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13-COLOR PHOTOMETRY OF SOLAR-TYPE STARS

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RESUMEN

Se reporta la fotometría de 13 colores de 81 estrellas de tipo solar, así como la fotometría derivada de 13 colores del Sol, del trabajo no publicado de R. I. Mitchell. Con estos datos se examinan efectos de metalicidad y luminosidad en estrellas de tipo solar y en el Sol; además se seleccionaron nueve estrellas cuyas características fotométricas son similares a las del Sol.

ABSTRACT

Thirteen-color photometry of 81 solar-type stars as well as the derived 13-color photometry for the Sun from the unpublished work of R. I. Mitchell is reported. This data is used to examine metallicity and luminosity effects in solar-type field stars and in the Sun. Nine stars are selected which are photometrically similar to the Sun.

Key words: PHOTOMETRY — METALLICITY — LUMINOSITY.

I. INTRODUCTION

In the spring of 1974 we undertook at the San Pedro Martir Observatory a 13-color photometric program of bright stars. The intention of the program is the measurement of all northern stars in the *Catalogue of Bright Stars* (Hoffleit 1964) that were not measured by Johnson, Mitchell and Latham (1967) or by Mitchell and Johnson (1969). As the first part of this program we decided to measure solar-type bright stars —that is, stars of spectral types F9 through G5 and luminosity classes, subdwarf, dwarf and subgiant. The photometry of such solar-type stars can have several applications. If we can somehow derive 13-color photometry for the Sun, our stellar photometry can then be used to arrive at a better understanding of how the Sun compares, both photometrically and spectroscopically, with other G dwarfs. Such comparisons can show us whether the Sun is in some way abnormal and perhaps they can give us ideas concerning the formation of the Sun and the solar system. Also, we can select stars which photometrically are very similar to the Sun and then use these special stars for more detailed studies such as a more refined determination of the solar colors, more exact comparisons of solar and stellar model atmospheres and metal abundances, as well as photometric albedo studies of the planets and their satellites.

In this paper we report on the 13-color photometry for the first 81 such solar-type stars. These data are used to briefly examine some metallicity and luminosity effects in solar-type field stars; further, using derived 13-color photometry for the Sun, 9 stars have been selected that photometrically are quite similar to the Sun. These 9 stars are used to examine the accuracy of the derived solar colors in the infrared, and then based on these derived solar colors we study briefly the luminosity class and metallicity of the Sun. In addition, we have been studying subdwarfs using 13-color photometry. The photometry of only two of these subdwarfs is reported here, but in total 27 of these subwarfs, of spectral types F9 to G5, and with magnitudes brighter than

TABLE 1

13 - Color Photometry of Solar Type Stars

Name	52	33-52	35-52	37-52	40-52	45-52	52-58
5	6.196	0.584	0.492	0.736	0.806	0.303	0.362
72	6.666	0.658	0.536	0.759	0.803	0.320	0.355
88	6.570	0.560	0.448	0.681	0.775	0.319	0.345
159	5.826	0.605	0.485	0.766	0.824	0.310	0.374
173	6.362	0.631	0.430	0.692	0.808	0.336	0.356
300	6.582	1.318	1.059	1.218	1.148	0.434	0.454
448	5.915	0.580	0.462	0.654	0.754	0.301	0.316
508	6.443	0.716	0.596	0.802	0.862	0.332	0.350
560	6.137	0.332	0.241	0.444	0.627	0.275	0.270
582	6.014	0.530	0.420	0.611	0.718	0.228	0.308
660	5.026	0.312	0.236	0.474	0.674	0.290	0.348
695	5.378	0.454	0.345	0.561	0.706	0.290	0.316
720	6.042	0.406	0.312	0.490	0.686	0.300	0.296
1262	6.064	0.450	0.370	0.601	0.738	0.292	0.322
1322	6.472	0.340	0.250	0.480	0.660	0.280	0.297
1532	5.626	0.466	0.380	0.615	0.749	0.302	0.325
1608	5.537	0.918	0.739	0.926	0.982	0.392	0.384
1662	6.324	0.452	0.341	0.554	0.714	0.301	0.316
1747	6.135	0.333	0.260	0.478	0.657	0.276	0.302
2007	6.138	0.426	0.313	0.584	0.740	0.296	0.331
2067	6.785	0.500	0.382	0.613	0.744	0.297	0.324
2141	6.266	0.375	0.279	0.482	0.674	0.285	0.308
2208	6.602	0.478	0.379	0.647	0.776	0.298	0.356
2251	5.879	0.391	0.299	0.548	0.700	0.291	0.326
3625	6.192	0.366	0.294	0.524	0.672	0.274	0.248
3626	6.133	0.593	0.502	0.710	0.784	0.310	0.294
3750	5.564	0.522	0.398	0.600	0.748	0.323	0.271
3862	5.109	0.278	0.202	0.396	0.594	0.260	0.228
3951	5.597	0.610	0.526	0.728	0.777	0.303	0.304
4027	6.614	0.512	0.416	0.621	0.728	0.300	0.288
4030	6.110	0.589	0.492	0.688	0.774	0.320	0.288
4098	6.668	0.367	0.279	0.514	0.684	0.297	0.279
4277	5.234	0.448	0.358	0.579	0.712	0.304	0.294
4285	6.213	0.392	0.292	0.460	0.652	0.298	0.274
4298	6.122	0.346	0.262	0.428	0.600	0.264	0.244
4328	6.623	0.392	0.296	0.514	0.688	0.302	0.286
4486	6.453	0.396	0.321	0.572	0.708	0.292	0.308
4529	6.326	0.488	0.389	0.550	0.672	0.282	0.264
4691	6.085	1.186	1.012	1.114	1.060	0.404	0.404
5148	6.454 :	0.237	0.184	0.394	0.599	0.268	0.276
5183	6.518	0.494	0.402	0.585	0.716	0.293	0.312
5270	6.392	1.292	0.916	0.880	1.052	0.510	0.430
5423	6.580	0.688	0.607	0.818	0.844	0.320	0.368
5534	6.027	0.346	0.282	0.498	0.668	0.282	0.310

