CLASSIFICATION OF VERY RED STARS USING NARROWBAND COLORS

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Received 7 August 1989, revised 27 October 1989

ABSTRACT

A classification technique for faint, very red stars is described, based on two composite colors, derived from flux measurements in six narrowbands in the visual and red parts of the spectrum. One of the composite colors, ST, is an M spectral type indicator, common to both dwarfs and giants. It can be used to predict the spectral types to within half a class. The other color, DG, is a dwarf-giant discriminator for spectral types later than about M4, and whose power increases for the later types, where most other methods fail. It reflects the differences in blanketing between the late-M type dwarfs and the giants. The method can be generalized to other, similar colors, depending on the data and task at hand. It should be useful in surveys for extreme low-mass dwarfs, or alternatively, for luminous red giants, or other kinds of objects. We illustrate the application of the method on an example of a very red star identified earlier by Blair and Long, and show it to be a distant red giant.

I. INTRODUCTION AND MOTIVATION

Low-mass stars and the faint end of the luminosity function are of considerable interest in many astrophysical problems. The subject has been recently reviewed by Liebert and Probst (1987), and in the proceedings edited by Kafatos *et al.* (1986).

The predominant mode of studies and searches for low-luminosity red dwarfs are broadband optical multicolor area surveys. Yet, in the photometric surveys there is often a problem of classification: broadband colors are rather poor spectral type discriminators at the very red end, and the problem can be remedied only partly by infrared photometry.

The separation of dwarfs and giants (especially in the presence of some interstellar extinction in the later case) is an even more difficult problem. Broadband colors are all but powerless as gravity indicators for very red stars. Even the low-resolution spectroscopy cannot always provide an easy classification: whereas there are some simple discriminators between dwarfs and giants for the early M types (e.g., the strength of the Na D absorption or the K I lines, the presence of the Hα emission in young dwarfs, etc.), the distinction becomes ever more difficult for the late M types, as the TiO bands hide most atomic spectral features, at the low spectral resolution generally necessary for apparently faint stars. Both extreme red dwarfs and red giants are of some interest, and there is at least one published case of a mistaken classification in the literature.

We propose here a classification system for red stars, which is based on narrowband colors derived from low-resolution spectroscopy, or alternatively, from narrowband photometry in the visual and red regions of the spectrum. We designed two colors, one indicating the M spectral type (designated ST), and one which separates late-M dwarfs from giants (designated DG).

Somewhat similar classification systems were previously proposed by Wing (1971) and White and Wing (1978), and also by Jones *et al.* (1981), but we were unaware of their work prior to the completion of our study. We compare briefly the different methods in Sec. VI, and find them to be complementary, with the choice of usage depending on the data and problem at hand. Reviews of the previous work in this field were given, e.g., by Wing and White (1978), and Wing and Yorka (1979).

The initial motivation for this study was to determine the nature of an intriguing, extremely red star discovered by Blair and Long (1988). Our application of the classification method on this star is presented in more detail in Sec. III.

II. THE METHOD AND THE CLASSIFICATION SYSTEM

As our basic dataset, we use the published spectra of M-type stars from the atlas by Turnshek *et al.* (1985). Our method was simply to read off the flux levels at several strategic points in the spectra (the "peaks" and the "valleys"), mentally averaged over about 30—40 Å, while avoiding any sharp absorption, emission, or noise features. At such resolution, most temperature-sensitive atomic lines are lost. These F_λ fluxes were converted into the relative flux magnitudes, AB_ν (Oke and Gunn 1983). The central wavelengths of the bands were at 578, 590, 612, 620, 655, 671, and 704 nm, and this choice was partly limited by a particular application, described in Sec. III. Data were obtained for ten dwarfs, ranging in type from M0 to M8, and for 17 giants, ranging from M0.5 to M10$^-$.

All possible color combinations of our seven bands were formed, and plotted against the spectral type. We then looked for colors which (a) correlated best with the spectral type, but did not segregate the dwarfs and the giants, or (b) separated most the dwarfs and the giants at a given spectral type. The two best color combinations of each type were selected and averaged. We found that the composite color

$$ST = AB_\nu(578) + AB_\nu(590) - AB_\nu(655) - AB_\nu(704), \quad (1)$$

was the optimal indicator of the spectral type, for both dwarfs and giants, whereas the composite color

$$DG = AB_\nu(578) + AB_\nu(590) - AB_\nu(612) - AB_\nu(620), \quad (2)$$

was the optimal dwarfs-giant discriminator. [Here $AB_\nu(\chi)$ indicates the flux magnitude at the wavelength of χ nm.] The DG color works effectively as a dwarf–giant discrimina-

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tor only for the types later than about M4, and the discrimination increases for the later types. For the earlier types, spectroscopic indicators such as the strength of the Na D absorption may be better. The two composite colors are plotted against the spectral type in Fig. 1. Figure 2 shows the corresponding color–color diagram. Theoretical colors for the pure blackbody spectra are shown in Fig. 3.

