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Comparing the Sun with Other Stars Along the Temperature Coordinate

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ABSTRACT. The temperature of the Sun relative to other stars is determined using high-precision measurements of the ratios of depths of spectral lines. In effect, the Sun is placed within the stellar grid of relative temperatures with an estimated uncertainty of ± 10 K. Among others, 16 Cyg A is found to be 5 ± 12 K hotter than the Sun, while 16 Cyg B is found to be 45 ± 12 K cooler than the Sun. In a similar manner, color indices are inferred with the results that $R-I$=0.338±0.002 on the Cousins system and $B-V$=0.648±0.006. This latter value supersedes the value of 0.656 published in 1992.

1. WHAT ARE WE UP TO?

In order to use the Sun dependably as a reference object for stellar astrophysics, we need to know how it fits into the basic parameter grid of stellar measurements. A critical fundamental parameter is temperature. We are not concerned in this study with absolute temperatures as such, but rather with the *relative* position of the Sun on the temperature axis compared to other dwarfs. The tools of such a job might be color indices, spectral types, or direct effective temperature measurements, for example. But the large angular size of the Sun coupled with its huge apparent brightness have made such seemingly simple comparisons elusive. In a previous paper (Gray 1992, hereafter referred to as Paper S), I cited several of the techniques that have been used, and a dozen and a half papers dealing with the determination of the $B-V$ color index of the Sun. I inadvertently missed others, such as the papers by Campbell (1984) and Neckel (1986), and since that time additional investigations have been published, including the solar analog quest by Friel et al. (1993) and the extensive color-index comparisons by Taylor (1994a).

In my 1992 investigation, I used the ratio of spectral-line depths for the two lines λ6251.83 V I/λ6252.57 Fe I as a function of temperature to infer color indices for the Sun. The spectral exposures for that study were done at Western Ontario with relatively high spectral resolving power of ≈100 000 and with signal to noise of several hundred. The same telescope and spectrograph were used for the Sun through the medium of skylight. Since that time, several questions have been raised concerning the technique and its dependability. One of these concerns the legitimacy of using skylight as a source of the solar spectrum because of possible filling in of lines by scattering (Kattawar et al. 1981). Another is the metallicity dependence of this particular line-depth ratio that arises because of the saturation in the Fe I line. These factors are considered here. New solar measurements using a flux heliostat (Gray 1972) and the moon show that for the lines employed in these investigations, skylight is not a biased source of the solar spectrum. The original line-depth ratio based on λ6251.83/λ6252.57 is corrected for metallicity and supplemented with ten additional ratios using weak lines that are not dependent on metallicity.

2. THE DATA

The telescope and spectrograph at Western Ontario have been used in numerous investigations, and a short description can be found in Gray (1986). With this conventional arrangement, light is fed into the spectrograph with the 1.2-m telescope; skylight and moonlight for the solar spectrum, and starlight for 67 other dwarf stars, many with multiple exposures. Additional and direct measurements of the Sun were obtained with a fiber-optics flux heliostat replacing the usual telescope (Gray 1972). This device images the rotationally smeared disk of the Sun for each of several fibers onto the entrance slot of the Richardson image slicer which is the entrance aperture of the spectrograph. Since several full disk images enter the spectrograph, the disk-integrated light, or flux, is being measured, as with other stars. The detector is an RL1872 Reticon self-scanned diode array with 15 μm wide pixels. The field centered at 6250 Å is approximately 65 Å wide. Table 1 lists the solar observations. Samples of these data are shown in a companion paper (Gray 1994, hereafter referred to as Paper T).

The depths of 14 spectral lines were measured using a vertically oriented parabola fit to the lowest three points of the profile. Eight of the lines are sensitive to temperature and the remainder are insensitive. Eleven ratios of line depths were selected as temperature indices. Each ratio was calibrated with temperature indirectly using the color indices $R-I$ on the Cousins system (Taylor 1994b) and $B-V$ on the Johnson system (Johnson and Morgan 1953; Hoffleit 1982) as intermediate parameters. Temperature is related to these indices in separate calibrations. The individual ratios range substantially in their sensitivity to temperature. Please refer to the earlier Paper T for additional details. In that paper, the original ratio of λ6251.83 to λ6252.57 was corrected for metallicity using [Fe/H] values tabulated by Taylor (1994c) and Cayrel de Strobel et al. (1992). The remaining 10 ratios employ only weak lines, and they were shown to be independent of metallicity over the range encountered in these studies.

