IUE SPECTRA OF G0 V–G5 V SOLAR-TYPE STARS

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ABSTRACT

One approach to the study of stellar activity is to identify stars which are nearly identical to the Sun and to search for subtle qualitative and quantitative differences stemming from magnetic structure and nonradiative heating. The observational difficulty of this approach may in large measure be offset in several ways: (1) the conversion of observed fluxes to stellar surface fluxes can be carried out with high precision since bolometric corrections relative to the Sun are small; (2) interpretation of data in terms of a solar analogy (e.g., presence of active regions) is particularly straightforward and appropriate; (3) the number of free parameters available to account for observed differences is small, since the general photospheric environment and the nature and extent of convection in the interior should not differ much from the Sun; and (4) there are now available well-calibrated rocket spectra of the disk-integrated solar flux, making it feasible to compare line and continuum fluxes of solar-like stars directly with the Sun with a high level of precision. In this context we present an atlas of IUE short-wavelength spectra for a set of 14 bright G0 V–G5 V stars and show that these indeed manifest a range of qualitatively different chromospheric and transition region spectra and significant differences in radiative flux originating at the temperature minimum level. A comprehensive survey of observational data and physical parameters has been done, and we present tabular summaries as a reference compendium of data for these stars.

Subject headings: stars: chromospheres — stars: late-type — ultraviolet: spectra

I. INTRODUCTION

a) General Background

The characteristics of a star’s outer atmosphere—the chromosphere, transition region, corona, and associated dynamic phenomena—depend on magnetic properties stemming primarily from the complex interaction of convection with differential rotation via (presumably) a dynamo mechanism (cf., e.g., Noyes 1981; Parker 1981). Although the magnetic characteristics are related to basic stellar parameters (mass, age, and chemical composition), we find considerable and sometimes radical outer atmospheric differences among stars of identical photospheric spectral type. As an example there is the striking dichotomy between the quiet dM stars and the active dMe stars; as another example there is the large range in coronal luminosity for stars of a given spectral type (cf. Vaiana et al. 1981; Johnson 1981; Ayres et al. 1981; Haisch and Simon 1982; Golub 1983).

This indicates the presence of important causal parameters governing the degree of magnetic structure and the fraction of the stellar thermonuclear energy that is diverted into outer atmospheric heating and atmospheric dynamics. Rotation is the currently favored candidate for the prime causal parameter (cf. Pallavicini et al. 1981; Walter 1981, 1982); rotational braking (i.e., rotational deceleration) has also been suggested (Gray 1983); Noyes et al. (1984) find a correlation between chromospheric emission and the ratio of rotation period to the convective overturn time, and Mangeney and Praderie (1984) find such a correlation for the X-ray emission of main-sequence stars. Other recent discussions of rotation-activity correlations have been published by Rucinski (1984) and by Marilli and Catalano (1984).

b) The Rationale for Observing Solar-like Stars

Programs are underway to study observable differences between the outer atmospheric structures of stars of diverse spectral types and the Sun, with emphasis on identification of gross differences as a function of spectral type (cf. the early IUE results of Linsky and Haisch 1979 suggesting a dividing line in the H-R diagram).

A complementary approach is to select stars which are in many respects identical to the Sun and to search for more subtle differences related to magnetic structure. The observational disadvantage of such an approach may in large measure be offset in several ways: (1) the conversion of observed fluxes to stellar surface fluxes can be carried out with high precision since bolometric corrections relative to the Sun are small, hence Barnes-Evans relationships involving (B–V) and (V–R) should be particularly reliable and can in any event be intercompared with angular diameters derived from knowledge of V and T eff; (2) interpretation of data in terms of a solar analogy (e.g., coverage of stellar surface by active
regions) is particularly straightforward and appropriate; (3) the number of free parameters available to account for any observed differences is relatively small, since the general photospheric environment and the nature and extent of convection in the interior should not differ much from the Sun; and lastly (4) there are now available well-calibrated rocket spectra of the disk-integrated solar flux, making it feasible to compare line and continuum fluxes of solar-like stars directly with the Sun with a high level of precision.