The ST color spans the Turnshek *et al.* useful range; it measures a broad baseline color from the red to the blend of Na I + TiO at 590 nm. The latter is affected by a blanketing additional to that at 578 nm, which is a high spot. The DG compares that pair of fluxes with those at 612 and 620 nm; the former is a high spot, the latter is very heavily blanketed by a blend of TiO with increasing contributions from CaOH in the late dM's. In giants, the Na I, K I, and CaOH are weak or absent, and these spectral regions are dominated by the TiO bands alone. Thus, DG measures a change of slope caused by additional absorptions present only in dwarfs (see Sec. V). There may be even more subtle effects known to those who classified stellar spectra; Merrill (1940) discusses the suppression of atomic lines in advanced type M giants, which in the blue are "packed with lines...while from λ 4600 toward longer wavelengths few can be recognized." This is now attributed to a stellar atmosphere in which the cool region of molecular-band formation overlies and masks that in which atomic lines are formed. Another possible version of the phenomenon is that spectral classification of M stars gave systematically different subtypes in the blue and in the red photographic regions.

We performed the least-squares fits to the two colors versus the spectral type (denoted below as MT), giving equal weights to all data points. The fits were done for all types, and then for the types M3 and later. For the spectral type predictor ST for both the dwarfs and the giants together, and all M types, we obtain:

$$\mathrm{ST} = (0.65 \pm 0.02)\mathrm{MT} + (0.1 \pm 0.1), \tag{3a}$$

$$\mathrm{MT} = (1.54 \pm 0.05)\mathrm{ST} - (0.85 \pm 0.15), \tag{3b}$$

and for the types M3 and later:

$$\mathrm{ST} = (0.74 \pm 0.02)\mathrm{MT} - (0.03 \pm 0.06), \tag{4a}$$

$$\mathrm{MT} = (1.35 \pm 0.05)\mathrm{ST} + (0.05 \pm 0.2). \tag{4b}$$

Thus, the ST color can be used to predict spectral types with the accuracy of about half a spectral class, which is about as good as we can expect from the accuracy of the data and the original classifications. For the dwarf–giant discriminator, DG, we obtain for the dwarfs of all M types the following fits:

$$\mathrm{DG} = (-0.08 \pm 0.03)\mathrm{MT} + (0.57 \pm 0.1), \tag{5a}$$

$$\mathrm{MT} = (-12 \pm 5)\mathrm{DG} + (6.9 \pm 1.2), \tag{5b}$$

and for the dwarfs of type M3 and later:

$$\mathrm{DG} = (-0.14 \pm 0.03)\mathrm{MT} + (0.95 \pm 0.2), \tag{6a}$$

$$\mathrm{MT} = (-7 \pm 2)\mathrm{DG} + (6.6 \pm 0.5). \tag{6b}$$

For the giants of all M types we obtain:

$$\mathrm{DG} = (0.18 \pm 0.01)\mathrm{MT} + (0.14 \pm 0.05), \tag{7a}$$

$$\mathrm{MT} = (5.65 \pm 0.3)\mathrm{DG} - (0.8 \pm 0.3), \tag{7b}$$

and for the giants of type M3 and later:

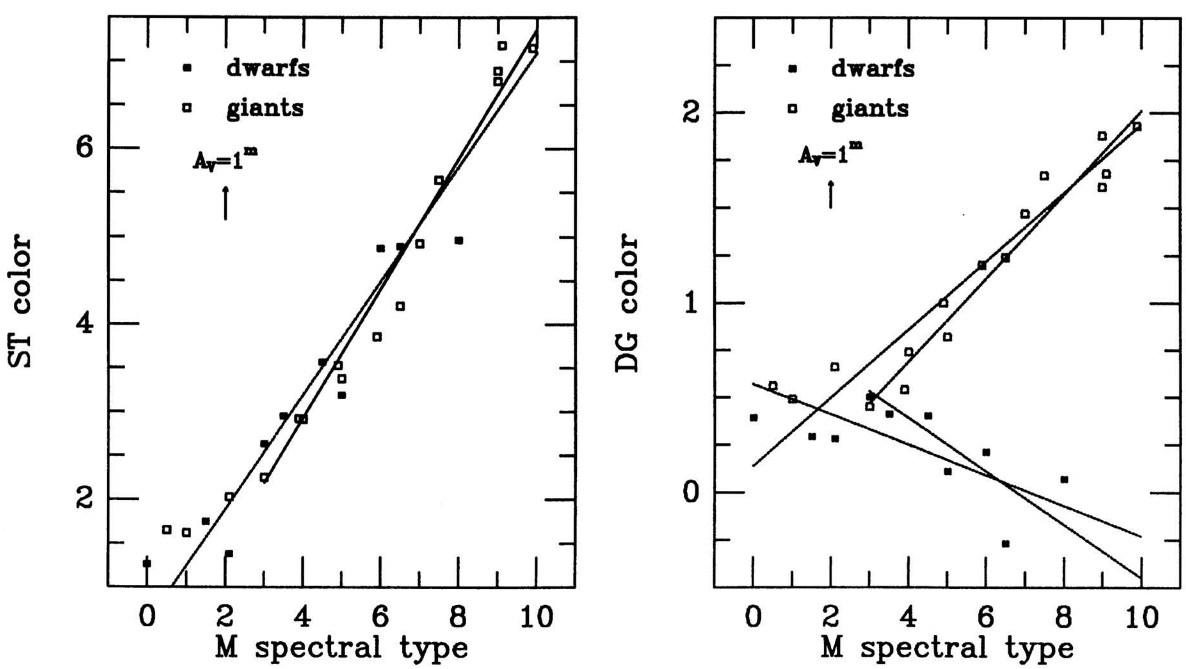

FIG. 1. Correlation of the spectral type indicator color (ST) and the dwarf–giant discriminator color (DG) with the spectral type. The definition of the colors is given in the text. The data points are from our measurements of spectra in the Turnshek *et al.* (1985) atlas, and the scatter is indicative of our errors, plus any uncertainties in the original spectral classifications. Solid lines represent least-squares fits to spectral types M3 and later, and the dotted lines represent fits to all data points, as given in the text. Reddening vectors are indicated with the arrows.

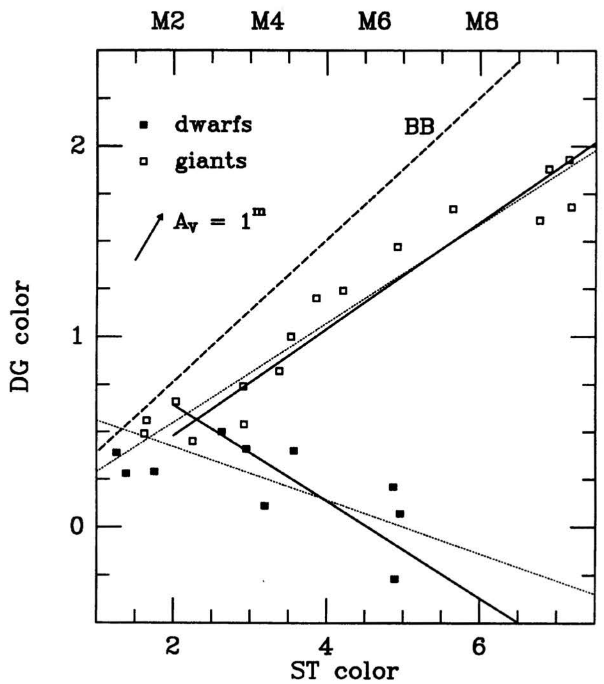

FIG. 2. ST vs DG color–color diagram as a classifier. Spectral types corresponding to the given ST colors are indicated at the top. Squares are the same data points as in Fig. 1. Solid lines are the least-squares solutions for the types M3 and later, and the dotted lines are the least-squares solutions for all data points, as given in the text. The dashed line is for the pure blackbody continuum. The reddening vector is indicated with the arrow.

$$DG = (0.22 \pm 0.01)MT - (0.19 \pm 0.04), \quad (8a)$$

$$MT = (4.5 \pm 0.15)DG + (0.85 \pm 0.2). \quad (8b)$$

These fits are shown in Fig. 1.