3. SUNLIGHT COMPARISONS

The angular size of the Sun makes direct stellar-like measurements of sunlight difficult. It is well known that the solar spectrum changes markedly from the center to the limb of

TABLE 1
Solar Data

Source	Date[a]	S/N[b]	θ[c]
Sky	17NO91	635	64
Sky	17NO91	638	64
Sky	17NO91	748	63
Sky	10MY92	770	68
Sky	28OC92	918	65
Sky	28OC92	718	65
Sky	28OC92	829	65
Sky	28OC92	784	65
Sky	28OC92	828	65
Sky	28OC92	689	65
Sky	28OC92	847	65
Sky	28OC92	582	65
Sky	28OC92	767	64
Sky	10MY93	561	33
Sky	10MY93	737	33
Sky	13JN93	557	83
Sky	13JN93	845	43
Sky	28JN93	904	38
Moon	28JN93	820	...
Moon	28JN93	695	...
Sky	04JL93	695	44
Sky	04JL93	773	47
Moon	21SE93	705	...
Moon	22OC93	664	...
Heliostat	08JL94	595	0
Heliostat	08JL94	830	0
Heliostat	08JL94	809	0
Heliostat	08JL94	654	0

[a]Date: day, month, year
[b]Signal-to-noise ratio of the continuum estimated from the photon count.
[c]Angular distance from the sun in degrees

the disk, and therefore it is imperative to properly handle the disk integration to obtain the flux spectrum as we do for other stars. Techniques for doing this have ranged widely over the years (see Paper S). Here we rely on three sources of solar flux: skylight, moonlight, and direct sunlight via the fiber-optics flux heliostat.

Fears that scattered light, especially skylight, might give a distorted measure of line depths is based on the filling in of spectral lines by inelastic molecular scattering. First noticed by Grainger and Ring (1962), there have been several investigations, a summary of which can be seen in Kattawar et al. (1981; see also Young and Kattawar 1983; Humphreys et al. 1984). Filling-in of spectral lines by up to several per cent of the depth of the line can apparently occur, particularly when the sky is observed at 90° from the solar direction. According to the observations of Barmore (1975), the effect drops exponentially with angle from the Sun, and is down by two orders of magnitude for angular separations of 25°. Since the scattering processes produce partially polarized light, there is the additional complication of analyzing effects arising from oblique reflections on coudé-train mirrors and from the diffraction grating.

Although scattered light will mimic the spectrum being scattered, to a first approximation it amounts to a zero-level offset. A (perfect) zero-level change does not affect *ratios* of line depths. A zero-level offset is most easily detected as an apparent change in the depth of strong lines, but most of the lines used here have depths $\approx 10\%$, implying that any distortion caused by scattering is diluted by a factor ≈ 10. The sky data listed in Table 1 range from 33° to 83° in angular separation from the Sun, call it θ. Plots of line depth versus θ, one for each of the 14 lines measured, show both positive and negative slopes, but none likely to be significant. The average slope, $dD/d\theta$, where D is the line depth, is -0.00003 ± 0.00007 in units of fractional line depth per degree. This is between one and two orders of magnitude smaller (depending on θ) than seen in Barmore's data. Similarly, when the line-depth *ratios* are plotted against θ, no significant variations are detected. The average slope for these 11 plots is -0.00014 ± 0.00015.

No discernable difference can be seen in the line profiles when plots of sky exposures are compared to plots of heliostat or lunar exposures. Relevant to the study at hand, I computed the ratios of line depths for (1) sky lines to heliostat lines and (2) moon lines to heliostat lines. These two ratios, averaged over 14 lines, are $+1.014$ and $+1.008$, respectively, i.e., the line depths are the same to $\approx 1\%$, and although the deviations from unity are unlikely to be significant, they would imply slightly *deeper* lines in the sky and lunar light than in direct sunlight, which seems unlikely. If there is any significance to the deviations from unity, it is more likely to be related to small focus errors in the spectrograph camera.

Since no differences can be seen among the different sources of sunlight, the results for all sunlight exposures are combined in the analysis that follows.