**c) Objectives of the Present Survey**

The objectives of this report are twofold. First we have collected and present a summary of the observational data and of the physical parameters for a sample of 14 nearby solar-like stars as a useful reference to fundamental data for this particularly interesting set of stars; this should also provide an impetus for further observational study to resolve outstanding discrepancies in spectral classification, abundance, temperature, age determinations, etc. Second, we present a set of IUE, low-dispersion, short-wavelength (SWP) spectra of the absolutely calibrated surface fluxes of these stars; these spectra are of interest for two reasons: (1) the usual ensemble of transition region and chromospheric emission lines may be directly compared with the Sun; and (2) the ~1600–2000 Å continuum provides an important determination of the temperature minimum, \( T_{\text{min}} \), region of the stellar atmosphere. Heretofore it has not been possible to use the latter as a stellar diagnostic, because of the unknown degree of contamination of the true flux by longer-wavelength scattered light in the IUE spectrograph; this problem has been studied in detail by Basri, Clarke, and Haisch (1984), and we are now in a position to make use of these continuum fluxes.

**II. PHOTOSPHERIC CRITERIA FOR SOLAR TWINS**

A program was begun several years ago by Hardorp to search for solar spectral analogs (in the photospheric spectrum) and conversely to locate the Sun in relationship to other G2 V stars (Hardorp 1978, 1980a, 1980b, 1981, 1982; Hardorp, Caldwell, and Wagener 1982; Hardorp, Tüg, and Schmidt-Kaler 1982; Hardorp and Tomkin 1983). Complementary stellar investigations have been carried out by Perrin and Spite (1981) and Cayrel de Strobel et al. (1981). solar investigations have been done by Barry, Crowell, and Schoolman (1978), Tüg and Schmidt-Kaler (1982, 1983) and Hurford and Tomkin (1983). Stellar investigations are listed in detail by Basri, Clarke, and Haisch (1984), and we are now in a position to make use of these continuum fluxes.

<table>
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<tr>
<th>Parameter</th>
<th>G0 V</th>
<th>G2 V</th>
<th>G5 V</th>
</tr>
</thead>
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<td>4.7</td>
<td>5.1</td>
</tr>
<tr>
<td>BC</td>
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<td>-0.07</td>
<td>-0.09</td>
</tr>
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<td>5790</td>
<td>5500</td>
</tr>
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</tr>
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<td>4.40</td>
<td>4.49</td>
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**III. CHARACTERISTICS OF THE STARS IN THE SAMPLE**

In Table 1 we summarize some fundamental parameters for solar-like stars. In Table 2 we present the basic observational data for the 14 stars in our sample. Spectral type, \( V, (B-V) \), and parallax are from Hoffleit (1982) except in the case of HD 20794, which is listed therein as G8 III, inconsistent with other published spectral information and inconsistent with the absolute magnitude of that star; other spectral classifications found in the literature are also listed. (\( V-R \)) colors are from Johnson et al. (1966). The parameter "Star Box" is a product of the Geneva Seven-Color Photometric System (cf. Golay 1980). The concept of defining "Photometric Star Boxes" in this system has been shown to be a useful method for identifying and grouping stars having similar characteristics; a detailed presentation of this methodology is given by Golay, Mandewewala, and Bartholdi (1977) and Nicolet (1981) (and see additional references therein). We have simply taken the conventional six colors in this system as given by Grenon and Rufener (1981) for each of our stars and for the solar twin HD 186427 and have calculated the deviation (total Euclidean distance in units of magnitude) for each star from the Geneva colors of HD 186427. The smaller this distance, the more a star is photospherically similar to HD 186427 and hence to the Sun. Physical parameters for the stars are listed in Table 3 from a variety of sources; in some cases significant discrepancies are obvious.