In practice, the classification of a star would be unknown, and determined from the ST vs. DG diagram. The locus of giants of all M types on this diagram is given by:

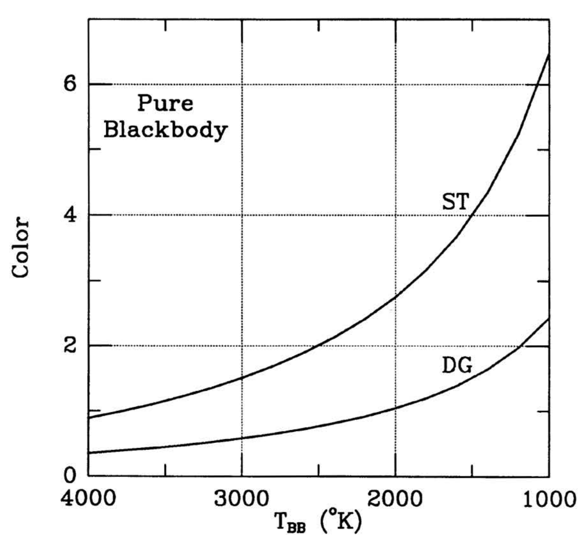

FIG. 3. Theoretical ST and the DG colors as a function of the temperature for the pure blackbody continuum.

$$DG = (0.26 \pm 0.01)ST + (0.03 \pm 0.03), \quad (9a)$$

$$ST = (3.8 \pm 0.2)DG - (0.1 \pm 0.2), \quad (9b)$$

and for the giants of type M3 and later:

$$DG = (0.28 \pm 0.02)ST - (0.08 \pm 0.06), \quad (10a)$$

$$ST = (3.55 \pm 0.2)DG + (0.3 \pm 0.2). \quad (10b)$$

The locus of dwarfs of all M types is given by:

$$DG = (-0.14 \pm 0.04)ST + (0.7 \pm 0.2), \quad (11a)$$

$$ST = (-7.1 \pm 3.0)DG + (4.9 \pm 0.8), \quad (11b)$$

and for the dwarfs of type M3 and later:

$$DG = (-0.26 \pm 0.07)ST + (1.2 \pm 0.2), \quad (12a)$$

$$ST = (-3.8 \pm 1.0)DG + (4.6 \pm 0.2). \quad (12b)$$

These fits are shown in Fig. 2. We note that the dwarf-giant discrimination is effective only for ST > 3 or so (spectral types ~ M4 and later), but it becomes increasingly better for the later types.

Finally, we estimate the selective extinction for these colors, using the interpolation formula by Seaton (1979):

$$E_{ST} = 0.327 A_V \quad (13a)$$

$$E_{DG} = 0.126 A_V. \quad (13b)$$

The reddening vectors are indicated in Figs. 1 and 2.

III. AN APPLICATION: THE CASE OF THE BLAIR–LONG STAR

In their study of the supernova remnant 3C 400.2, Blair and Long (1988) obtained narrowband Hα images of the field. One star showed an unusually strong excess in the Hα band, relative to the comparison band centered at 6100 Å. Blair and Long speculated that this star may be related to the x-ray source in the remnant, but their data were insufficient to determine the nature of the object. We observed the Blair–Long star at the Palomar 200-in telescope, on the night of UT 1988 June 23. The conditions were marginally nonphotometric, but with a fair seeing (FWHM ~ 1.5 arcsec). The instrument was the Double Spectrograph (Oke and Gunn 1982), with the slit 2 arcsec wide, the dichroic split at ~5000 Å, and the effective spectral resolution of about 10 Å (FWHM). Two exposures of the Blair–Long star were obtained, one of 800 s, and one of 700 s. Only the red side data were extracted, since the star was barely detected on the blue side. Exposures of the flux standard BD + 26° 2606 (Oke and Gunn 1983) were used for calibrations, but were taken through some cirrus; we estimate that the uncertainty of our absolute calibration zero point is about 0.5^m. The data were reduced using the standard procedures. From the spectra and the diameter of the star on the POSS red print, we estimate the magnitude R ≃ 15 ± 0.5. The star shows no discernible proper motion between the POSS and GPS red prints, i.e., less than ~2 arcsec over the baseline of 27.05 yr.