4. METALLICITY EFFECTS

The 10 ratios based on weak lines are independent of metallicity, as shown in Paper T. Further, the original ratio used in Gray and Johanson (1991) can be corrected for metallicity (also done in Paper T). Actually, because many stars were used in the previous inference of the solar colors (Paper S), and since these stars had a reasonable symmetric distribution of metallicity around the solar value, the results turn out to be almost independent of metallicity.

The calibration curves employing $B-V$ were done with $B-V$ corrected for metallicity, according to Eq. (3) of Paper T, using the [Fe/H] ratios of Taylor (1994c) and Cayrel et al.

TABLE 2
Temperature Comparisons

Star	T[a]
44 And	5864 ±21
59 Vir	5858 ±15
HR 7914	5855 ± 8
χ^1 Ori	5838 ±13
HR 4345	5810 ±19
18 Sco	5808 ± 8
HR 8314	5796 ±23
16 CygA	5796 ± 6
Sun	5791 ±10
26 Dra	5788 ±14
π^1 UMa	5782 ±24
16 CygB	5746 ± 6
51 Peg	5730 ± 1
κ Cet	5718 ± 5
72 Her	5716 ±13
20 LMi	5681 ± 4

[a]Relative temperature, ° K

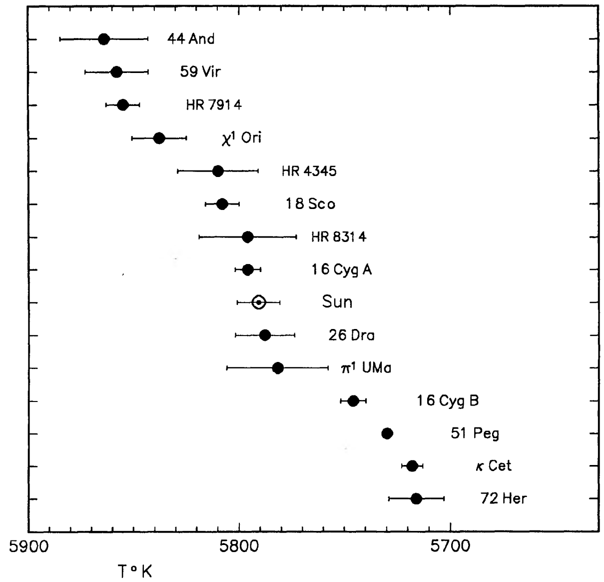

FIG. 1—Stars near the Sun on the temperature coordinate are shown. These stars are mainly near the hot end of the domain over which these particular line-depth ratios are sensitive indicators of temperature. This accounts for the relatively large error bars. The stars from HR 4345 through π^1 UMa are within error of the solar value.

(1992). The corrected colors show a somewhat tighter fit of the points to the calibration curves thus improving the precision slightly. [The intermediate value of the solar $B-V$ inferred from these curves must then have the 0.0148 zero offset of Eq. (3) of Paper T applied even though [Fe/H] is zero for the Sun.] No metallicity corrections were applied to $R-I$.

5. THE SOLAR TEMPERATURE

The calibration curves relating line-depth ratios to temperature are described and illustrated in Paper T. The mean solar line depths are read into these curves to obtain temperatures. Some care should be exercised here. We are *not* talking about a fundamental determination of the solar effective temperature. Rather, we are comparing stars with each other, ordering them by temperature within the errors of measurement and calibration.

The errors of such ordering depend on the signal-to-noise ratios of the observations, the accuracy of the calibration, and the sensitivity of the particular line-depth ratio to temperature. As shown previously in Paper T, these particular lines rapidly loose their sensitivity for temperatures hotter than the solar value, so with the solar case, we are working near the edge of the usable domain for these spectral lines. A subset of the stars from Paper T, along with the current solar results, is given in Table 2 and illustrated in Fig. 1. Again, these are relative, not absolute, temperatures.

The range in errors for similar temperature stars stems from the variation in signal-to-noise ratios in the observations. The error for the solar case is estimated from the scatter of the individual values, determined from the 11 line depths, around their mean. A large fraction of this error arises from uncertainty in the calibration polynomials, and a relatively small fraction from the signal-to-noise ratios of the solar observations. Significantly smaller errors occur for cooler stars because the sensitivity of the line-depth ratios increase markedly toward cooler temperatures. This implies that the uncertainty in the (relative) solar temperature might be reduced if more suitable spectral lines could be found.

