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RESEARCH NOTE: 13-COLOR PHOTOMETRY, SAN PEDRO MARTIR, 1973-79

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RESUMEN

Se presentan y se discuten datos de extinción atmosférica, errores probables de observación, listas de estrellas estándar, procedimientos de observación, ecuaciones de reducción y otros datos diversos para 225 noches de fotometría de 13-colores observadas en el Observatorio de San Pedro Mártir, Baja California. Se presenta una bibliografía parcial para los sistemas fotométricos de 13-colores y de Borgman y los usos de tales fotometrías de banda intermedia.

ABSTRACT

Atmospheric extinction data, probable errors of observation, standard star lists, observing procedures, reduction equations, and other miscellaneous data are given and discussed for 225 nights of 13-color photometry observed at the San Pedro Mártir Observatory in Baja California. In addition a partial bibliography for the 13-color and Borgman photometric systems and for the uses of such intermediate-band photometry is presented.

Key words: PHOTOMETRY – STARS-STANDARDS

I. INTRODUCTION

The 13-color system of intermediate band ($\Delta\lambda$90-620 Å) photometry was originally developed for the study of early-type stars, interstellar reddening and stellar classification (Johnson, Mitchell and Latham 1967; Mitchell and Johnson 1969; Johnson and Mitchell 1975, hereinafter abbreviated JML, MJ and JM, respectively). The seven bluest filters match very closely the seven filters of Borgman (1960, 1963), chosen to measure the continuum properties of early-type stars such as the Balmer jump, while avoiding strong spectral lines. The six red and infrared filters of the 13-C system were selected with respect to the Paschen jump, while avoiding also telluric atmospheric features.

A description of the 13-C system is contained in the papers by JML, MJ and JM. Tables 7, 8 and 9 of MJ and Table 7 of JM give the defining observations of the 13-C system, and several bright stars from these tables can be used as primary standards. The filter-detector response functions, definitions of the zero points, the absolute calibration, comparisons with other photometric systems, corrections to monochromatic magnitudes, blackbody relative gradients, northern and southern hemisphere 13-C observations are given and discussed in the above-mentioned papers. Johnson and Mitchell (JM and MJ) concluded that the 13-C system is linear, "homogeneous to an unusual degree", and potentially very useful as a calibrated accurate photometric system with filters "narrow enough to behave nearly like monochromatic measurements".

Besides the bright-star photometry of the above references, the 13-C and Borgman photometries have been used in a number of astrophysically interesting studies prior to the San Pedro Mártir (hereinafter referred to as SPM) programs. Borgman (1960, 1961, 1963) and Borgman and Blaauw (1964) studied early-type (O, B and A) stars, their intrinsic colors, absolute magnitudes, distance moduli, photometric effects caused by companions and the wavelength dependence of interstellar extinction. Johnson (1977) also studied interstellar extinction for several regions of the sky using 13-C data to supplement broad-band observations. Wallerstein (1964) and Smith (1968) discussed the sensitivity of the Borgman-LPL indices to stellar metal abundances, and Johnson and Mitchell (1968) examined blanketing and the spectral-energy curves of subdwarfs. Mitchell (1969) used the full 13-C to study the albedo of Mars, and Mendoza (1969, 1971*a, b, c*) the 8C part to investigate the Magellanic Clouds, the Scorpio Centaurus association, southern bright stars and the eclipsing binary V Puppis. Iriarte (1973) used 8C color-color diagrams and the energy calibration to examine 27 faint blue stars at high galactic latitudes. Finally, Underhill (1979) and Underhill *et al.* (1979) used the 13-C photometry of JM plus satellite ultraviolet measures and LTE model atmospheres of Kurucz to determine effective temperatures, angular diameters, distances and linear diameters for a number of O and B stars. In the above publications the usefulness of 13-C photometry for studying not only early-type stars but also stars as late as the K-types and planets was shown.

In 1973 the two 13-C photometers arrived at SPM and were put into operation by the personnel of the Mexican National Observatory. A bright-star (Hoffleit 1964) program was undertaken for cataloguing purposes, and was broken into several parts such as solar-type stars (Schuster 1976*a*), Be stars (Alvarez and Schuster 1978, 1981), supergiants, and O-type stars (Schuster (1982), to produce more scientifically interesting results. Faint-star programs included the author's dissertation concerning subdwarf stars (Schuster 1976*b*; 1979*a, b, c;* 1981) and studies of IRC + 10420 (Craine *et al.* 1976), Nova V1500 Cygni 1975 (Carrasco *et al.* 1979), comet West (Schuster and López 1976), MWC645 and + 38°2179. Other 13-C programs concerning high-velocity stars, stars with large ultraviolet excesses, members of the Hyades and Praesepe clusters, and calibration stars with known compositions and effective temperature are in process.

We have found particular usefulness in the 13-C photometry for studying F, G and K-type stars and Be stars. For the cooler stars this photometric system has allowed us to select solar analogues (Schuster 1976*a*) and to study in detail the blanketing, evolutionary status and physical parameters for F and G subdwarfs (Schuster 1979*a, b, c*). Good separation between temperature, composition and surface gravity can be obtained from 13-C indices for the F and G stars; *45 – 63* and *58–99* are good temperature indices, *37–45* very sensitive to composition and G = *(35–52)-(37–45)* a good gravity index (Schuster 1979*a*). For Be stars the 13-C system has allowed us to separate the effects of interstellar reddening from the stars' intrinsic ultraviolet and infrared excesses (Alvarez and Schuster 1978) and to correlate the ultraviolet and infrared variability of some Be stars (Alvarez and Schuster 1981).

The aim of this research note is to present basic procedural and reduction data from 225 nights of photometry performed at SPM during the years 1973-1979. We give information for 13-C photometry analogous to that given in the appendix to the workshop over multicolor photometric systems at the Dudley Observatory (Philip 1979). Much of this type of information has already appeared in the publications of JML, MJ and JM. This note contains data and discussions concerning the 13-C standard stars, atmospheric extinction, standard lamp problems, probable errors of observation, reduction equations, observing procedures, interstellar reddening ratios, and other miscellaneous information.