Angular diameters have been determined in several different ways. For these stars the bolometric corrections must all be essentially the same, and equal to that of the Sun; hence,

\[
\frac{f_{\text{bol},\odot}}{f_{\nu,\odot}} = \frac{f_{\nu,\circ}}{f_{\nu,\odot}} = 10^{-0.4r_{\nu}} = \frac{R_{\odot}^2 T_{\star}^4}{d^2} R_{\odot}^2 T_{\odot}^4,
\]

where \( f_{\text{bol}} \) is the total bolometric flux, \( f_{\nu} \) is the \( V \) band flux, \( d \) is the distance to the star in parsecs, and \( p \) is 10 pc. The angular diameter, \( \phi = 2R/d \) (in radians), is then simply a function of \( V \) and \( T_{\text{eff}} \), and in the usual units of milli-arcsec is

\[
\phi = 0.931 \left( \frac{5770}{T_{\star}} \right)^2 10^{-0.2(V-4.83)}.
\]

For a given effective temperature, if the bolometric correction of a star differs from that of the Sun by \( \pm 0.1 \) mag, the uncertainty in \( \phi \) is only 5%. We have used the range of temperatures for a given star in Table 3 to derive a corre-
TABLE 2

Observational Parameters for the Sample of Solar-like Stars

<table>
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<tr>
<th>HD No.</th>
<th>HR No.</th>
<th>Bayer/Flamsteed</th>
<th>Sp. Type</th>
<th>$V^a$</th>
<th>$B - V^a$</th>
<th>$V - R^b$</th>
<th>Parallax$^a$</th>
<th>Star Box$^c$</th>
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<td>88</td>
<td>9 Cet</td>
<td>G2 V</td>
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</table>

$^a$From Hoffleit 1982 unless otherwise noted.
$^b$From Johnson et al. 1966 unless otherwise noted.
$^c$Euclidean distance from HD 186427 using all six Geneva colors from Grenon and Rufener 1981.
$^d$From Perrin et al. 1977.
$^e$From Soderblom 1983.
$^f$From Grenon and Rufener 1981.
$^g$From Duncan 1981.

sponding range of angular diameters. Angular diameters have also been determined from the Barnes and Evans (1976) ($V, V - R$) relationship and from the Barnes, Evans, and Moffett (1978) ($V, B - V$) relationship for solar-type stars. All four of these determinations of $\phi$ for each star are listed in Table 4. The quantity $SF$ is the resulting, adopted scale factor used to convert from flux at Earth, $f$, to stellar surface flux, $\pi F$.

IV. THE SOLAR ULTRAVIOLET SPECTRUM

The full-disk solar spectral irradiance on 1980 July 15 is shown in Figure 1. This measurement was made by a University of Colorado sounding rocket (Mount and Rottman 1981), and the full ~1 Å resolution data set was made available to us by G. Rottman. The UV spectrum of the Sun between 1150 and 1900 Å shows clear evidence of solar-cycle-related (and other) variability (cf. Cook, Brueckner, and VanHoosier 1980; Heath and Thekaekara 1977; Rottman 1981; Mount, Rottman, and Timothy 1980); this particular spectrum is representative of solar maximum. Apart from the usual ensemble of chromospheric and transition region lines, we point out three distinctive absorption features (McAllister 1960), $\mathrm{Si\,i} \sim \lambda 1850 (3p^2 3S^2 - 4d^2 3P^0)$, $\mathrm{Si\,i} \sim \lambda 1900 (3p^2 3P^0 - 3d^2 3P^0)$, and $\mathrm{Al\,i}$ autoionization $\sim \lambda 1935 (3p^2 3P^0 - 3s3p^2 2S)$, which can be identified in many of the stellar spectra.