52-63	52-72	52-80	52-86	52-99	52-110	NB	NR	SP
0.586	0.753	0.924	0.978	1.062	1.146	2	2	dG4
0.518	0.748	0.895	0.949	1.039	1.131	2	2	G0
0.544	0.723	0.869	0.924	1.017	1.143	1	2	dG2
0.607	0.806	0.969	1.047	1.142	1.284	2	2	G5V
0.602	0.843	1.028	1.098	1.226	1.394	2	2	dG3
0.728	0.980	1.200	1.306	1.465	1.667	2	2	G5IV
0.516	0.690	0.856	0.908	0.990	1.108	2	2	dG2
0.569	0.762	0.935	0.993	1.094	1.200	2	2	dG4
0.457	0.661	0.808	0.845	0.912	1.042	2	2	dG0
0.494	0.638	0.794	0.839	0.918	1.000	2	2	dG1
0.566	0.754	0.919	0.978	1.070	1.192	2	2	G0V
0.516	0.709	0.872	0.938	1.021	1.173	2	2	G1V
0.497	0.664	0.816	0.870	0.957	1.056	2	2	dG0
0.534	0.709	0.870	0.913	0.990	1.093	2	2	dG1
0.488	0.655	0.811	0.851	0.925	1.022	2	2	G0IV
0.520	0.707	0.861	0.911	0.989	1.118	2	2	dG1
0.645	0.860	1.060	1.150	1.271	1.418	2	2	dG4
0.529	0.726	0.890	0.938	1.018	1.144	2	2	dG2
0.490	0.635	0.805	0.850	0.930	1.054	2	2	dG0
0.554	0.725	0.885	0.961	1.035	1.168	2	2	dG4
0.539	0.734	0.904	0.959	1.040	1.136	1	2	dG0
0.506	0.668	0.834	0.888	0.966	1.048	1	2	dG0
0.581	0.744	0.907	0.963	1.044	1.124	1	2	dG4
0.528	0.706	0.876	0.932	1.020	1.133	1	2	dG0
0.448	0.624	0.768	0.824	0.864	0.930	2	2	dG0
0.507	0.672	0.844	0.912	0.964	1.090	2	2	dG3
0.487	0.689	0.861	0.921	1.000	1.107	2	2	G2V
0.394	0.562	0.696	0.735	0.782	0.880	2	2	G0V
0.517	0.686	0.858	0.914	0.977	1.060	2	2	G4V
0.492	0.702	0.874	0.908	0.956	1.069	2	2	dG0
0.498	0.687	0.852	0.915	0.972	1.061	2	2	dG2
0.492	0.699	0.849	0.903	0.955	1.051	2	2	G1V
0.491	0.668	0.814	0.868	0.902	1.064	2	2	G0V
0.472	0.678	0.816	0.850	0.954	1.002	2	2	dG0
0.412	0.586	0.716	0.752	0.791	0.882	2	2	G0V
0.484	0.696	0.843	0.898	0.954	0.944	2	2	G2V
0.522	0.734	0.888	0.958	1.024	1.171	2	2	dG1
0.448	0.634	0.768	0.822	0.872	0.967	2	2	G0
0.656	0.900	1.094	1.180	1.313	1.434	2	2	dG2
0.455	0.624	0.753	0.783	0.832	0.783	2	2	dF9
0.513	0.707	0.876	0.974	1.003	1.155	2	2	dG2
0.760	1.086	1.331	1.453	1.613	1.774	3	5	(?)
0.584	0.756	0.920	1.030	1.048	1.174	2	2	dG4
0.512	0.682	0.820	0.875	0.938	0.989	2	2	dG2

TABLE 1 - Continued

Name	52	33-52	35-52	37-52	40-52	45-52	52-58
5618	5.055	0.450	0.362	0.596	0.738	0.310	0.360
5659	6.852	0.624	0.532	0.740	0.804	0.312	0.376
5727/8	5.162	0.316	0.254	0.470	0.644	0.276	0.310
5734	6.729:	0.418	0.346	0.554	0.676	0.280	0.324
5853	6.051	0.576	0.501	0.721	0.800	0.310	0.378
5911	6.184	0.309	0.232	0.472	0.674	0.296	0.330
5968	5.551:	0.412	0.314	0.522	0.688	0.306	0.335
5996	6.457	0.644	0.542	0.716	0.774	0.302	0.366
6060	5.623	0.506	0.426	0.636	0.752	0.296	0.358
6063/4	5.322	0.354	0.282	0.488	0.667	0.292	0.340
6269	6.127:	0.689	0.578	0.748	0.823	0.326	0.389
6441	6.602	0.486	0.378	0.531	0.678	0.292	0.329
6458	5.554	0.409	0.298	0.536	0.698	0.304	0.328
6538	6.714	0.498	0.414	0.641	0.736	0.288	0.332
6836	6.542	0.273	0.167	0.426	0.591	0.258	0.271
6847	6.476	0.482	0.392	0.622	0.734	0.294	0.336
6998	6.051:	0.475	0.386	0.630	0.762	0.311	0.351
7162	5.313	0.360	0.274	0.517	0.672	0.275	0.299
7272	6.610	0.596	0.500	0.709	0.788	0.310	0.316
7291	6.413	0.346	0.242	0.478	0.617	0.254	0.283
7293/4	5.990	0.542	0.447	0.684	0.779	0.319	0.301
7569	6.236	0.528	0.398	0.630	0.740	0.320	0.292
7637	5.993	0.364	0.266	0.506	0.649	0.278	0.278
7672	5.886	0.408	0.308	0.545	0.682	0.290	0.284
7914	6.606:	0.410	0.299	0.541	0.706	0.298	0.302
7994	6.444	0.576	0.434	0.646	0.760	0.320	0.302
8041	6.366	0.566	0.455	0.657	0.744	0.310	0.306
8148	6.781	0.616	0.490	0.776	0.840	0.312	0.392
8283	5.300	0.606	0.474	0.676	0.782	0.320	0.324
8314	6.068	0.350	0.266	0.488	0.669	0.294	0.280
8544/5	5.682	0.380	0.285	0.536	0.698	0.292	0.301
8631	5.861	0.668	0.552	0.762	0.844	0.344	0.344
8737	6.553	0.506	0.372	0.613	0.740	0.307	0.316
8792	6.562	0.343	0.242	0.456	0.632	0.271	0.287
8931	6.649	0.234	0.146	0.369	0.592	0.272	0.275
9074/5	5.923	0.285	0.202	0.410	0.620	0.260	0.273
9107	6.252	0.504	0.322	0.522	0.718	0.319	0.318

52-63	52-72	52-80	52-86	52-99	52-110	NB	NR	SP
0.581	0.774	0.946	1.010	1.102	1.204	2	2	dG1
0.587	0.798	0.972	1.032	1.108	1.180	2	2	G5V
0.502	0.672	0.820	0.856	0.922	1.016	2	2	G2V/G2V
0.516	0.702	0.818	0.862	0.918	0.994	2	2	dG0
0.606	0.802	0.973	1.030	1.126	1.159	2	2	dG5
0.542	0.735	0.884	0.955	1.034	1.064	2	2	G2V
0.539	0.712	0.857	0.911	1.003	1.061	2	2	G2V
0.576	0.746	0.894	0.942	1.024	1.086	2	2	G4IV-V
0.574	0.765	0.918	0.969	1.042	1.154	2	2	dG1
0.543	0.724	0.884	0.943	1.002	1.048	2	2	dF6/dG1
0.613	0.809	0.972	1.010	1.098	1.216	2	2	dG3
0.524	0.695	0.839	0.887	0.951	1.073	2	2	G3IV
0.538	0.715	0.856	0.964	1.020	1.134	2	2	G2V
0.534	0.712	0.850	0.884	0.956	0.944	2	2	dG2
0.458	0.618	0.733	0.795	0.862	0.991	1	1	G0V
0.548	0.718	0.870	0.905	0.986	1.082	2	2	dG0
0.582	0.763	0.933	0.989	1.070	1.203	2	2	dG4
0.497	0.692	0.858	0.900	0.973	1.125	1	2	G0V
0.518	0.696	0.852	0.896	0.977	1.083	2	2	dG1
0.460	0.603	0.725	0.775	0.826	0.931	2	2	dF9
0.498	0.697	0.863	0.913	0.983	1.083	1	2	G4V/G4V
0.500	0.732	0.890	0.936	1.024	1.145	2	2	G2V
0.478	0.666	0.802	0.849	0.930	1.046	2	2	G0V
0.471	0.674	0.830	0.870	0.958	1.022	2	2	dG1
0.499	0.694	0.858	0.909	0.994	1.074	2	2	dG2
0.512	0.746	0.891	0.954	1.053	1.146	2	2	dG1
0.492	0.649	0.818	0.868	0.953	1.042	2	2	G1V
0.644	0.874	1.051	1.150	1.266	1.458	2	2	dG4
0.537	0.716	0.900	0.938	1.028	1.167	2	2	G2IV
0.469	0.648	0.790	0.830	0.906	1.003	2	2	dG0
0.504	0.687	0.827	0.889	0.975	1.088	2	2	dG1/dG2
0.581	0.798	0.974	1.034	1.148	1.273	2	2	dG3
0.518	0.702	0.863	0.918	0.997	1.115	2	2	dG1
0.450	0.629	0.761	0.801	0.858	0.955	2	2	dG0
0.452	0.627	0.773	0.812	0.875	0.984	2	2	dG0
0.456	0.616	0.761	0.800	0.855	0.939	2	2	dG0/dG0
0.537	0.743	0.926	0.984	1.083	1.205	2	2	G2V