II. 13-C STANDARD STARS

In Table 1 we list the primary 13-C standard stars used for reducing our data from the years 1973-79 employing photometric values taken from Table 7 of

TABLE 1

13-COLOR STANDARD STARS USED AT SAN PEDRO MARTIR, 1973-79

BS	Name	Sp	*V*	*52*	*58*	NB	NR
45	χ Peg	M2 III	4.80	5.198	4.446	29	18
617	α Ari	K2 III	2.00	2.315	1.754	63	42
{ 718	ξ² Cet	B9 III	4.28	4.284	4.290	56	31
{ 753	. . .	K3 V	5.82	6.138	5.533	6	18
{ 875	. . .	A1 V	5.17	5.196	5.144	26	19
{ 1084	ε Eri	K2 V	3.73	3.967	3.471	41	17
937	ι Per	G0 V	4.04	4.185	3.885	12	2
1017	α Per	F5 Ib	1.79	1.937	1.663	14	2
1855	β Ori	B0 V	4.63	4.571	4.661	87	28
2852	ρ Gem	F0 V	4.16	4.263	4.094	39	33
2890/1	α Gem	Am+A1 V	2.85, 1.99	1.599	1.576	16	2
2990	β Gem	K0 III	1.15	1.388	0.908	16	2
{ 3249	β CnC	K4 III	3.52	3.945	3.193	99	54
{ 3454	η Hya	B3 V	4.30	4.275	4.336	99	24
4456D	90 Leo	B3 V	5.95	5.914	5.976	53	12
4534	β Leo	A3 V	2.14	2.125	2.087	10	48
4550	. . .	G8 VI	6.45	6.627	6.236	49	40
5340	α Boo	K2 IIIp	0.06	0.243	0.371	5	12
{ 5685	β Lib	B8 V	2.61	2.605	2.631	99	69
{ 5854	α Ser	K2 III	2.65	2.930	2.358	99	66
5947	ε Crb	K3 III	4.15	4.458	3.861	31	39
6092	τ Her	B5 IV	3.89	3.895	3.942	31	35
{ 6603	β Oph	K2 III	2.77	3.061	2.488	90	54
{ 6629	γ Oph	A0 V	3.75	3.751	3.744	74	48
7001	α Lyr	A0 V	0.04	0.039	0.038	4	36
7906	α Del	B9 V	3.77	3.764	3.779	2	56
8622	10 Lac	O9 V	4.88	4.846	4.912	99	40
8832	. . .	K3 V	5.57	5.872	5.254	68	24

MJ; newer values including more data for BS3249, BS3454, BS5685, BS5854, BS6603 and BS6629 are given in Table 7 of JM. The number of blue (8C) and red (6RC) observations (NB and NR, respectively) of Table 1 are from JM, and only the stars with NB or NR > 10 are used as standards in our reductions. The original definition of the 13-C system depended on all observations of MJ –966 stars in Table 7, 21 stars in Table 8 and 30 in Table 9 (Mitchell 1975) but only very small differences ($\lesssim$ .01 magnitude) exist between the mean photometric values of JM and MJ for the stars of Table 1.

Several "extinction pairs" are indicated in Table 1 where each pair includes one red and one blue star to be observed together at several different air masses to determine both the extinction coefficients and transformation color-terms. For example, BS718 and BS753, BS875 and BS1084, BS3249 and BS3454, BS5685 and BS5854, and BS6603 and BS6629 all fall within 10° of the celestial equator, and so at SPM have an air mass at meridian passage less than 1.35 and obtain at least 2 air masses within four hours of the meridian. The pairs BS5947 and BS6092, and BS8622 and BS8832 are very good for determining color coefficients but are located too far north to vary rapidly in air mass.

Finally, the stars of Table 1 range in visual brightness (V) from approximately 0.0 to 6.5, in spectral type from O9 to M2, and in luminosoty class from VI to Ib, and so the distribution of standard stars with spectral type, luminosity, and color is adequate, but the distribution over the sky is somewhat limiting.

In Table 2 we present new 13-C data from SPM for twelve new secondary standards. BS1351, BS1389, BS1411 and BS1412 (Hyades 30, 56, 71 and 72 respectively) have been observed for use as standards within the Hyades cluster; BS1351 and BS1389 are good 6RC standards, and the other two, good 8C standards. BS5634 and BS5640 and BS7181 and BS7202 have been used as extinction pairs in the special extinction studies to be discussed later; both pairs have a separation of less than 0°.5 and declinations of 25-26°. Since the stars BS753, BS5340, BS7001 and BS7906 were not good 8C standards having NB < 10, we have made additional 8C observations of these stars, given in Table 2 averaged with the older observations. These four stars have been used as 6RC standards during 1973-1979 as shown by the increased NR values.

However, Arcturus and Vega are not good standards even with the additional observations. First, both are too bright to be used as standards with the 1.5 m telescope of SPM; the high-voltage of the 6RC photometer

TABLE 2

NEW 13-COLOR STANDARDS

Object	Sp	*52*	*33–52*	*35–52*	*37–52*	*40–52*	*45–52*	*52–58*	*52–63*
1351	A9n	5.656	0.302	0.211	0.254	0.339	0.129	0.155	0.258
1389	A2IV	4.320	0.101	0.074	0.085	0.069	0.014	0.048	0.061
1411	K0III	4.086	1.478	1.295	1.408	1.268	0.439	0.462	0.728
1412	A7III	3.469	0.316	0.255	0.205	0.210	0.064	0.095	0.171
753	K3V	6.143	1.366	1.195	1.485	1.209	0.303	0.603	0.907
5340	K2IIIp	0.217	2.400	2.032	2.090	1.698	0.554	0.610	0.969
7001	A0V	0.028	0.035	0.039	0.011	0.002	0.003	0.006	0.001
7906	B9V	3.768	– 0.337	– 0.295	– 0.272	– 0.096	– 0.018	– 0.005	– 0.012
5634	F5V	5.011	0.153	0.104	0.273	0.482	0.221	0.220	0.373
5640	gK1	6.106	2.311	2.023	2.115	1.715	0.561	0.591	0.938
7181	K2III	5.572	2.294	2.000	2.090	1.687	0.541	0.609	0.974
7202	B5V	5.679	– 0.852	– 0.792	– 0.529	– 0.128	– 0.005	– 0.010	– 0.016