The spectrum of the star is shown in Fig. 4. It is an unusually red, late-M type star. The Blair and Long "Hα excess" was apparently caused by the placement of their comparison band at 6100 Å. We compare our spectra with the spectral energy distributions of three known extreme red dwarfs, LHS 2924 and LHS 2930 (Probst and Liebert 1983; Liebert *et al.* 1984), and RG 0050–2722 (Reid and Gilmore 1981; Liebert and Ferguson 1982). The data on LHS 2924 plotted in Fig. 4 were obtained from Palomar double spectrograph CCD data of Liebert *et al.* (1984), who improved on the Probst and Liebert (1983) Steward Reticon data. The data

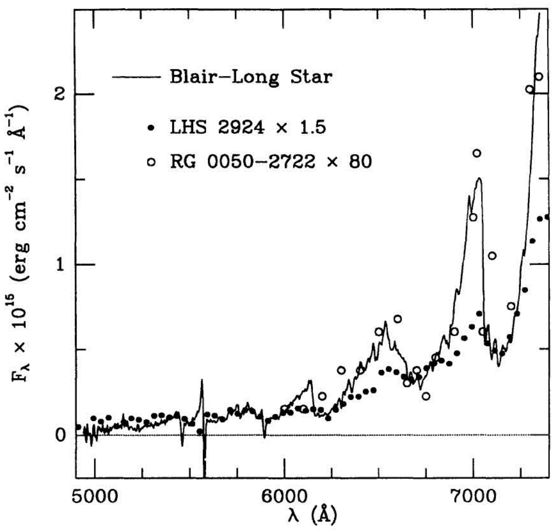

FIG. 4. Comparison of the spectral energy distribution of the Blair–Long star (solid line) with those of the two known extreme red dwarfs, LHS 2924 (older data, solid dots) and RG 0050 − 2722 (open circles). The spectra of the two reference stars have been scaled as indicated, in order to match the continuum of the Blair–Long star.

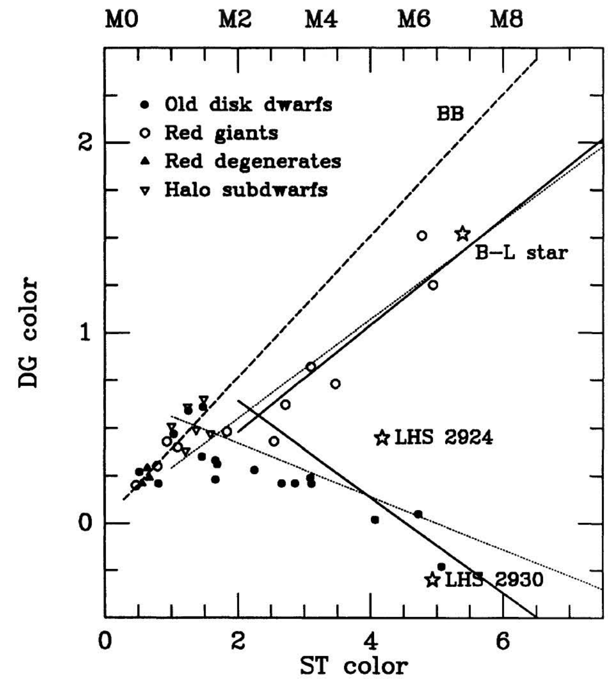

FIG. 5. Application of the ST vs DG color–color diagram, using Palomar digital data. Multichannel spectrophotometry of giants; double spectrograph data for dwarfs, halo subdwarfs, and red degenerates. Different stellar types are plotted as different symbols, as shown, and described in the text. Spectral types corresponding to the given ST colors are indicated at the top. The open stars correspond to the Blair–Long star and the two known extreme red dwarfs. The lines are the same as in Fig. 2.

on RG 0050–2722 were read off the published spectrum by Liebert and Ferguson (1982). The spectra of LHS 2924 and RG 0050–2722, shown in Fig. 4, were scaled as to match the visual/red continuum of the Blair–Long star, and demonstrate its extreme redness. Its spectroscopic color is $(V-R)_{\rm instr} \simeq 4$, with a possible systematic error of at least $0.5^{\rm m}$. If this star were a red dwarf, it would be one of the intrinsically faintest now known. This possibility prompted our study of spectral type classifications and red dwarf–giant discrimination.

The placement of the Blair–Long star and the comparison dwarfs on the ST vs DG diagram is shown in Fig. 5. The Blair–Long star is unambiguously a giant. In this figure we used improved spectrophotometric data on the very faint stars LHS 2924, LHS 2930, taken with the Palomar 4-Shooter. We also show the colors we derived from Palomar multichannel spectrophotometry, at 20–40 Å resolution, and available sets of Palomar Double Spectrograph CCD spectra including old disk M dwarfs, halo subdwarfs, and the reddest known degenerate dwarfs (Greenstein 1986). These are all on the Gunn–Oke AB79 photometric system; a full discussion of the new data is in Sec. IV.