ninth, are plotted in several of our color-color diagrams for the purpose of comparison and analysis.

II. OBSERVATIONS

All of our bright star photometry has been taken with the 60″ photometric telescope of the San Pedro Martir Observatory. The observations were done during seven nights in May and six nights in September and October 1974. The 13-color narrow band photometric system that we have been using combines the 8 color (8C) photometry defined by Johnson *et al.* (1967) with the 6 color (6RC) photometry defined by Mitchell and Johnson (1969). Each of these two photometric systems has a filter at approximately 5830Å, so that the two sets of data can be tied together using only colors. We have been using the original photometers, filters, and photomultipliers that were used to define this photometric system.

In Table 1 we present the 13-color observations of the 81 solar-type stars. Column 1 gives the number of the star from the *Bright Star Catalogue,* column 2 the 52 magnitude, columns 3 through 14 the other 12 colors measured with respect to 52, columns 15 and 16 the number of measurements made with the 8C and 6RC photometers respectively, and column 17 the spectral type from the *Bright Star Catalogue.*

All of the nights of observing were good for determining colors. However, three of the nights in May were not particularly reliable for measuring magnitudes, and so those 52 magnitudes which are followed by colons in Table 1 have been determined, in part, from the 58 magnitude of 6RC photometry plus the 52-58 color of 8C photometry. These 52 magnitudes should be considered less reliable than the others.

The standard stars used in all of our 13-color observations are the primary standards from Table 7 of Mitchell and Johnson (1969). In Table 2 we list the mean extinction coefficients from 26 nights of 8C observing and 30 nights of 6RC observing at the San Pedro Martir Observatory. These nights include those of subdwarf observing as well as those of bright star observing. Also in Table 2 the extinction coefficients for the Catalina Observatory (Johnson *et al.* 1967, Mitchell and Johnson 1969), and for Cerro Tololo and La Silla in Chile (Mendoza 1971) are listed. We see from this data that the San Pedro Martir site is probably slightly better than the Catalina and La Silla sites but slightly inferior to Cerro Tololo, although the differences are small.

The estimated probable errors of a single observation for the San Pedro Martir observations are in Table 3. These probable errors are compared to those of the Catalina observations (Johnson *et al.* 1967, Mitchell and Johnson 1969). We estimated

TABLE 2

13-COLOR EXTINCTION

Filter	San Pedro	Catalina	Tololo Feb 66	Tololo May 66	Tololo Nov 68	Tololo Ave	La Silla Jan 68
33	0.664	0.692	0.643	0.671	0.635	0.650	0.686
35	0.540	0.570	0.544	0.562	0.529	0.545	0.587
37	0.443	0.459	0.409	0.464	0.423	0.432	0.463
40	0.335	0.352	0.303	0.341	0.316	0.320	0.364
45	0.222	0.237	0.192	0.220	0.199	0.204	0.241
52	0.165	0.180	0.162	0.149	0.139	0.150	0.173
58	0.147	0.164	0.141	0.108	0.117	0.122	0.163
58′	0.145	0.158					
63	0.109	0.122	0.097	0.064	——	0.080	0.150
72	0.078	0.096					
80	0.064	0.077					
86	0.051	0.061					
99	0.057	0.05					
110	0.050	0.05					

TABLE 3

PROBABLE ERRORS OF A SINGLE OBSERVATION

Color	P.E.'s San Pedro	P.E.'s Catalina
52	0.024	0.017
33–52	0.018	0.014
35–52	0.017	0.012
37–52	0.016	0.011
40–52	0.012	0.011
45–52	0.008	0.009
52–58	0.013	0.011
52–63	0.015	0.013
58	0.022	——
58′	0.019	0.025
58–72	0.015	0.021
58–80	0.014	0.019
58–86	0.015	0.021
58–99	0.017	0.023
58–110	0.028	0.033

our probable errors using the residuals of the standard stars from 15 nights of 8C photometry and 23 nights of 6RC photometry —nights when 9 or more standard stars were observed. These standard star residuals are the differences between the calculated colors and the standard colors from Table 7 of Mitchell and Johnson (1969). When calculating these probable errors we divided the quantity under the radical by $n - 3$ rather than by $n - 1$ (where n is the number of standard stars observed) to account for the fact that these same standard stars have been used to solve for the extinction and transformation coefficients in each of the nights (i.e. the number of degrees of freedom has been reduced by two). Also, we have corrected our probable errors to an air mass of 1.25 —aproximately the average air mass of the Catalina observations. For the 6RC photometry the San Pedro Martir probable errors are approximately 25% smaller than the Catalina values and together with the smaller extinction values of San Pedro Martir indicate that this site is very good for red and infrared photometry. For the 8C photometry the story is different —the 40 – 52, 45 – 52, 52 – 58 and 52 – 63 probable errors are quite similar to those of the Catalina Observatory while the 33 – 52, 35 – 52, and 37 – 52 colors and the 52 magnitude have probable errors larger by about 40%. Perhaps the larger errors for the three ultraviolet colors are not really significant since only 15 nights of photometry were involved and since the analysis of a larger number of subdwarf observations gives probable errors for these colors nearly equal to the Catalina values. Many more nights of 8C photometry are needed for San Pedro Martir to see whether or not this site is indeed inferior to the Catalina site for ultraviolet observations. However, for the 52 magnitude, all observations of both the standard stars and the subdwarfs, show probable errors larger than the Catalina value. In contrast it should be noted that our probable error for the 58 magnitude is smaller than the Catalina value. These results strongly indicate that the standard lamp of the 8C photometer, which is used to calculate the 52 magnitude, is not as stable as it once was.