Object	Sp	*58–72*	*58–80*	*58–86*	*58–99*	*58–110*	*NB/NR*	Notes
1351	A9n	0.192	0.266	0.275	0.302	0.368	2/10	Hyades 30
1389	A2IV	0.025	0.044	0.031	0.057	0.082	2/10	Hyades 56
1411	K0III	0.503	0.715	0.807	0.959	1.127	13/6	Hyades 71
1412	A7III	0.122	0.173	0.175	0.227	0.262	15/5	Hyades 72
753	K3V	0.575	0.807	0.906	1.063	1.258	14/35	
5340	K2IIIp	0.717	1.008	1.144	1.376	1.574	13/19	Arcturus
7001	A0V	0.007	0.012	0.001	0.019	0.009	19/46	Vega
7906	B9V	– 0.012	– 0.022	– 0.028	– 0.047	– 0.054	11/72	α Del
5634	F5V	0.288	0.403	0.434	0.466	0.533	10/14	Extinction
5640	gK1	0.659	0.926	1.056	1.265	1.455	8/12	Pair
7181	K2III	0.675	0.956	1.087	1.295	1.505	5/7	Extinction
7202	B5V	– 0.019	– 0.025	– 0.045	– 0.098	– 0.126	5/7	Pair

must be lowered to observe Arcturus linearly (gains 4 + 1 to 6 + 6), and the 8C high voltage lowered to observe Vega (is offscale at 1 + 1 for 700V and the 45 filter). Second, both show some evidence for variability in the 13-C observations. Four previous 8C observations of Vega from JML and JM give *37–52* = 0.043 ± .020 (p.e.) while fifteen observations at SPM give *37–52* = 0.002 ± .008. The JM observations were made from April 1965 to September 1966 at an average air mass of 1.11, and the SPM observations from May 1975 to August 1978 at an average air mass of 1.18. The large probable error for the JM observations (see Table 10) and the systematic difference between the two sets of data suggest variability. Wisniewski and Johnson (1979) have discussed prior observations which indicate that Vega is variable both photometrically and spectroscopically. For Arcturus, the SPM observations show probable errors in the range 0.016 to 0.035 for the *52* and *58* magnitudes and for the *33–52*, *35–52* and *37–52* colors; and a systematic difference of 0.047 magnitude from four previous *52* observations of JM.

III. OBSERVING PROCEDURES

The 13-C observing procedures have evolved somewhat during 1973-79; the following outlines those procedures which best fit the DC equipment and observing conditions of SPM. For each filter ten-second integrations are taken in the order star-sky-star. . ., and for bright stars at small air masses usually three integrations are sufficient. For standard stars at large air mass or for faint stars more integrations per filter are made, and sometimes we run through the filter order more than once. The following are the usual orders of observation: (a) for 8C: *33, 35,* . . . *52, 58, 63,* S.S. and (b) for 6RC: *72, 80, 86, 99, 110, 58,* S.S., where "S.S." represents the standard source (lamp). In this manner the standard lamp, is observed soon after the *52* and *58* measures, which are reduced as magnitudes compared to the S.S. For a fifth-magnitude solar-type star, the 1.5 meter telescope, and a high voltage of 900VDC, the 6RC filters *72, 80, 86* and *99* require a gain of 5 + 1 or 5 + 2 on the DC amplifier N°1; filter *58* one magnitude more gain; and *110* approximately three magnitudes more gain. Under similar conditions, 8C photometry and 700VDC, the gain minimizes at approximately 2 + 5 for the *45* filter. These gain settings refer to the original filter set used throughout 1973-79.

We have observed during the 225 nights using exclusively DC equipment of the form: DC amplifier, voltage to frequency convertor, counter and a printer plus digital clock. A chart recorder was used as backup. We have used the amplifier N°1 (tube type), which is one of the first designed and constructed by Johnson (1962) for nearly all of the observations 1973-79; amplifier N°4 (solid state) was used only very infrequently. Both amplifiers have 0.5 and 2.5 magnitude steps giving a total range of 15.0 magnitudes. Amplifier N°1 was calibrated approximately every 6 months from 1973 to 1976 and every 3 or 4 months from 1977 to the present, using the high precision AC/DC calibrator built by Ortega (1971). With this calibrator the gain steps have been measured to within ±.001 magnitude or better. We have found that amplifier N°1 is very stable showing on the average less than a 0.02 magnitude change in the total gain table from October 1973 to the present. M. Alvarez has been regularly using amplifier N°4 from 1977 to the present, and we find that this amplifier is less stable, particularly for the fifth 2.5 magnitude gain setting (5 + 1 thru 5 + 6). Amplifier N°4 should be calibrated more frequently, preferably once during each observing run.

When possible, we have observed each night at least ten 13-C standards to determine the extinction and transformation coefficients. Sometimes we have observed one extinction pair at small, intermediate and large air masses with other 13-C standards observed at small air masses. At other times we have observed two extinction pairs at small and large air masses. On the average, per night four standards were observed at small air mass ($X < 1.3$), four at intermediate air mass ($1.3 < X < 1.8$), and two to four at large air mass ($X > 1.8$).

The 1P21 and 7102 photomultipliers of the 8C and 6RC photometers, respectively, have always been dry-ice cooled in cold boxes of the type described by Johnson (1962). The 1P21 has been operated with a high-voltage of 700VDC and the 7102 approximately 900-950V. The noise of our particular 7102 increases dramatically for voltages over 950V, and the signal of the 7102 is linear only for gains 4 + 1 to 6 + 6. For bright red stars the 6RC high voltage must be lowered so that the signal remains on-scale for these gains.

