares fit will give α explicitly. It will also highlight stars with peculiar *vis* magnitudes, including those of anomalous spectroscopic correction. This would allow extending equation (4) into the regime of variable stars, given concurrent photoelectric coverage of the variables under test. The author suspects that a combination of these two methods might be best. Carefully optimized general triplets should yield the most accurate $\overline{\alpha}$ for a given number of observations. The one-color standards sequence might be best for studying non-linearities and spectroscopic anomalies.

8. Conclusion and acknowledgements

I have found, as an amateur observer, that this type of analysis is a worthwhile break from strictly routine observations. However, the ongoing visual work is really the essential thing for me. This can be generalized: We should not let our interest in technique and possible improvements to the data overshadow the fact that variable star observers already produce a valuable and abundant resource for the astronomical world.

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