III. METALLICITY AND LUMINOSITY EFFECTS

In addition to the 81 solar-type stars which we observed, the 13-color photometry of another 19 has been taken from the work of Mitchell and Johnson (1969). The bright star numbers and spectral types of these are given in Table 4. In Figure 1 we have plotted one of the many possible

TABLE 4

PREVIOUSLY OBSERVED SOLAR-TYPE STARS

Name	S_p
219D	G0V
483	G2V
937	G0V
996	G5V
1729	G0V
2047	G0V
3771	G2IV
3881	G1V
4374/5	G0V/G0V
4785	G0V
4983	G0V
5072	G5V
5235	G0IV
5868	G0V
6212D	G0IV
6623	G5IV
7503	G2V
7504	G5V
8729	G5V

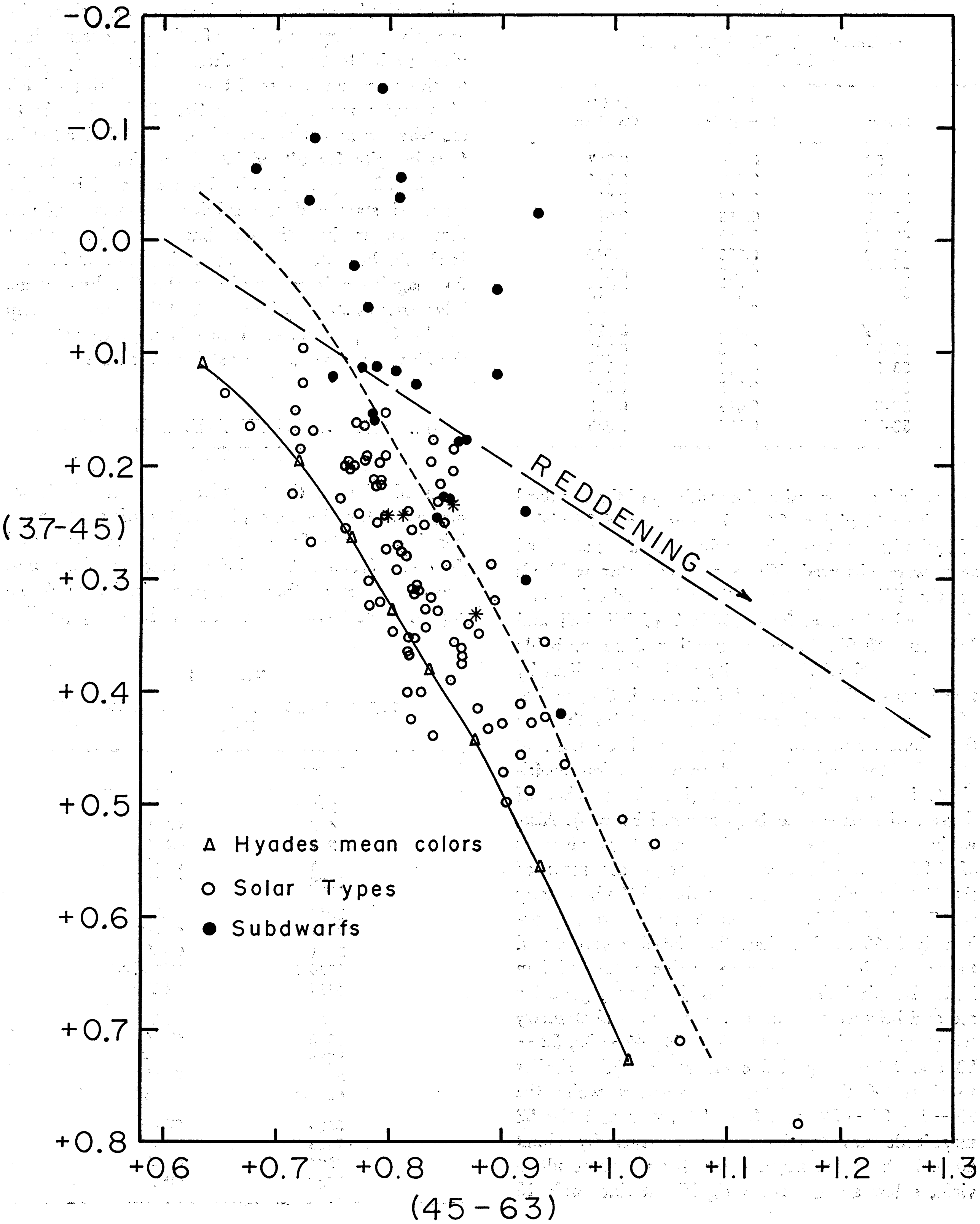

FIG. 1. The 37-45 versus 45-63 diagram containing the mean Hyades colors (triangles and solid line), the solar-type field stars (open circles) and the subdwarfs (filled circles). The four asterisks are explained in the text. No correction for interstellar reddening have been applied.

color-color diagrams from the 13-color photometry. This is the 37 − 45 versus 45 − 63 plot which Johnson and Mitchell (1968) have shown to be particularly sensitive in discriminating between stars of different metal content. In this diagram the solid line and triangles represent the Hyades main sequence as defined by the photometry of Johnson and Mitchell (1968) and by additional unpublished San Pedro photometry (Schuster 1976); the open circles are the solar type stars, and the filled circles are the 27 subdwarfs (Schuster 1976). The four asterisks will be explained later.

In Figure 1, and in the other color-color diagrams to follow, the reddening lines have been derived from the work of Borgman (1961). Figure 1 clearly shows that the solar stars on the average have a 37 − 45 excess (δ (37 − 45)) of +0.06 to +0.08 with respect to the Hyades main sequence, where the 37 − 45 excess is defined as the difference between the Hyades mean 37 − 45 color and a star's 37 − 45 color for equal 45 − 63 colors. This ultraviolet excess merely reaffirms the fact that the Hyades are metal rich when compared to general field dwarfs and to many other clusters (for example, see Alexander 1967, and Bell 1971). The dotted line of Figure 1 shows the locus where the 37 − 45 excess is +0.15 magnitude. It is seen that this dotted line very nicely borders the lower extent of the known subdwarfs; we can therefore use this dotted line in the range $0.70 \lesssim (45 - 63) \lesssim 0.95$, to select possible new subdwarfs, or other metal deficient stars. Stars whose 13-color photometry places them above this dotted line will be considered likely candidates as metal poor objects. We see that 14 of our solar-type stars satisfy this condition. These 14 stars are listed in Table 5 where the first column gives the bright star number, the second column the spectral type, and the third column the 37 − 45 excess. Of these 14 candidates BS6063/4 and BS219D should not be considered too seriously since the photometry of BS6063/4 is for a pair of stars, one of spectral type dF6 and the other dG1, and since the photometry of BS219D is contaminated by a fainter nearby star (this is the meaning of the "D" suffix given by Mitchell and Johnson).