Both photometers contain standard sources (S.S.'s) which are observed quickly after each star for use in the magnitude reductions. By means of a 1P39 phototube and feed-back electronics the S.S.'s should maintain a constant brightness over an entire night, and observations of S.S.'s are used to cancel out any effects which change the sensitivity of the photomultipliers such as drifts in the high-voltage supply. However, our experience has shown that the S.S.'s are themselves sometimes slightly variable. For example, the 6RC S.S. was very constant for the years 1973-77, but in 1978 it started to cause problems. Problems with the 6RC S.S. are minor since we have usually published only the colors from 6RC photometry, using 6RC magnitudes only as a check on the 8C values. However, the 8C S.S. has also shown small fluctuations for most of the period 1973-79. As normal procedure starting in 1975 because of the stability of the 1P21 and the DC amplifiers, we have reduced all 8C photometry both with and without the S.S. and then used that solution which gives the smallest residuals. Finally, we emphasize that the color observations and reductions do not depend in any way on the S.S. measurements.

IV. REDUCTION PROCEDURES

The original 13-C reduction program, used for the data of JML, MJ and JM, has been used for the SPM photometry (Mitchell 1975). This computer program uses the standard star observations to make a least-squares solution for the constants a, b, Δk, a_c, b_c and Δk_c in the transformation equations:

$$M_s = M' - \Delta k Z + a + bC_s$$
$$\text{and } C_s = a_c + b_c(C' - \Delta k_c Z)$$

where M_s and C_s are the standard magnitudes and colors respectively, M' and C' the instrumental values including the mean atmospheric extinction, and X the air mass. The constants a and a_c are the magnitude and color zero-points respectively, b and b_c the color terms, and Δk and Δk_c corrections to the mean extinction coefficients. We have been observing at SPM with the original filters and photomultipliers and so have not used any second-order terms, such as those discussed by Crawford and Barnes (1970) for *uvby* photometry, in the transformation equations. Also, due to the narrowness of the filters we have not included any color term in the extinction; this assumption will be tested below. In general we have solved, whenever possible, for the full six coefficients and have rarely used mean values for the color and extinction terms.

In the original transformations of JML, MJ and JM the color coefficients were 0.0000 for magnitudes and 1.0000 for colors. In Table 3 we give the yearly average coefficients from 222 nights of SPM photometry 1973-79. (For 8C photometry, the *52* magnitude was reduced using the *33–52* color, and the *58* magnitude using *52–58*. For 6RC photometry *58* was reduced using the colors *58–80* and *58–72*). We see that the filters have not changed during the seven years of our observations (within the precision of our determinations), but have changed slightly since the definition of the 13-C system. For example, from Table 3 and from a transmission curve measured in Ensenada, we conclude that the filter *35* now in use on SPM has an effective wavelength closer to that of filter *52* than originally. Also, the filters now show visible evidence of deterioration, but to date we have rarely encountered trouble transforming our data onto the standard 13-C system, neither for subdwarfs, nor for the stars of Table 1 (red standards occasionally have given large residuals for *35–52*). We have compared (Schuster 1976*b*) previous 8C observations of 24 subdwarfs and Hyades stars (Johnson and Mitchell 1968, plus JML and MJ) and previous 6RC photometry of 7 subdwarfs (MJ) with SPM photometry. The 8C comparisons showed significant systematic differences of approximately 0.015 for only the 52 magnitude and the *52–63* color, and the 6RC comparisons no systematic differences larger than 0.009. The original 63 filter is not an interference filter but a long-pass red glass filter, and so systematic differences in *52–63* may reflect changes in the photomultiplier or its refrigeration.

The 13-C computer program used in our reductions is versatile, allowing solutions with or without the S.S. measures, mean transformation coefficients and/or mean extinction coefficients for each of the magnitudes or colors. We have generally used an air mass criterion of

TABLE 3

AVERAGE COLOR COEFFICIENTS-ORIGINAL FILTER SET

Year	*52*	*33–52*	*35–52*	*37–52*	*40–52*	*45–52*	*52–58*	*52–63*	*58*	No. Nights
1973	0.0023	1.0135	1.0181	0.9995	1.0299	0.9987	1.0002	0.9999	0.0075	7
1974	0.0053	1.0094	1.0306	0.9881	1.0262	1.0090	0.9984	1.0027	0.0273	30
1975	0.0027	1.0022	1.0265	0.9900	1.0221	0.9882	0.9825	0.9992	0.0299	12
1976	0.0057	1.0026	1.0282	0.9865	1.0225	0.9928	0.9894	0.9996	0.0357	29
1977	0.0039	1.0049	1.0268	0.9882	1.0256	0.9944	0.9906	1.0043	0.0236	34
1978	0.0046	1.0078	1.0311	0.9899	1.0252	0.9917	0.9941	1.0025	0.0280	9
1979	0.0040	1.0149	1.0231	0.9934	1.0362	1.0030	0.9947	1.0035	0.0188	5
Mean	0.0045	1.0062	1.0277	0.9889	1.0253	0.9973	0.9924	1.0020	0.0271	126

Year	*58*	*58–72*	*58–80*	*58–86*	*58–99*	*58–110*	*58*	No. Nights
1973	– 0.0046	1.0283	1.0168	1.0208	1.0181	1.0220	– 0.0061	8
1974	+ 0.0437	1.0485	1.0277	1.0212	1.0142	1.0118	+ 0.0620	32
1975	0.0445	1.0398	1.0212	1.0132	1.0073	1.0141	0.0635	7
1976	0.0402	1.0467	1.0271	1.0186	1.0119	1.0110	0.0572	14
1977	0.0305	1.0519	1.0314	1.0251	1.0192	1.0170	0.0440	15
1978	0.0415	1.0430	1.0242	1.0203	1.0135	1.0119	0.0590	15
1979	+ 0.0126	1.0515	1.0348	1.0261	1.0220	1.0250	+ 0.0183	5
Mean	0.0352	1.0458	1.0266	1.0209	1.0148	1.0142	0.0502	96

0.8 and a color criterion of 0.5 magnitude in our reductions. That is, if the range of air mass of the standard star observations is greater than 0.8, a least squares solution for the correction to the mean extinction is made. If not, default corrections are used, and these can be selected according to the conditions of the observing run. For example, an air mass range less than 0.8 and default extinction corrections of 0.000 imply that only the mean extinction values will be used in the reductions. Similarly, if the color range of the standard stars exceeds 0.5 magnitude, solutions for b and b_c are made; if not, mean values are assumed. Also, a third criterion, multiplied by the air mass, is used to define the level of acceptance or non-acceptance of a standard star observation. We have usually taken a large value (0.15 magnitude) for this criterion in order to throw out only observations affected by gross copy errors, such as an incorrect gain setting.