A second absolutely calibrated full-disk solar spectrum was made available to us by G. Rottman from a flight of the same instrument on 1982 May 17. Although the difference in time is only 2 yr, this second spectrum is at nearly solar minimum values (G. Rottman, private communication). These two spectra are shown together at the top of Figure 2. We find that (1) the emission lines in the solar minimum spectrum are generally ~2–3 times fainter than in the solar maximum spectrum (except for $\mathrm{Si\,ii}$, which is curiously higher at minimum); (2) the ~1600 to ~1750 Å continuum is also significantly fainter at minimum; but (3) the continuum between ~1750 and ~2000 Å is virtually identical in the two spectra.

Next we have smoothed the two solar spectra to IUE low-dispersion resolution (~5 Å) as shown at the bottom of Figure 2. This is what the Sun would look like as a star.
<table>
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<tr>
<th>HD No.</th>
<th>$T_{\text{eff}}$</th>
<th>[Fe/H]</th>
<th>$\log g$</th>
<th>$M/M_\odot$</th>
<th>Log Age</th>
<th>$v \sin i$ (km s$^{-1}$)</th>
<th>$P$(Rot.) (days)</th>
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observed by IUE. We have drawn in the Planck functions $\pi B_\lambda$ over the UV continuum, and the best fit is $T \sim 4700$ K. The formation of the UV continuum has been modeled in detail by Vernazza, Avrett, and Loeser (1981, 1976) and by Samain (1980) for plane-parallel model atmospheres (which is not at all what the Sun actually looks like at these wavelengths, as discussed below); this spectral region is shown to form at the temperature minimum, and although $T \sim 4700$ K derived from this simple blackbody fit is high compared with the model value of $\sim 4200$ K, our objective is to do differential intercomparisons of UV continua of solar-like stars, and in this context the simple fitting of blackbody surface fluxes should result in a reasonably good estimate of temperature minimum differences between the Sun and the stars observed by IUE.

V. THE IUE SWP STELLAR SPECTRA

a) The IUE Grating Scattered-Light Problem

A serious problem plaguing low-dispersion, short-wavelength IUE observations of cool stars has been the suspected

TABLE 3 — Continued

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<tr>
<th>HD No.</th>
<th>T$_{\text{eff}}$</th>
<th>[Fe/H]</th>
<th>Log $g$</th>
<th>M/M$_{\odot}$</th>
<th>Log Age</th>
<th>$v$ sin $i$ (km s$^{-1}$)</th>
<th>P(Rot.) (days)</th>
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TABLE 4

ANGULAR DIAMETERS OF THE SOLAR-LIKE STARS

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<th>T(low)</th>
<th>T(high)</th>
<th>T(low)</th>
<th>T(high)</th>
<th>(B - V)</th>
<th>(V - R)</th>
<th>Adopted</th>
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Fig. 1.—The full-disk solar spectral irradiance (expressed as a surface flux, $\pi F$) for the Sun at maximum on 1980 July 15 as measured by Mount and Rottman (1981); the resolution is $\sim 1$ Å.

Fig. 2.—Shown at the top (Figs. 2a–2b) are the ($\sim 1$ Å resolution) full-disk solar spectral irradiance measurements of Mount and Rottman for the "maximum Sun" and the "minimum Sun." At the bottom (Figs. 2c–2d) are the same spectra smoothed to IUE low-dispersion resolution ($\sim 5$ Å); also shown are blackbody surface fluxes, $\pi B_\lambda$, to fit the UV continuum. These indicate a temperature of $\sim 4700$ K for the temperature minimum.
IUE SPECTRA OF SOLAR-TYPE STARS

Fig. 3.—Smoothed pairs of IUE spectra for three stars in our sample. In all cases the top spectrum is the observed one, and the bottom spectrum is the one corrected for the contribution of scattered light using the method of Basri, Clarke, and Haisch (1984). Although there would be considerable change in the continuum below ~1600 Å, above that point—where the temperature minimum blackbody fits to the UV flux are made—the effects of scattering are minimal.

but heretofore uncertain level of long-wavelength light scattered by the cross-dispersion grating onto the short-wavelength spectrum. This problem was thought to be acute for cool stars, including stars like the Sun, having a very steeply falling UV flux, so that a small fraction of the bright, long-wavelength light scattered along the direction of the dispersed spectrum by the grating could easily overwhelm the measured short-wavelength flux.