IV. ADDITIONAL DIGITAL DATA: A CONSISTENCY CHECK

It seemed worthwhile to test the applicability of this method to other, independent sources of data, especially those known to be on the absolute scale of fluxes of Oke and Gunn (1983). Available in printout form was multichannel spectrophotometry of about 25 dwarfs and giants obtained for the Gunn–Stryker (1983) energy distributions, giving AB_ν magnitudes at 20 or 40 Å resolution. In addition, twenty spectra taken by J. B. Oke, at 10 Å resolution and with a high signal/noise ratio were kindly made available to one of us (J.L.G.); among these were 6 sdM's with extremely weak bands and lines, i.e., low metallicity, halo subdwarfs. In addition, new spectra of the very faint dwarfs, LHS 2924, LHS 2930 were provided by J. Gunn, M. Schmidt, and D. Schneider (private communication), obtained with the Palomar 4-Shooter spectrograph. While all these datasets represent an overkill, with precision unlikely for faint stars, they permit detailed study on a known photometric system, and encourage an explanation of the behavior of the dwarfs. They are plotted in Fig. 5, along with the straight-line fits already determined for dwarfs and giants in Fig. 2. The 30 Å wide mean proved difficult to estimate on the 10 Å resolution data; the data could have given much more precise values of $AB_\nu(578)$ than we used, and some scatter in the DG in Fig. 4 arises from such rough estimates. We had two independent spectra only for G231-27, a halo sdM with very sharp Na I; they give STs differing by $0\overset{\rm m}{.}08$ and DGs by $0\overset{\rm m}{.}03$, and these numbers are probably indicative of our internal accuracy.

Within the observational limits, the new data agree with the Turnshek *et al.* data on the location and slopes. Note that all the new measurements of colors of these comparison stars, as well as the Blair–Long star, are from our own CCD and multichannel spectroscopy, and thus are operationally very different from the Turnshek *et al.* atlas measurements used to derive the color–color relations. Even so, the results are encouraging: the known dwarfs indeed sit on the dwarf branch, and the giants on the giant branch. The halo subdwarfs, confined to small ST, have slightly more DG than do the old disk dM's of normal composition. They, and the red degenerates are close to the pure blackbody line, as they indeed should be. LHS 2930 is clearly a very red dwarf, among the coolest now known (dM7, according to its ST color).

We also note that LHS 2924 appears at a relatively moderate M type for its proposed low luminosity. Probst and Liebert (1983) and Liebert *et al.* (1984) also noted spectroscopic peculiarities of this star, which are probably reflected in its position on the ST vs DG diagram. The cause of these deviations is still not fully understood. Figure 4, based on older data of Liebert *et al.* (1984), shows its relatively smooth spectrum, features shallower than the very late dM, RG 0050 − 2722. In Fig. 5 it is not as red on the ST scale as LHS 2930, and its DG is intermediate between giants and dwarfs. Yet its USNO parallax *makes it the faintest known star*, except for the several brown dwarf candidates proposed in the literature, all of which still need to be confirmed as such. Probably, the most likely explanation is that the blanketing is far weaker than in normal old disk stars. This might arise from lower abundance of the metals, but the impression from Liebert, Boroson, and Giampapa (1984) is that all the spectral features are veiled. They propose a lower temperature from the appearance of VO bands; increased VO relative to TiO characterizes the lowest temperature giants. We can confirm the VO from the as yet unpublished Palomar 4-Shooter spectra. This star presents a tantalizing glimpse of the lower end of the main sequence.

V. AN ATTEMPT AT PHYSICAL EXPLANATION

The high signal/noise Double Spectrograph output permits description of the spectral regions measured; points at 578 and 590 nm bracket a strong, broad, complex TiO band blended with CaH. The pair is a known population discriminant, and will vary with composition. The point at 655 nm is almost coincident with Hα, and was used (Greenstein 1989) as a "continuum" point for the most blanketing-free color possible in the red optical region. Both points at 578 and 590 nm become increasingly depressed in the redder dwarfs. (In a wider-baseline coverage, it might be preferable to replace these with a single point at 740 nm, which is less blanketed.) The point at 620 nm provides a measure within the deepest TiO complex while the one at 655 nm is in a relatively high spot. The difference between the two measures, which we define as Δ_{620}, is the apparent depth of the 620 nm band; it is $\sim 1^{m}.5$ on a dM5 spectrum. In late dM's, CaOH contributes increasingly to the 620 nm feature, broadening and deepening its profile. Although we must remember that all these regions are "depressed," we define the extra depression at 620 nm as Δ_{620}. Also heavily depressed are the 578 and 590 nm regions, the 578 nm band including several small absorptions. But the 590 nm band is dominated by the Na I pressure-broadened doublet superposed on a weaker TiO band. We call the additional depression on top of the 590 band as Δ_{590}.