Finally, after the least-squares solutions, the program prints tables of residuals for each magnitude and color. Each residual is the difference between a standard star's calculated color, using the derived transformation and extinction coefficients, and the standard 13-C color. By examining these residuals as a function of air mass, color and time, we can decide whether or not the night was really good for photometry, if the S.S. was constant, whether the mean coefficients (if used) are adequate, and so forth.

V. ATMOSPHERIC EXTINCTION

In Tables 4, 5 and 6 we give atmospheric extinction data for SPM covering the years 1973-79. Tables 4 and 5 contain yearly and monthly averages, respectively, from 212 nights of normal photometry with approximately ten standards observed each night, and Table 6 extinction data from two special nights in 1977 when a single extinction pair was observed repeatedly over a wide range of air masses. In Figure 1, we plot the average extinction for the seven years and the data for individual stars from the two special nights. In Table 4 and Figure 1 the 6RC extinction has been adjusted to the 8C values at the *58* filter. As implied above, the color extinctions

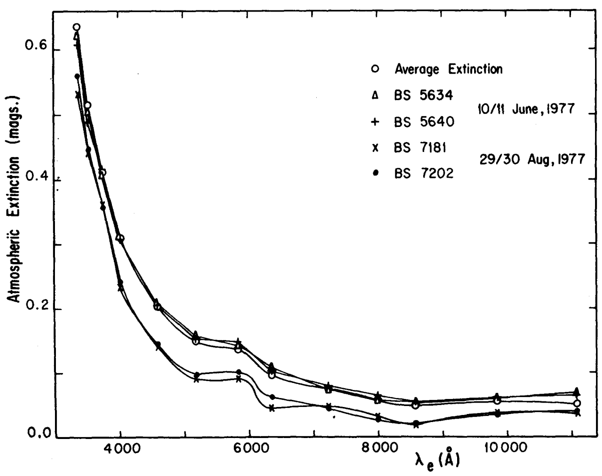

Fig. 1. Atmospheric extinction versus the effective wavelengths of the 13-C filters. Circles represent average values from 119 nights of 8C photometry and 93 nights of 6RC photometry. Triangles (BS5634), pluses (BS5640), crosses (BS7181), and dots (BS7202) show the data from the two special extinction nights.

TABLE 4

AVERAGE EXTINCTION-YEARLY VALUES

Year	*33*	*35*	*37*	*40*	*45*	*52*	*58*	*63*	No. Nights
1973	0.589	0.473	0.389	0.299	0.170	0.120	0.110	0.067	5
1974	0.667	0.542	0.438	0.325	0.217	0.161	0.145	0.107	26
1975	0.676	0.553	0.458	0.342	0.231	0.179	0.168	0.120	12
1976	0.642	0.520	0.412	0.315	0.209	0.155	0.143	0.103	29
1977	0.613	0.493	0.384	0.290	0.188	0.133	0.122	0.083	33
1978	0.613	0.493	0.384	0.297	0.193	0.139	0.120	0.082	9
1979	0.600	0.484	0.389	0.286	0.186	0.133	0.120	0.081	5
Mean	0.637	0.515	0.411	0.310	0.203	0.149	0.136	0.096	

Year	*58*	*72*	*80*	*86*	*99*	*110*	No. Nights
1973	0.134	0.060	0.059	0.036	0.046	0.060	7
1974	0.145	0.078	0.059	0.052	0.061	0.052	32
1975	0.146	0.078	0.065	0.056	0.063	0.058	7
1976	0.122	0.064	0.049	0.037	0.048	0.051	13
1977	0.103	0.043	0.028	0.021	0.025	0.017	14
1978	0.102	0.051	0.028	0.018	0.023	0.015	15
1979	0.070	0.019	0.002	0.009	0.014	0.004	5
Mean	0.124	0.062	0.045	0.036	0.043	0.039	93
Corr. to 8C	0.136	0.074	0.057	0.048	0.055	0.051	

TABLE 5

AVERAGE EXTINCTION-MONTHLY VALUES

Month	*33*	*35*	*37*	*40*	*45*	*52*	*58*	*63*	No. Nights
February	0.648	0.528	0.437	0.328	0.227	0.183	0.169	0.124	11
March-April	0.629	0.505	0.406	0.307	0.202	0.151	0.138	0.096	13
May	0.649	0.537	0.430	0.323	0.215	0.162	0.162	0.118	19
June	0.676	0.550	0.438	0.336	0.228	0.172	0.147	0.112	21
July-August	0.651	0.519	0.416	0.313	0.202	0.142	0.127	0.085	19
September	0.591	0.470	0.358	0.268	0.165	0.105	0.098	0.062	13
October	0.596	0.484	0.380	0.287	0.180	0.131	0.119	0.078	10
November	0.617	0.496	0.396	0.295	0.189	0.133	0.114	0.079	9
Dec.-Jan.	0.597	0.489	0.376	0.274	0.178	0.125	0.110	0.074	4
Mean	0.637	0.515	0.411	0.310	0.203	0.149	0.136	0.096	119

Month	*58*	*72*	*80*	*86*	*99*	*110*	No. Nights
February	0.146	0.080	0.067	0.063	0.054	0.041	12
March-April	0.151	0.071	0.060	0.052	0.045	0.041	6
May	0.127	0.062	0.048	0.039	0.044	0.048	18
June	0.126	0.072	0.051	0.040	0.052	0.050	16
July-August	0.118	0.064	0.042	0.030	0.046	0.031	11
September	0.128	0.062	0.045	0.036	0.049	0.065	7
October	0.108	0.050	0.039	0.014	0.033	0.028	7
November	0.111	0.040	0.026	0.018	0.033	0.008	10
Dec.-Jan.	0.083	0.034	0.012	0.006	0.004	0.023	6
Mean	0.124	0.062	0.045	0.036	0.043	0.039	93