We see that along the temperature coordinate, the Sun is close to HR 8314, 16 Cyg A, 26 Dra, and π^1 UMa. The uncertainty in the values for HR 8314 and π^1 UMa is large. Of particular interest are the binary components of 16 Cyg since they have been studied extensively as solar analogues (Hardorp 1980; Branch et al. 1980; Cayrel de Strobel et al. 1981; Perrin and Spite 1981; Hardorp and Tomkin 1983; Taylor 1984; Cayrel et al. 1985; Neckel 1986; Friel et al. 1993). According to the line-depth measurements, the A component is 5 ± 12 K hotter than the Sun, while the B component is some 45 ± 12 K cooler than the Sun. These values agree well with those derived by Neckel (1986) from energy distributions, namely, 8 ± 20 K and 59 ± 20 K for these same star-sun differences.

There is no implication that all the stars in Table 2 near the solar temperature are actually similar to the Sun in other parameters. One can expect some variation in age and surface gravity, metallicity, rotation rates, magnetic activity, and possibly granulation. For example, 72 Her has [Fe/H] $=-0.47$ Taylor (1994c), and both χ^1 Ori and π^1 UMa show $v \sin i \approx 9$ km/s (Gray 1984; Soderblom et al. 1989), compared to 1.9 km/s (sidereal) for the Sun. Similarly, the lines of HR 4345 and HR 8314 show significant rotational broadening. The spectra that look most line the Sun's come from 18 Sco, 16 Cyg A, 26 Dra, and 16 Cyg B, but even for these, there are noticeable differences in line strengths. This sample of stars does not contain an exact "solar analogue."

6. SOLAR $R-I$ AND $B-V$

Calibration curves were made, as with the temperature determinations above, by fitting a polynomial through each plot of line-depth ratio versus color index. These plots are qualitatively similar to those shown in Paper S. This process was done for 11 ratios and two color indices, and the mean observed solar ratios were then read into each curve. The $R-I$ index is on the Cousins system, with the stellar $R-I$ values being taken from Taylor (1994b). The $B-V$ indices were taken from Hoffleit (1982), but corrected for metallicity using the [Fe/H] values tabulated by Taylor (1994c), or when no value was given by Taylor, the value of Cayrel de Strobel et al. (1992) was used. For the one metallicity-dependent line-depth ratio, λ6251.83/λ6252.57, the ratio was also corrected for [Fe/H]. The results are

$$(R-I)_{\odot}=0.338\pm0.002,$$

$$(B-V)_{\odot}=0.648\pm0.006,$$

where the errors are computed from the scatter of the values derived from the individual line-depth ratios.

The value of $R-I$ is essentially identical to the 0.337 ±0.002 derived by Taylor (1992). The Paper S value I derived for $(B-V)_{\odot}$, 0.656 ± 0.005, was based on fewer sky exposures and only one line-depth ratio, namely λ6251.83/λ6252.57, and no corrections for metallicity were applied, either to the $B-V$ scale or to the ratio itself. Even so, that value agrees within error with the revised value determined in this paper. The current value of 0.648 is right in the middle of the range of previously published determinations (ref. Paper S). Friel et al. (1993) found 0.651 ± 0.008 from three solar analogues. In another recent investigation, Taylor (1994a) found the solar $B-V$ values to be clustered about either 0.633 or 0.665 depending, he suspected, on whether the measurements were done in the blue or red spectral regions. But the current line-depth measurements are in the "red," and they fall exactly midway between Taylor's two camps, i.e., the mean of his two values is 0.649, essentially identical to the value deduced above.

7. FUTURE IMPROVEMENTS

The main limitation in the line-depth determination of relative temperatures seems to be the precision with which the calibration curves can be determined, as discussed in Paper T. Aside from accumulating data for vastly more stars to correct this problem, one might expand the wavelength coverage, not just to incorporate more line-depth ratios, but to seek out those lines that are particularly sensitive to temperature near the solar temperature.

The fundamental limits to this process will likely be set by intrinsic variations arising from surface features and rotational modulation, and from variations during stellar magnetic cycles having time scales of a decade. Such variations can produce apparent temperature changes of several degrees K.

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