Of the remaining 12 candidates two others, BS300 and BS3771, need special consideration since they are subgiants. That is, we need to examine luminosity effects in the 37 − 45 versus 45 − 63 diagram. In Figure 2 are plotted the Hyades main sequence, subgiants, giants and supergiants in the same 37 − 45 versus 45 − 63 diagram as in Figure 1. The 13-color data for these subgiants, giants and supergiants has been taken from the present paper, from Mitchell and Johnson (1969), and from Johnson and Mitchell (1975). For stars bluer than approximately 45 − 63 = +0.9 the subgiants are displaced very little with respect to the *field* dwarfs while the giants and supergiants are shifted to more positive 37 − 45 colors. That is, for $45 - 63 \lesssim +0.9$, the effect of luminosity (plus reddening for the supergiants) is to decrease the 37 − 45 excess, while for $45 - 63 \gtrsim +0.9$ the effect of luminosity is to increase the 37 − 45 excess. Thus, for BS300 and BS3771, in each of which 45 − 63 is greater than +1.0, the 37 − 45 excess is at least partly due to greater luminosity rather than totally due to decreased metal content. Hence, at this point we are left with a list of 10 definite candidates for new subdwarfs or metal poor stars. (We can only say that these are candidates for metal poor objects; only a more detailed spectroscopic analysis can show this definitely. It is possible that these ultraviolet excesses are due to other factors. See for example, Conti and Deutsch 1966, 1967).

TABLE 5

SOLAR-TYPE STARS WITH ULTRAVIOLET EXCESSES

Name	S_p	δ(37-45)
3625	dG0	0.166
5618	dG1	0.210
5911	G2V	0.220
5968	G2V	0.194
6063/4	dF6/dG1	0.197
6269	dG3	0.156
6458	G2V	0.172
6998	dG4	0.178
8931	dG0	0.156
9107	G2V	0.226
173	dG3	0.220
300	G5IV	0.266
660	G0V	0.246
1608	dG4	0.230
219D	G0V	0.163
3771	G4IV	0.180

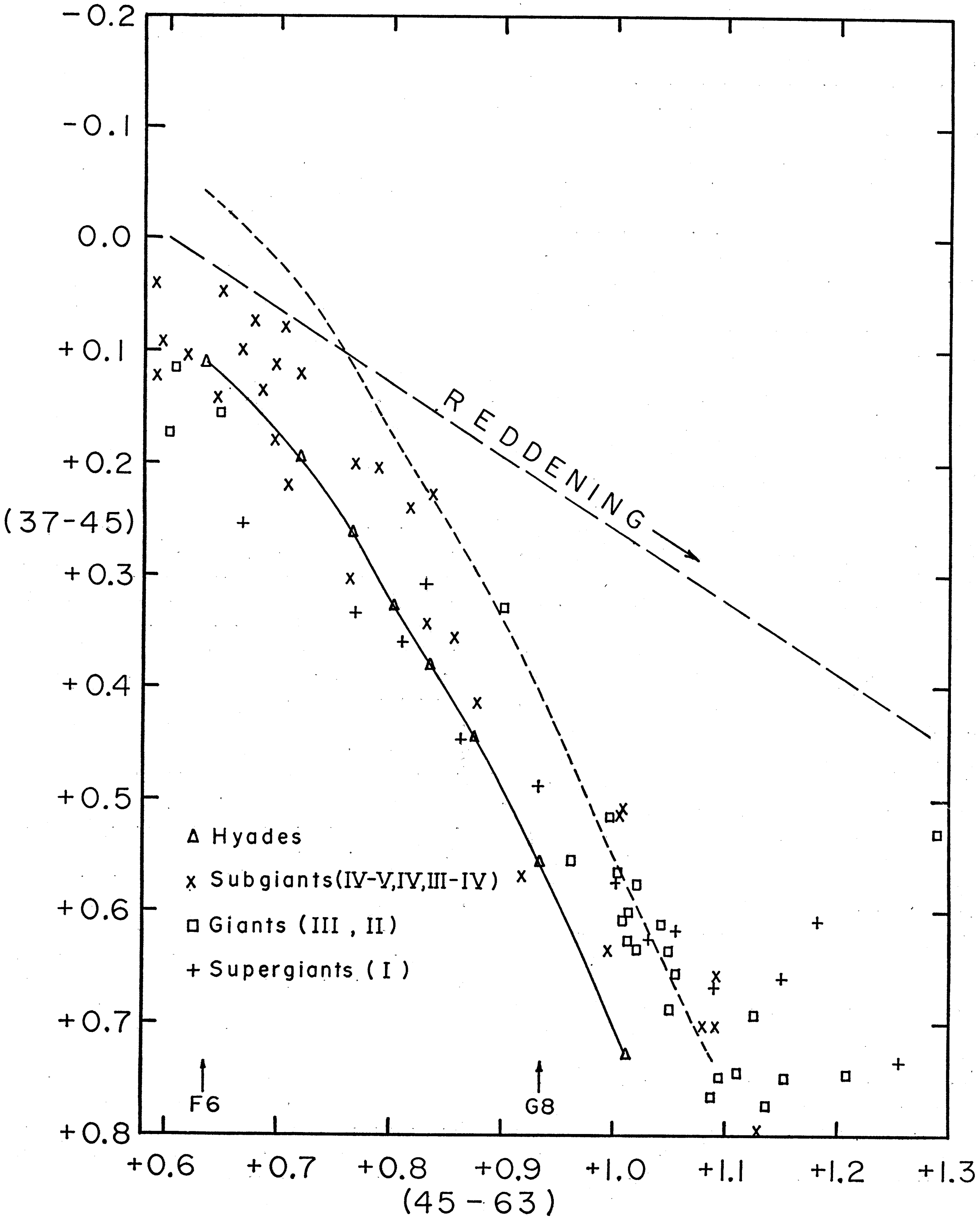

FIG. 2. The 37-45 versus 45-63 diagram containing the mean Hyades colors (triangles and solid line), subgiants (X's), giants (open squares), and supergiants (plus signs).

TABLE 6A

DERIVED 13-COLOR PHOTOMETRY FOR THE SUN

Color	Value	σ_{MEAN}
33–52	0.400	0.002
35–52	0.318	0.002
37–52	0.542	0.001
40–52	0.710	0.006
45–52	0.308	0.001
52–58	0.342	0.006
52–63	0.549	0.008
52–72	0.730	0.014
52–80	0.871	0.020
52–86	0.915	0.024
52–99	0.968	0.037
52–110	1.079	0.041

TABLE 6B

INDIVIDUAL VALUES WHICH GO INTO THE AVERAGES OF TABLE 6A

Filter	6-Color	Satellite UBVRI	S_p G2V (red only)
33	0.398	0.401	.....
35	0.316	0.320	.....
37	0.542	0.541	.....
40	0.716	0.705	.....
45	0.307	0.309	.....
52	0.000	0.000	0.000
58	−0.336	−0.348	.....
63	−0.542	−0.565	−0.543
72	−0.707	−0.755	−0.729
80	−0.832	−0.897	−0.881
86	−0.865	−0.939	−0.935
99	−0.897	−0.991	−1.019
110	−0.997	−1.099	−1.135