This has now been studied by Basri, Clarke, and Haisch (1984), and indeed it is found that spectra like the Sun's would suffer from a considerable amount of contamination for wavelengths below ~1600 Å. However, at longer wavelengths—where our temperature minimum blackbody fits are made—while there is some flattening of the slope of the continuum, the change is on the order of a few percent. It was also found that the complementary problem of loss of measurable flux out of spectral lines due to scattering could amount to as much as 15–35%, with greater scattering losses occurring at the shorter wavelengths. However, neither of these findings warrants a correction for scattering in this study given the accuracies of temperature fits for the UV fluxes; and in the cases of spectral-line intercomparisons we are interested more in the considerable differences that are even qualitatively apparent.

In order to show directly that the problem is not major in the context of the present investigation, we have applied the procedure for scattered-light removal outlined by Basri, Clarke, and Haisch (1984) to three of the stars in our sample for which we also had available IUE long-wavelength (LWR) low-dispersion data. These data allowed us to correctly remove light scattered from the LWR wavelength range into the SWP spectra, and hence to see the scattered-light contribution.

The results for these three stars are shown in Figure 3, in which we show smoothed IUE SWP spectra as observed and after correction for the scattered-light component. In the ~1650–1950 Å region the effects of scattering are unimportant.

b) IUE Spectra of the Fourteen Stars

A log of the IUE observations is given in Table 5. Spectra have been weighted by exposure time and added to arrive at a single spectrum for each star. Since all the stars are alike, it is easy to intercompare the quality of the spectral data for a given star. We have defined a data quality index (DQ), proportional to the total exposure time and to the flux at Earth; this ranges from 3 to 62 on this scale (the scale is proportional to the total number of photons counted).

The 14 IUE low-dispersion spectra are shown in Figure 4; note that all of the spectra including the solar spectra in Figure 2 are surface fluxes (using the scaling factors in Table 4), and that they are all on a common linear scale. Reseau marks and saturated pixels have been removed (as has Lyman-α), and in several cases the spectrum longward of 1800–1900 Å has been cut off by saturation. The temperature minimum blackbody curves are drawn in, and the order of the spectra is according to increasing temperature, i.e., higher and steeper UV continua.

In addition to the usual ensemble of chromospheric and transition region lines (which we discuss below) there are four peculiar emission features, which we have labeled A, B, C, and...
D in the plots of the stellar fluxes. Feature D (\(-1710\) Å) appears only in the spectrum of HD 72905 and is most likely an Fe ii line or line blend (cf. the numerous Fe ii lines in that region of the solar spectrum in Fig. 1); however, it is unknown why this particular feature should be enhanced. By contrast, features A (\(-1490\) Å), B (\(-1500\) Å), and C (\(-1510\) Å) appear singly and in combinations in nine of the 14 spectra; there is nothing at all of significance in this region of our solar spectrum. Possible identifications are (cf. Cohen 1981): N iv at \(1486.5\) Å, Ni ii at 1500.4, 1502.2, and 1510.9 Å, and C i at 1511.0 Å.

VI. DISCUSSION

a) Correlation of Parameters

The spectra in Figure 4 have been arranged by increasing UV continuum, and there is clearly an enormous difference in these fluxes, ranging from lower than solar to much higher for these optically quite similar stars. The two coolest stars are indeed the G5 V stars, as might be expected; the three hottest stars are G0 V, in accordance with spectral typing. However, in between there is little correlation between the observed UV continuum intensity and spectral type or between \(T_{\text{min}}\) and \(T_{\text{eff}}\).