TABLE 6

SPECIAL EXTINCTION NIGHTS-INDIVIDUAL VALUES

Date	Star	Sp	*33*	*35*	*37*	*40*	*45*	*52*	*58*	*63*	Maximum Air Mass	No. Obs.	S.S.
10/11 June 1977	BS5634	F5 V	0.621	0.504	0.406	0.310	0.209	0.157	0.143	0.107	4.311	22	with
10/11 June 1977	BS5640	gK 1	0.609	0.488	0.410	0.307	0.203	0.154	0.145	0.104	4.947	21	with
29/30 Aug 1977	BS7181	K2 III	0.532	0.441	0.360	0.232	0.139	0.091	0.090	0.043	3.363	14	with
29/30 Aug 1977	BS7202	B5 V	0.560	0.446	0.357	0.240	0.145	0.097	0.101	0.060	4.401	14	with

Date	Star	Sp	*58*	*72*	*80*	*86*	*99*	*110*	Maximum Air Mass	No. Obs.	S.S.
10/11 June 1977	BS5634	F5 V	0.141	0.075	0.057	0.051	0.060	0.068	7.468	25	without
10/11 June 1977	BS5640	gK 1	0.147	0.078	0.065	0.053	0.060	0.066	5.005	25	without
29/30 Aug 1977	BS7181	K2 III	0.092	0.046	0.031	0.017	0.037	0.037	5.318	17	with
29/30 Aug 1977	BS7202	B5 V	0.097	0.040	0.026	0.020	0.034	0.040	5.874	17	with

are always well determined but magnitude extinctions will sometimes contain the effects of S.S. problems; we have generally taken greater care to remove S.S. variations from 8C data than from 6RC data since only 6RC colors are published.

In Table 4 we see that the atmospheric extinction of SPM has *not* increased with time perhaps because the prevailing winds are from the southwest, off the ocean, and not from the urban centers to the northwest. If we plot the *mean* visual (550 nm, average of filters *52* and *58*) optical thickness of SPM against its altitude (2830 m), the point falls on the "unpolluted air" curve of Galloway (1975, 1979) calculated using only Rayleigh scattering, stratospheric ozone, and tropospheric and stratospheric aerosols. Further, we note that the average extinctions of the years 1977-79 are in fact *lower* than the average values for 1974-76, and also that in Table 5 the average extinctions of the fall and first winter months are lower than the values for the other seven months. These facts are probably due to the rainfall patterns at SPM during 1973-79. The rains of summer and fall remove part of the tropospheric particle content leading to smaller extinctions during the fall and early winter months. In 1977 a long dry spell ended for SPM with much rain during the second half of the year, and 1978 and 1979 were years of high rainfall. Such variations, when analyzed in terms of the models of Galloway (1975, 1979) suggest that during some months or years SPM *was* somewhat polluted with a particulate content corresponding to a ground level concentration as high as 30 $\mu g/m^3$ while at other times the visual optical thickness of SPM actually falls beneath the "unpolluted air" curves of Galloway. Such variations probably depend not only on rainfall but also on wind direction with a significant "pollution" contribution being dust from the deserts to the north and northeast as well as urban pollution.

In Table 7 we compare mean visual extinction data for various observatories (from Galloway 1975) with our mean value for SPM. For SPM we have used only 8C data from the years 1976-79. The mean SPM value is the average of the *52* and *58* extinctions, but the standard deviation was calculated from only the *52* values. According to Galloway (1975) and references therein, the first five observatories of Table 7 are classified as maritime sites, the next twelve sites as continental, and the last six as urban. SPM was designated as a continental site by Galloway, but we feel that with prevailing winds from the southwest, off the ocean, SPM would usually classify as a maritime site. Infrequently the winds do come from the north, and under such conditions SPM would perhaps better classify as a continental site. In Table 7 we note that SPM has one of the lowest values of the mean visual extinction, surpassed only by Mauna Kea. However, the SPM extinction data do have an unusually large dispersion considering the elevation and distance from urban centers. Such a large dispersion implies that the use of mean extinction coefficients is not as appropriate for SPM as for other sites.

The comparison of Tables 4, 5 and 7 together with the author's experience concerning "seeing" at SPM and the results of Walker (1971) suggest the following speculative interpretation of the conditions on SPM. South to west winds off the cold ocean classify SPM as a maritime site and produce laminar flow over the observatory leading to good seeing and relatively low photometric extinction values. Northern winds produce conditions more like a continental site with higher turbulence (poor seeing) and higher extinction due to urban and dust pollutants from the north. Rainfall has modulated such variations in the extinction by periodically cleansing particulates from the troposphere. Less speculative conclusions require rainfall and wind direction data for the years 1973-79.

The extinction curves of Figure 1 show a very definite "red hump" at filter *58*, and a preliminary examination of this data by Galloway (1980) suggests that this hump is caused exclusively by ozone. An unusual size distribution for the aerosols, such as discussed by Porch

TABLE 7

MEAN VISUAL EXTINCTION AT VARIOUS OBSERVATORIES (GALLOWAY 1975)