IV. SOLAR-LIKE STARS

In Table 6A is listed the 13-color photometry derived for the Sun from the unpublished work of Mitchell (1974). In short, this solar photometry has been derived from Preski's (1970) UBVRI photometry of earth satellites and from Stebbins and Kron's (1957) and Kron's (1963) six color photometry of the Sun and stars. Stars which have been compared to the Sun via Preski's work or by that of Stebbins and Kron and which have been observed with the 13-color system are used to interpolate (or extrapolate) for solar colors. For the colors 33, 35, 37, 40, 45, 52 and 58 a straight average is taken between the values derived from Preski's work and the values from Stebbins and Kron. For the colors 63, 72, 80, 86, 99 and 110 the agreement between these two sets of colors is not too good, and so a third set, the mean colors of the stars BS483 and BS7503, is included in the average with equal weight. The stars BS483 and BS7503 both have spectral types G2V and are thought to be photometrically quite similar to the Sun (for example, see Mitchell and Johnson 1969, Figure 25). The second column of Table 6A gives these average solar colors, and the third column contains the standard deviations, which indicate only the internal agreement of the two or three values used to obtain the average. In Table 6B the individual values which go into the averages of Table 6A are shown. In column 2 are the values derived from Stebbins and Kron's 6-color photometry, in column 3 the values from Preski's UBVRI satellite works, and in column 4 the averages of the two G2V stars (in the red only). Table 6B shows how well the results from the Stebbins and Kron photometry agree with the Preski results. Also, Table 6B indicates how much the photometry of BS483 and BS7503 might possibly bias the final solar colors (in the red).

Using the derived solar colors of Table 6A we have searched through our list of solar-type stars to find stars that photometrically are most similar to the Sun. In searching for these stars we have used exclusively the 8C colors since we feel that the derived 6RC photometry for the Sun is not too reliable. Nine stars have been selected whose 8C photometry matches the Sun's to within ± 0.03 magnitude for all colors; these are listed in Table 7. Two of these stars BS5384 and $+17°3154$, are from our subdwarf list; the photometry of these two subdwarfs is given in Table 8. In Table 9 the average 13-color photometry of these 9 stars and the derived solar colors are compared. The agreement is fairly good except for the 99 and 110 filters where the 9 solar-like stars are about 0.04 magnitudes redder than the derived solar colors. Perhaps this difference is due to an actual infrared excess of the solar-like stars with respect to the Sun. But more likely the difference arises from uncertainties in extrapolating the Stebbins and Kron photometry to derive the 52 − 99 and 52 − 110 colors. Stebbins and Kron

TABLE 7

STARS MOST LIKE THE SUN ACCORDING TO THEIR 13-COLOR PHOTOMETRY

Name	S_p
483	G2V
2007	dG4
2251	dG0
4486	dG1
5734	dG0
5968	G2V
6458	G2V
5384	dG3
+17°3154	G2V

(1957) and Kron (1963) point out that their I measurement for the Sun is the most uncertain of the lot, and it is this I magnitude which primarily determines the derived infrared colors. If the 52 − 99 and 52 − 110 colors from the Stebbins and Kron work are left out, the differences between the solar-like star average and the derived solar colors become +0.001 and +0.006 for the 52 − 99 and 52 − 110 colors respectively. Hence it seems probable, but cannot be proven, that the derived 6RC solar colors of Table 6A are good except for the 52 − 99 and 52 − 110 colors which should be revised to +1.005 and +1.117 respectively.

Of the nine stars which have 13-color photometry similar to the Sun's, the star BS5968 shows the closest similarity. In Figure 3 are plotted the relative

TABLE 8

13-COLOR PHOTOMETRY OF TWO SUBDWARFS

Color	Name BS5384	+17°3154
52	6.414	9.288
33–52	0.384	0.400
35–52	0.293	0.298
37–52	0.551	0.527
40–52	0.722	0.681
45–52	0.305	0.299
52–58	0.320	0.312
52–63	0.536	0.548
52–72	0.733	0.711
52–80	0.907	0.871
52–86	0.965	0.893
52–99	1.046	1.002
52–110	1.183	——

TABLE 9

COMPARISON OF SOLAR PHOTOMETRY WITH AVERAGE OF NINE SOLAR-LIKE STARS

Color	Average of Nine Solar-like stars	Solar Photo-metry	Diffe-rence
33–52	0.406	0.400	+0.006
35–52	0.311	0.318	−0.007
37–52	0.548	0.542	+0.006
40–52	0.703	0.710	−0.007
45–52	0.296	0.308	−0.012
52–58	0.323	0.342	−0.019
52–63	0.533	0.549	−0.016
52–72	0.716	0.730	−0.014
52–80	0.867	0.871	−0.004
52–86	0.928	0.915	+0.013
52–99	1.006	0.968	+0.038
52–110	1.123	1.079	+0.044

spectral-energy distributions for BS5968 and for the Sun. These relative energies are derived from the 13-color photometry and from the energy calibration of Mitchell and Johnson (1969, Table 2). For the Sun the relative energies according to the photometry of Table 6A as well as according to the revisions mentioned above have been plotted.

V. METALLICITY AND LUMINOSITY OF THE SUN

In Figure 1 the asterisk which seems to represent the colors of a mild subdwarf (45 − 63 =0.857 and δ (37 − 45) = +0.180) is from the derived colors of the Sun. The other three asterisks are for the two stars BS5868 (45 − 63 = 0.798) and BS7503 (45 − 63 = 0.875), which according to Mitchell and Johnson (1969, Figure 25) have 13-color energy distributions similar to Arversen *et al.'s* (1968) direct solar measurement, and for the star BS483 (45 − 63 = 0.811), which was used in deriving the solar 13-color photometry. The fact that the 13-color photometry of the Sun is like that of a mild sub-dwarf is not too surprising. If we take Johnson's (1965) UBV photometry for the Sun (this is not strictly an independent analysis since this UBV solar photometry is also derived from Stebbins and Kron's work) and plot it in a two color (U − B versus