Figure 5 is a plot of \(T_{\text{min}}\) versus \(T_{\text{eff}}\). The two stars HD 20794 and HD 102365 clearly have lower values for both than the other stars, and this is consistent with their later spectral type, G5 V. For the remaining stars there seems to be no correlation whatsoever between \(T_{\text{eff}}\) and \(T_{\text{min}}\). The three stars manifesting the highest UV continuum are the least well fitted by blackbody emission (the UV continua rise too steeply); we have assigned \(T_{\text{min}} \approx 5100\) K in our plot, but whether or not a blackbody fit is a good representation of these UV fluxes, it is clear that these stars manifest significantly higher temperature minima than the other stars, and yet the range of \(T_{\text{eff}}\) is the same as for the entire sample less the two G5 V stars.

We have also measured the Mg ii k line fluxes for 12 of these stars for which we had available LWR spectra. Emission-line integrated surface fluxes have thus been measured for the lines O i \(\lambda\)1304, C ii \(\lambda\)1335, Si iv \(\lambda\)1398, C iv \(\lambda\)1550, He ii \(\lambda\)1640, C i \(\lambda\)1657, and Mg ii k \(\lambda\)2795; these are presented in Table 6.

In Table 7 we have arranged the stars according to increasing temperature minimum, i.e., increasing temperatures for the blackbody fits to the \(1700-1900\) Å continuum. We have tabulated a variety of stellar parameters: chromospheric and transition region emission lines normalized to the stellar bolometric fluxes, coronal X-ray luminosities, \(T_{\text{min}}/T_{\text{eff}}\) ratios, spectral types, and ages. A clear dichotomy emerges when these data are arranged in order of increasing \(T_{\text{min}}\); the hotter half of the list (ordered by \(T_{\text{min}}\)) exhibits significantly greater “activity” than the cooler half.

We first examine \((T_{\text{min}}/T_{\text{eff}})^4\), a measure of the energy flux coming from the temperature minimum region compared with the deeper photosphere. The active stars have values of this ratio ranging from 0.48 to greater than 0.67, while the inactive stars lie in the range 0.38–0.52. If there were no nonradiative heating, one might naively expect the temperature minimum to occur at the gray-atmosphere boundary value; this would imply a value of 0.44 for \((T_{\text{min}}/T_{\text{eff}})^4\), which happens to be exactly our blackbody fit for the Sun in this analysis. However, a non-LTE treatment of the continuum naturally gives rise to a positive temperature gradient above this minimum—a phenomenon referred to as the Cayrel mechanism (cf. Mihalas 1978)—but the temperature minimum would still approximately equal the gray-body value. Unfortunately this simple picture is vitiated by non-LTE line transfer effects (Athay 1970), which show a strong net cooling counteracting the Cayrel mechanism. It is thus not obvious what to expect for the actual value of the temperature minimum; in fact semiepipirical determinations of \(T_{\text{min}}\) for the Sun range from less than 4000 K to \(\sim 4500\) K (Ayres 1981; Chapman 1981).

As one moves to chromospheric diagnostics, the dichotomy becomes quite clean, with one exception: HD 63077. In both Ca ii and Mg ii the inactive group lies a factor of 2 or more below the active group. The ratio of Ca ii K emission to bolometric flux is in the range \(R(K) < 3\) to \(\sim 9\) (in units of
Fig. 4.—HUE SWP low-dispersion spectra of the 14 solar-like stars arranged according to increasing UV continuum flux. The scattered-light contribution is clearly evident as a more or less flat continuum below ~500 Å for the brighter stars. Segments of the spectrum which have been smoothed because of saturation or removal are indicated by L.
Fig. 4—Continued
Fig. 5.—Effective temperature, $T_{\text{eff}}$, vs. inferred temperature minimum, $T_{\text{min}}$, for the solar-like stars and the Sun. The $T_{\text{eff}}$ ranges are from Table 4 except that a minimum range of 50 K is adopted. The two stars in the lower left-hand corner are G5 V and clearly manifest lower temperatures than the other stars; for the rest there is no correlation between $T_{\text{min}}$ and $T_{\text{eff}}$.