Inspection of Greenstein's (1989) low-resolution spectrophotometry of late dM's on the $AB_\nu - \log \nu$ scale shows that they are concave upwards. The middle of the normal and near-infrared region is dominated by overlapping TiO bands of the so-called γ and γ' system; after they die out, being replaced by the weaker α system in the green and blue, the "continuum" apparently recovers substantially. It is impossible to predict *a priori* the relative size of Δ_{590} and Δ_{620}; our initial expectation that $\Delta_{590} \geqslant \Delta_{620}$, proved false. We cannot make a similar study of the giants, but Turnshek *et al.* (1985) mention that by M2 III the 589 nm band is "overwhelmed by TiO absorption." Our high-resolution spectra of dwarfs show that the central depth of Na I ranges from near zero to $1^{m}.6$, even at our low resolution of 10 Å; in the halo subdwarfs it reaches $0^{m}.63$, and the TiO contribution is negligible.

While we plot and rely on results for the bright giants from the Gunn-Stryker multichannel data, DGs for the fainter dwarfs average $0^{m}.15$ more positive than with our higher resolution CCD spectra. Two have discordant, more positive DG; we, therefore, omit them from Fig. 5, and from further discussion. Studying spectra of the halo stars shows that they lie slightly above the old disk dwarfs' locus in the direction of the early M-type giants. This cannot be a gravity effect; it must be an abundance effect, reflecting the weaker lines and bands in the halo subdwarfs.

Correlating the ST and DG colors with temperature, gravity, and composition requires fully-detailed model-atmosphere computation, now still unavailable. The Mould (1976) computations for dwarf old disk stars in the 4250–3000 °K range appear insufficiently comprehensive to image correctly the blanketing by all the bands and lines which may be relevant. But they do indicate for $0^{m}.72 \leqslant \mathrm{ST} \leqslant 1^{m}.91$ that $\mathrm{DG} \sim 0^{m}.25$, and is nearly constant. In a 3000 °K model it jumps to $0^{m}.57$, the wrong sense of change according to observations. But it is satisfying that metal-poor models, over a more limited range of temperature, and less affected by blanketing, have $\mathrm{DG} \sim 0^{m}.34$, and agree with the data in Fig. 5.

A simple approximation can provide interesting information about the blanketing; these cool stars are observed on the exponential tail of their energy distribution. Assume for the moment their energy distribution to be blackbody, at temperature T, which is far lower than $T_{\rm eff}$ and probably near the boundary temperature T_0; here we use T as merely an arbitrary number. From the definition of AB_ν, we predict:

$$AB_\nu = 1.563 \times 10^7/(T\lambda) + \text{const.} \tag{14}$$

Based on our earlier description of the properties of the six bands used, we assume that measurements at 590 and 620 nm are really $AB_{590} + \Delta_{590}$ and $AB_{620} + \Delta_{620}$. We compute the blackbody colors $\mathrm{ST_{BB}}(T)$, and $\mathrm{DG_{BB}}(T)$, which are free of blanketing (Fig. 3). Then, the observed colors should be:

$$\mathrm{ST} = \mathrm{ST_{BB}}(T) + \Delta_{590}, \tag{15}$$

$$\mathrm{DG} = \mathrm{DG_{BB}}(T) + \Delta_{590} - \Delta_{620}. \tag{16}$$

The first definite conclusion is that the observed DG for dwarfs requires that *the correction term to be applied to DG_{BB} (T) in Eq. (3) must be negative*, i.e., $\Delta_{620} \geqslant \Delta_{590}$. From observations, this difference becomes larger, ranging from $-0^{m}.4$, for early dM's, to $-1^{m}.2$ for late dM's. Dwarfs must have upwardly concave spectral energy distributions, dominated by the systematics of the TiO bands. The zero point of the scale of ST as function of T shifts with Δ_{590}, the blanketing near 590 nm. For example at 4250° K, (which in real stars is dK5), the blackbody $\mathrm{ST_{BB}}(T) = 1^{m}.77$; from our observed relation between the spectral type MT and the ST color this corresponds to $\mathrm{MT} \simeq 1^{m}.9$, or spectral type dM2. Thus, the correction $\Delta_{590} \sim 0^{m}.7$ for our hottest stars, and from Eq. (3), $\Delta_{620} \sim 1^{m}.1$. Both blanketings in late dM's, with $\mathrm{ST} \sim 5$ must be very large, since their difference, $\Delta_{590} - \Delta_{620}$ approaches $-1^{m}.2$.