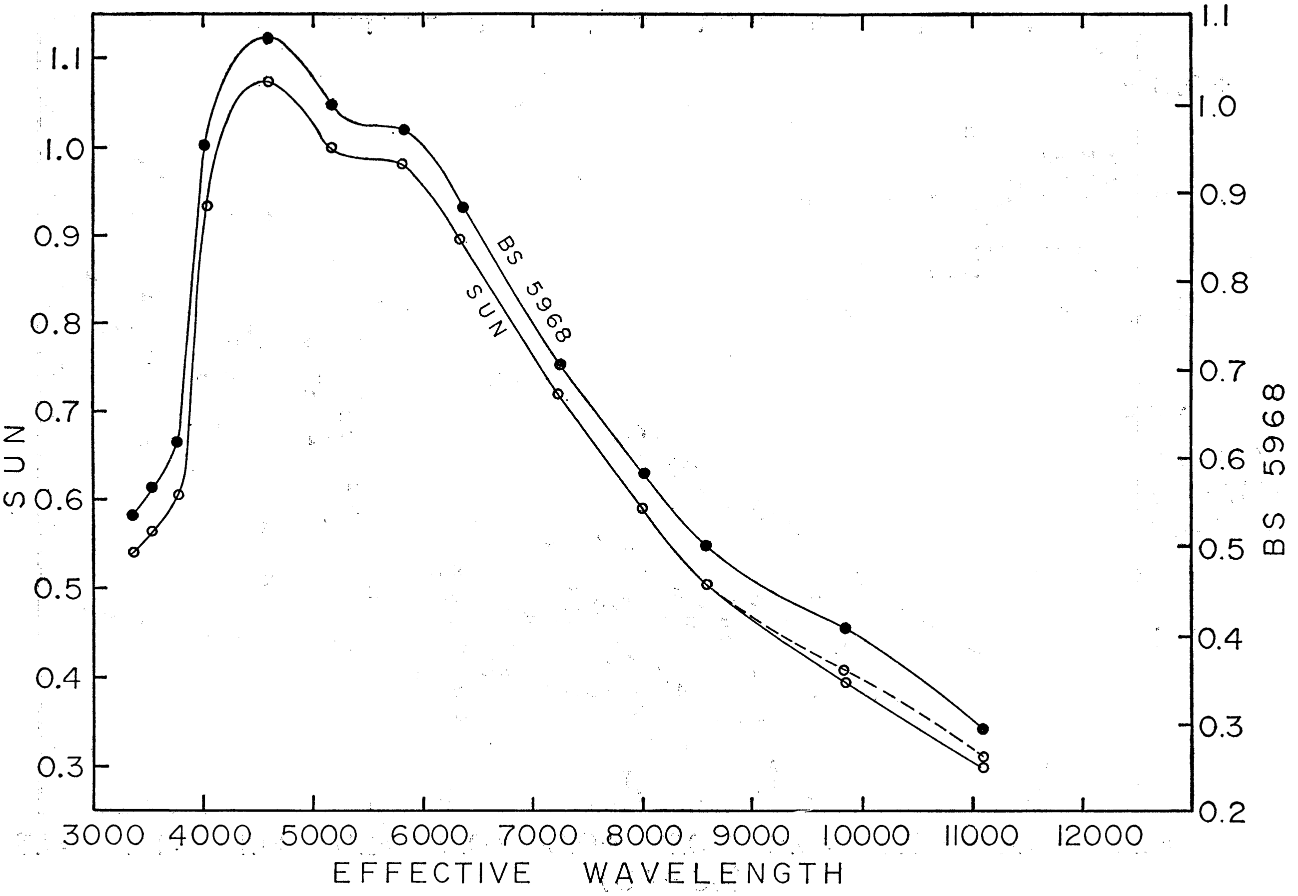

FIG. 3. F(λ)/(5180Å) versus the effective wavelength (in angstroms) for the Sun (open circles) and for BS5968 (filled circles). That is, the ordinate is a linear flux density scale normalized at the 52 filter. The curves are derived using the energy calibration of Mitchell and Johnson (1969, Table 2) and so are independent of the response curves of the phototubes. In the infrared the solid line for the Sun represents the photometry of Table 6A while the dotted line represents the revised values mentioned in the text.

B − V) diagram, and if we use Sandage and Eggen's (1959) adopted two color relation for the main sequence, we obtain δ (U − B) = 0.117 for the Sun which according to criteria of Sandage (1963) includes the Sun as a subdwarf candidate. In contrast, Sandage and Eggen (1959) (again using Stebbins and Kron's results) obtained δ (U − B) = +0.08 for the Sun, and Eggen (1962), applying a somewhat more complicated analysis, δ (U − B) = +0.05. These last two values for δ (U − B) would not qualify the Sun as a subdwarf candidate, but all of these results do show that the Sun has a small to moderate ultraviolet excess indicating a smaller metal abundance than the Hyades. The ultraviolet excess of the derived 13-color photometry for the Sun, as well as the other photometric results mentioned above, agree with the spectroscopic analysis of Alexander (1967) who finds values of [Fe/H] of +0.2 to +0.3 for the Hyades.

However, with the 37 − 45 versus 45 − 63 diagram we can say little about the luminosity class of the Sun; it would be interesting to check whether the solar photometry indicates any significant evolutionary effects for the Sun. (Solar models have indicated that the Sun has become significantly brighter —approximately ½ magnitude— in the last 5 billion years. For example, see Schwarzschild, Howard and Härm 1956). As Figure 2 showed, for 45 − 63 approximately equal to 0.9, the 37 − 45 versus 45 − 63 diagram is independent of luminosity

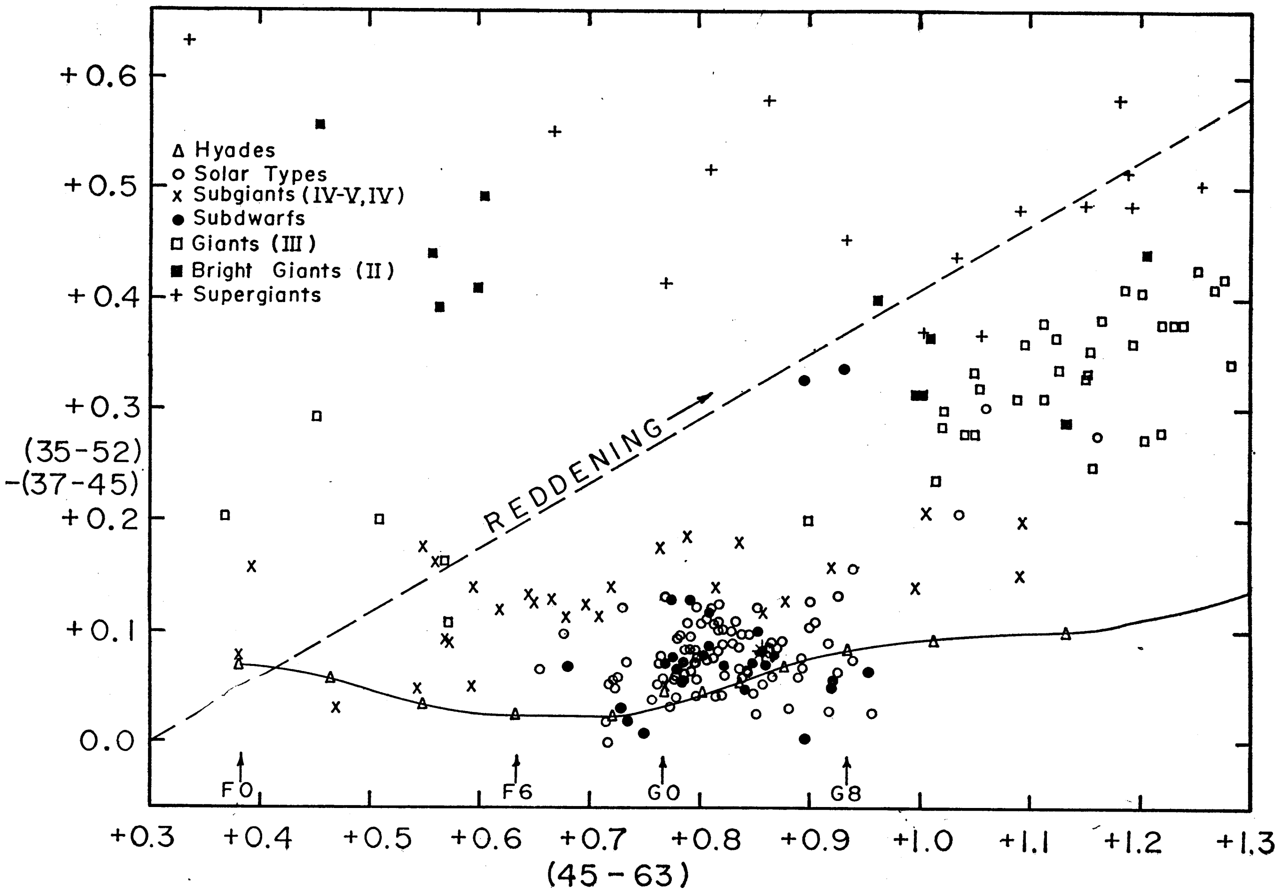

FIG. 4. The (35–52) — (37–45) versus 45-63 diagram containing the mean Hyades colors (triangles and solid line), solar-type field stars (open circles), subdwarfs (filled circles), subgiants (X's) giants (open squares), bright giants (filled squares), and supergiants (plus signs). The Sun is also plotted (as an asterisk) at 45–63 = 0.857 and (35–52) — (37–45) = 0.084. None of the observations have been corrected for interstellar reddening.