Observatory	k_V (mag)	Elevation (m)	Epoch
Royal, Cape of Good Hope, S. Africa	0.177 ± .008	10	1968
Mt. Stromlo, Australia	0.168 ± .003	768	1962-63, 67-70
Mt. John, New Zealand	0.172 ± .040	1029	1971
Siding Spring, Australia	0.158 ± .004	1164	1964-72
Mauna Kea, Hawaii	0.110 ± .005	4170	1966
Le Houga, France	0.241 ± .007	140	1963-65
Yerkes, Wisconsin	0.215 ± .025	334	1965
Haute Provence, France	0.231 ± .006	651	1956-61
Rattlesnake Ridge, Washington	0.302 ± .017	1080	1966-69
Lick, California	0.179 ± .005	1283	1960-67
Boyden, South Africa	0.187 ± .005	1387	1958-65
Radcliffe, South Africa	0.227 ± .009	1542	1966-69
Kitt Peak, Arizona	0.182 ± .003	2064	1960-70
Mc Donald, Texas	0.173 ± .003	2081	1960-68
Cerro Tololo, Chile	0.149 ± .003	2195	1964-70
Lowell, Arizona	0.189 ± .006	2210	1953-66
European Southern, Chile	0.166 ± .008	2400	1970
Javan, Sweden	0.346 ± .024	84	1968-71
Chabot, California	0.426 ± .041	107	1972-73
Flower + Cook, Pennsylvania	0.384 ± .021	155	1961-65
DAO, Canada	0.29 ± .002	229	1956
Mt. Wilson, California	0.228 ± .041	1742	1960-62
Republic, Johannesburg, S. Africa	0.268 ± .013	1806	1964-71
SPM, Baja California, México	0.136 ± .022	2830	1976-79

et al. (1973), is not required, and Galloway (1980) feels that this extinction curve can be explained in terms of Rayleigh scattering, ozone, aerosols and water.

In Table 6 we see that not using a second-order color term for the extinction is a good assumption for all filters except *33*. During both of the special extinction nights the bluer star showed a somewhat larger extinction in *33* than the red star. However, ignoring this second-order correction would lead to errors less than 0.015 magnitude for B-thru K-type stars observed at unit air mass.

In Table 8 we give mean atmospheric extinction values for other photometric systems at SPM. These figures have merely been read from Figure 1 at the effective wavelengths of the filters as given by Allen (1973) and can be combined directly to give color extinctions. For example, in the Strömgren system $k(b-y) = 0.052$, $k(m_1) = 0.041$, and $k(c_1) = 0.154$ for SPM.

TABLE 8

MEAN ATMOSPHERIC EXTINCTION AT SPM FOR VARIOUS PHOTOMETRIC SYSTEMS

System	Mean Extinction SPM
Johnson five-color:	*U* – 0.456
	B – 0.232
	V – 0.141
	R – 0.078
	I – 0.050
Strömgren Intermediate Band:	*u* – 0.534
	v – 0.287
	b – 0.194
	y – 0.142
Six Color:	*U* – 0.502
	Vi – 0.268
	B – 0.171
	G – 0.138
	R – 0.075
	I – 0.054

VI. PROBABLE ERRORS OF THE OBSERVATIONS

In Tables 9, 10 and 11 are given probable errors of a single observation for the 13-C observations on SPM during 1973-79. The values of Table 9 were derived from the standard star residuals of the least-squares reductions. These errors include a correction $[(n-1)/(n-3)]^{1/2}$ where n is the number of standard stars observed each night, because the least-squares procedure solves for three transformation and extinction coefficients. The errors of Table 9 correspond to the air masses of observation (an average air mass of approximately 1.5 for most years), and are larger than the errors for many program stars. The standard star residuals include observations of extinction pairs at large air masses.

In Table 10 the errors have been separated according to spectral type, corrected exactly to unit air mass, and multiplied by $[(n-1)/(n-3)]^{1/2}$, where in this case n is the average number of standards observed per night. The data of Table 10 cover only the years 1975-79 whose computer outputs exist on magnetic tape; also, five 8C nights from 1975, two 8C nights from 1976, and the two extinction nights are not included in Table 10.

Probable errors of a single observation from the two extinction nights are given in Table 11. These errors were calculated at the air masses of observation, and the least-squares solutions and residuals were obtained for each star of a pair individually.

In Table 9 we see that the errors have on the average decreased with time due to improved observing tech-

TABLE 9

PROBABLE ERRORS OF SINGLE OBSERVATION FROM LEAST-SQUARES RESIDUALS

Year	*52*	*33–52*	*35–52*	*37–52*	*40–52*	*45–52*	*52–58*	*52–63*	*58*	Ave. Air Mass	No. Nights
1973	0.0240	0.0189	0.0137	0.0168	0.0096	0.0086	0.0152	0.0136	0.0204	1.314	7
1974	0.0276	0.0173	0.0220	0.0175	0.0135	0.0104	0.0154	0.0187	0.0232	1.477	30
1975	0.0163	0.0161	0.0195	0.0134	0.0135	0.0079	0.0112	0.0139	0.0182	1.480	13
1976	0.0143	0.0105	0.0193	0.0147	0.0083	0.0066	0.0081	0.0112	0.0150	1.531	30
1977	0.0154	0.0128	0.0189	0.0154	0.0102	0.0057	0.0076	0.0089	0.0146	1.568	34
1978	0.0113	0.0115	0.0192	0.0116	0.0071	0.0054	0.0076	0.0092	0.0132	1.536	9
1979	0.0099	0.0146	0.0157	0.0185	0.0064	0.0034	0.0064	0.0058	0.0131	1.477	5

Year	*58*	*58–72*	*58–80*	*58–86*	*58–99*	*58–110*	Ave. Air Mass	No. Nights
1973	0.0226	0.0180	0.0238	0.0159	0.0160	0.0338	1.453	8
1974	0.0201	0.0157	0.0142	0.0153	0.0166	0.0287	1.517	33
1975	0.0103	0.0089	0.0105	0.0111	0.0146	0.0196	1.556	7
1976	0.0104	0.0072	0.0063	0.0061	0.0079	0.0275	1.556	14
1977	0.0146	0.0095	0.0097	0.0087	0.0109	0.0183	1.530	15
1978	0.0161	0.0079	0.0076	0.0079	0.0114	0.0170	1.557	15
1979	0.0236	0.0063	0.0073	0.0058	0.0093	0.0119	1.446	5