VI. CONCLUSIONS

The above examples illustrate the usage, the power, and even more importantly, the limitations of our proposed classification technique. Alternative color systems may be constructed in similar ways, depending on the data available. For example, broader bandpasses may be used, but it is really the placement of the bands that is important. It is likely that a larger wavelength baseline, and in particular inclusion of redder bandpasses would strengthen the power of such a classifier. Our colors and calibration were derived from a dataset which is far from optimal, i.e., hand-and-eye measurements of the published spectra from the Turnshek *et al.* atlas. Our new digital, but heterogeneous data confirm the placement of the lines representing the ST, DG loci for giants and dwarfs. But it would be desirable to have a *homogeneous* set of digital spectra of a comparable or larger number of stars with firm spectral and luminosity types, and the resulting classifier would presumably be more reliable. Once such library of spectra is available, it would be also possible to design a filter set, suitable for producing an equivalent photometric classifier. Such undertakings are beyond the scope of this paper.

Wing (1971) and White and Wing (1978) designed an eight-color photoelectric system for classification of late-type stars. The bands were centered on the absorption features of TiO, CN, and VO, and continuum, in the wavelength range $\sim$ 7100–11000 Å. Applications of their system were also discussed by Wing (1973 and 1983), Wing *et al.* (1976), Wing and White (1978), Wing and Yorka (1979), and Wing and Dean (1983). Another, four-color system was designed by Jones *et al.* (1981), who applied it in a search for faint red dwarfs. The bands were centered on the absorption features of CaH and TiO, and two continuum points, in the wavelength range $\sim$ 6050–7500 Å. Both Wing *et al.* and Jones *et al.* systems have a wider useful spectral type coverage than our system, presumably because they have larger baselines in the wavelength, and go further to the red. Our bands are concentrated in the yellow-red region, corresponding to the peak sensitivity of most CCDs. We have also avoided measurements inside the molecular absorption bands of CaH, VO, and TiO, because of the composition sensitivity of the CaH/TiO ratio (Greenstein 1989; Mould 1976). We are unable at this time to make more detailed comparisons of the three systems, because most of our data do not reach to sufficiently large wavelengths. However, it is our impression that these systems are largely complementary, and the choice of the particular method would depend very much on the scientific task, or the data in hand.

Such methods should be useful in filtering out the undesirable luminosity classes in surveys for extreme red dwarfs, or alternatively, luminous and distant and/or obscured red giants. It is worth remarking how slowly the extension to redder and fainter dM's has proceeded; the most individually interesting late dM's are found from proper-motion surveys, such as the LHS (Luyten 1979). Our quantitative classification system can profitably be applied to the very late dwarfs, using spectra of the quality illustrated, for example, by Hawkins and Bessel (1988).

Another interesting possibility would be to design an optimal color discriminator for high-redshift quasars. Broadband optical/UV colors were already shown to be a good selection mechanism for quasars at most redshifts, and even up to $z > 4$ (cf. the numerous review papers in the proceedings edited by Osmer *et al.* 1988). However, as one approaches $z \sim 5$, confusion with red dwarfs becomes prohibitive for the broadband based methods. A carefully selected set of narrowband colors could be a very efficient tool in discovering extremely distant quasars, as well as rare types of Galactic stars.

It is a pleasure to thank the staff of Palomar Observatory for their expert assistance at the telescope, in particular to Juan Carrasco, Dave Tennant, and John Henning, and to Charles Evans for assistance with the observations of the Blair–Long star. We are grateful to Jim Gunn for the detailed printout of his multichannel spectrophotometry, to Bev Oke for data on the dM's taken with the Double Spectrograph, and to Jim Gunn, Maarten Schmidt, and Don Schneider for 4-Shooter output on the faintest dM's. We also acknowledge very illuminating discussions with Jim Liebert. We thank the referee for directing us to several useful references about the related previous work. This work was supported in part by Alfred P. Sloan Foundation and California Institute of Technology (S.D.), and by a Special Caltech Institute Fellowship (D.J.T.).

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