effects (for F and G stars), while for the Sun, 45 − 63 = 0.857. In Figure 4 we have plotted a (35 − 52) − (37 − 45) versus 45 − 63 diagram. According to Table 3 of Johnson and Mitchell (1968) and also according to analysis of the San Pedro Martir subdwarf photometry this diagram is nearly independent of line blanketing (metallicity effects) for F and G dwarfs and subdwarfs. The index (35 − 52) − (37 − 45) changes by about −0.02 magnitude as one goes from normal dwarfs to extreme subdwarfs; 45 − 63 changes by about −0.03 magnitude. In Figure 4 the triangles and line represent the Hyades main sequence as defined by the photometry of Johnson and Mitchell (1968) plus additional unpublished San Pedro photometry (Schuster 1976). Also plotted are our solar type dwarfs, our subdwarfs (Schuster 1976), and subgiants, giants, bright giants and supergiants from the present paper and from the work of Mitchell and Johnson (1969) and Johnson and Mitchell (1975). This diagram is very sensitive to luminosity effects; at G0 there is at least a 0.1 magnitude range for dwarfs and subgiants. This compares quite favorably with the sensitivity of the c_1 index of Strömgren's uvby photometry (for example, see Strömgren 1963). (Detailed studies of 13-color indices have shown that (35 − 52) − (37 − 45) is one of the most luminosity sensitive indices for F and G stars while 45 − 63 is an excellent temperature index). Hence we see that the (35 − 52) − (37 − 45) versus 45 − 63 diagram is very important for its ability to separate luminosity from metallicity effects, being sensitive to luminosity changes but insensitive to metallicity. Also, in this diagram lines of constant luminosity are nearly horizontal, and so photometric accidental errors in the 45 − 63 index have negligible effect when determining the luminosity of a star; this compensates, in part, for the larger accidental errors of the 4-color (35 − 52) − (37 − 45) index. Also, further analyses have shown that this 4-color index retains its sensitivity to luminosity over a wider temperature range than is possible with a simple 2-color index. In Figure 4 the asterisk (at 45 − 63 = 0.857 and (35 − 52) − (37 − 45) = 0.084) is plotted from the derived solar photometry. The Sun's colors fall in amongst those of the subdwarfs and solar-type field stars indicating no significant evolutionary effects for the Sun. Also, in Figure 4 there is no significant separation between the Hyades, the solar-type field stars, and the majority of the subdwarfs. Since the (35 − 52) − (37 − 45) index measures primarily the Balmer discontinuity which is sensitive to the surface gravity, we can conclude either that there is no difference in surface gravity between dwarfs and subdwarfs or that any existing differences are small and are masked by other effects such as blanketing.

VI. SOME PARTICULAR STARS

If we now use the graph of Figure 4 to examine our remaining 10 subdwarf candidates, we find that BS1608 shows subgiant characteristics even though it has a spectral classification of dG4 (Hoffleit 1964). Also, this star has $45 - 63 > 0.9$ which indicates that at least part of its 37 − 45 excess is a luminosity effect; hence we cannot conclude any definite metal deficiency for this star. The remaining 9 stars appear as dwarfs (or subdwarfs) in Figure 4 and so remain as good subdwarf candidates.

In Figure 4, four other stars —BS3862, BS4285, BS4298 and BS4529— appear as subgiants. One of these, BS4529, causes no problems since Hoffleit (1964) lists its spectral type simply as G0, but the other three stars (BS3862, BS4285 and BS4298) have dwarf classifications (G0V, dG0, and G0V, respectively). Two others BS1322 and BS8283 have subgiant classifications (G0 IV and G2 IV, respectively) but appear as dwarfs in Figure 4. (All other discrepant stars are marked by a "D" meaning that their photometry is contaminated by a fainter nearby star). These disagreements probably reflect uncertainties and errors of the spectral classifications as well as photometric accidental errors.

Four other stars need special comment. BS5270 was included in our program since Hoffleit lists its spectral type as G0 VI. However, other observers (for example, Wallerstein *et al.* 1963) have shown that this is a red giant with extreme metal deficiency. In Figure 4, BS5270, without making any reddening corrections, appears as a supergiant (with 45 − 63 = +1.270). The star BS4691 appears as a giant in Figure 4 while Hoffleit lists it as dG2. This discrepancy is most likely a classification error since the photometric error needed to explain it is much too great. Also, two of our subdwarfs, +41°3735 and −9°5491 appear as giants, or even bright giants, in Figure 4. Yet these two stars show (37 − 45) excesses in Figure 1 much larger than can be explained by luminosity effects. Most certainly +41°3735 and −9°5491 are metal poor giants rather than subdwarfs. These last two stars demonstrate clearly the great potential usefulness of our 13-color indices for separating and studying metallicity and luminosity effects in stars of this temperature range.

VII. CONCLUSIONS

From the above analysis we can draw the following conclusions:

a) In the 37 − 45 versus 45 − 63 diagram, for the range $0.70 \lesssim (45 - 63) \lesssim 0.95$, an ultraviolet excess, δ (37 − 45), greater than or equal to +0.15 can be used as a criterion for selecting subdwarf candidates. Of our solar-type stars nine appear as good candidates for being mild subdwarfs (mildly metal deficient).

(b) The (35 − 52) − (37 − 45) versus 45 − 63 diagram is particularly, sensitive to luminosity, comparing quite favorably with the Strömgren c_1 versus b-y diagram for early G stars. This diagram can be used to identify those stars whose ultraviolet excess δ (37 − 45) results, at least partly, because they are evolved (for 45 − 63 $\gtrsim$ 0.9).

(c) The derived 13-color photometry for the Sun has been used to identify 9 stars whose 8C colors are very similar to the Sun's. The average colors from these 9 stars indicate that probably the derived 52 − 99 and 52 − 110 colors for the Sun need revision.

(d) The derived solar 13-color photometry includes the Sun as a candidate for being a mild subdwarf with δ (37 − 45) = + 0.180. This ultraviolet excess is probably largely due to an actual metal deficiency. In the (35 − 52) − (37 − 45) versus 45 − 63 diagram the Sun shows no significant evolutionary effects.

(e) The two stars +41°3735 and −9°5491 are metal poor giants rather than subdwarfs.

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