TABLE 10

PROBABLE ERRORS AT UNIT AIR MASS FOR STANDARD STARS

Spectral Types	*52*	*33–52*	*35–52*	*37–52*	*40–52*	*45–52*	*52–58*	*52–63*	*58*	NB
O, B	0.0096	0.0073	0.0086	0.0078	0.0068	0.0041	0.0072	0.0084	0.0112	360
A, F, G	0.0115	0.0096	0.0107	0.0082	0.0066	0.0039	0.0068	0.0089	0.0125	194
K, M	0.0116	0.0111	0.0141	0.0088	0.0070	0.0041	0.0061	0.0075	0.0121	357
Spectral Types	*58*	*58–72*	*58–80*	*58–86*	*58–99*	*58–100*	NR			
O, B	0.0100	0.0060	0.0061	0.0060	0.0081	0.0195	276			
A, F, G	0.0102	0.0073	0.0067	0.0060	0.0080	0.0145	108			
K, M	0.0137	0.0074	0.0075	0.0073	0.0093	0.0134	245			

TABLE 11

SPECIAL EXTINCTION NIGHTS-PROBABLE ERRORS FROM LEAST-SQUARE RESIDUALS

Date	Star	*52* with S. S.	*33–52*	*35–52*	*37–52*	*40–52*	*45–52*			
10/11 June 1977	BS5634	0.0085	0.0088	0.0059	0.0047	0.0089	0.0040			
10/11 June 1977	BS5640	0.0097	0.0101	0.0090	0.0052	0.0082	0.0042			
29/30 Aug 1977	BS7181	0.0145	0.0143	0.0132	0.0099	0.0097	0.0073			
29/30 Aug 1977	BS7202	0.0169	0.0160	0.0158	0.0163	0.0148	0.0098			
Date	Star	*52–58*	*52–63*	*58* with S. S.	*52* with-out S.S.	Ave. Air Mass	No. Obs.			
10/11 June 1977	BS5634	0.0037	0.0069	0.0090	0.0083	1.669	22			
10/11 June 1977	BS5640	0.0032	0.0067	0.0089	0.0079	1.699	21			
29/30 Aug 1977	BS7181	0.0127	0.0165	0.0160	0.0151	1.659	14 (15)			
29/30 Aug 1977	BS7202	0.0176	0.0225	0.0111	0.0156	1.899	14			
Date	Star	*58* with S. S.	*58–72*	*58–80*	*58–86*	*58–99*	*58–110*	*58* with-out S.S.	Ave. Air Mass	No. Obs.
10/11 June 1977	BS5634	0.0096	0.0075	0.0095	0.0102	0.0080	0.0310	0.0042	2.049	25
10/11 June 1977	BS5640	0.0072	0 0089	0.0081	0.0090	0.0078	0.0182	0.0062	1.749	25
29/30 Aug 1977	BS7181	0.0054	0.0060	0.0061	0.0046	0.0066	0.0118	0.0194	1.902	17
29/30 Aug 1977	BS7202	0.0070	0.0110	0.0078	0.0082	0.0086	0.0114	0.0181	2.146	17

niques and to greater familiarity with, and minor improvements in, the equipment. For example, with practice we now can observe a bright star much more quickly than originally giving less time for small extinction fluctuations.

The data of Table 10 can be used in variability studies of bright stars, such as Be stars or supergiants. However, some values of Table 10 may only apply to the original 13-C filter set used on SPM during 1973-79 and not to the four new sets purchased in 1980. For example, the original *35* filter occasionally gave large *35–52* residuals ($\gtrsim$0.05 magnitude) for red standard stars. This behaviour may be related to the deterioration of the filters, and so the large *35–52* error for K, M stars in Table 10 would not apply to the new filter sets. Also, the new *63* filters are interference filters and require larger amplifier gains than the original long-pass *63* filter; the *52–63* errors of Table 10 may need revision for the new filter sets. The large *58–110* error for 0, B stars is due to the low sensitivity of the 7102 photomultiplier and the relative faintness of the O, B stars at 1.1 μ.

The errors of Table 11 show that during some nights at SPM fairly accurate photometry can be taken to very large air masses. For example, during the night of 10/11 June 1977, 8C residuals of only 0.01 to 0.04 magnitude were obtained to approximately 5 air masses and 6RC residuals of only 0.01 to 0.03 to 7.5 air masses (excluding the *58–110* color). The results of Schuster and López (1976) from 8C observations at SPM during March 1976 also showed good photometric precision to nearly three air masses.

VII. MISCELLANEOUS DATA

Approximate interstellar reddening ratios for the 13-C system are given in Table 12, normalized to

TABLE 12

MEAN INTERSTELLAR REDDENING RATIOS (normalized for *45-63*)

Color	Reddening Ratio
33–52	1.3
35–52	1.15
37–52	1.0
40–52	0.8
45–52	0.4
52–58	0.35
52–63	0.6
52–72	0.9
52–80	1.1
52–86	1.25
52–99	1.55
52–110	1.7
B-V	0.75
45–63	1.00

45–63 = 1.00. Also shown is the ratio for the Johnson *B – V* index. This data represents a mean of values taken from the works of Whitford (1958), Whiteoak (1966), Johnson (1977) and Borgman (1961).

A grid of theoretical 13-C photometry has been provided by Kurucz (1975) for compositions 1, 0.1 and 0.01 times the solar composition, for effective temperatures from 5500°K to 10000°K and for surface gravities from log g = 2.0 to 4.5. This grid was constructed using the filter-detector response functions of JML and MJ, Kurucz's (1974, 1979; Relyea and Kurucz 1976) Kitt Peak grid of model atmospheres, and the 13-C observations of Vega for normalization. The precision and usefulness of this theoretical photometry has been discussed by Schuster (1979*a, b*), by Kurucz (1979), and by Relyea and Kurucz (1976). A newer grid of model atmospheres with an improved treatment of convection and with a wider range of composition now exists (Kurucz 1979) and will eventually be used to construct a revised grid of theoretical 13-C photometry.

Mean colors for the Hyades main sequence for spectral types A4 to K4 have been given by Schuster (1979*a*), and derived 13-C photometry for the Sun by Schuster (1976*a*). Calibrations of the 13-C indices for composition ([Fe/N]), effective temperature, surface gravity, bolometric corrections, and blanketing have been presented by Schuster (1976*b*; 1979*a, b*).

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