$10^{-6}$) for the first half of the sample, including the Sun, and lies in the range $R(K) \sim 16$ to $\sim 25$ for the stars with the highest $T_{\text{min}}$. Interestingly the two adjacent stars in the table, HD 19373 and HD 1835, manifesting an order-of-magnitude difference in $R(K)$ have the same $T_{\text{min}}$. Thus we see that the same agent which led to the ordering of the observed temperature minima is at work higher in the atmosphere. Conversely this is direct evidence for nonradiative heating at the level of the temperature minimum in at least the active group of stars.

The dichotomy extends to the transition region and corona as well, as shown by the C iv ratios and the X-ray luminosities. While the few coronal X-ray luminosities are consistent with this inferred dichotomy, it is important to bear in mind that the range in $L_x$ for the Sun is at least an order of magnitude between quiet Sun and active Sun. Of course one might worry about variability and activity cycles confusing the picture, but there is little suggestion of this for the chromospheric diagnostics. In a detailed study of one of the stars (HD 39587) Boesgaard and Simon (1984) found that Mg ii exhibited excellent short-term stability, while transition region diagnostics like C iv were much more variable; this is consistent with our sample, for although the general ordering is still preserved in C iv, there is much more scatter in the active and inactive groups.

A very suggestive explanation for the dichotomy is found by examining the ages of these stars. We have drawn mostly on the work of Duncan (1981) for these; he used the Li strength as an age indicator. One finds that the active group stars are all 1.5 billion years old or younger, while the inactive group stars are all about 2 billion years of age or older. We note that the effects of chromospheres on Li strengths discussed by Giampapa (1984) would only serve to make the young group appear even younger, since they have the stronger chromospheres and additional heating in the temperature minimum region. Our observations thus imply that solar-type stars lose their youthful activity in the age range 1–2 billion years or so. The star HD 63077 therefore appears to be anomalous owing to a temperature minimum that is too hot for both its age and its level of chromospheric activity. Its continuum is the steepest of any in the sample in the $\sim 1800$ Å region. Perhaps a small, hot companion is present; or perhaps it is really a late-F star.

b) The Nature of the Solar Temperature Minimum

Since the stars in question are all solar-like, it is particularly instructive to consider the nature of the solar temperature minimum. Figure 6 is an image of the Sun in the $\sim 1600$ Å (130 Å FWHM passband) continuum obtained on 1980 September 23 by a French experiment, the Laboratoire de Physique Stellaire et Planétaire “Transition Region Camera” (TRC), on board a Lockheed sounding rocket. Despite the name of this experiment, the contributions of chromospheric and transition region lines in the filter passband are negligible.

TABLE 6

Emission-Line Surface Fluxes

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<th>Si iv λ1398</th>
<th>C iv λ1550</th>
<th>He ii λ1641</th>
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<td>...</td>
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Note.—Units are $10^4$ ergs cm$^{-2}$ s$^{-1}$.
Fig. 6.—The Sun at 1600 Å on 1980 September 23 taken by the LPSP TRC on board a Lockheed solar rocket (see Bonnet et al. 1982). (top) About half of the solar disk is shown, centered on an active region, in this underexposed image. Three distinct structures are apparent: very bright points and clusters of points in the central active region, active region plage, and the network; note, however, that plage and network differ little in brightness, and it is likely that the plage is simply a larger collection of the same magnetic flux tubes that constitute the network. (bottom) A blowup of the active region and the surrounding network from a longer-exposure observation. This short increase in exposure brings out an entirely new component, the “cell bright points” seen inside the network (supergranule cells) everywhere on the disk.
in comparison to the temperature minimum continuum on the solar disk. Further discussion of the instrumentation may be found in Bonnet et al. (1982). Other imaging observations of the solar temperature minimum atmosphere have been reported by Brueckner (1980) and by Cook, Brueckner, and Bartoe (1983) from a Naval Research Laboratory rocket experiment viewing the Sun at 1600 Å (37 Å FWHM passband), and by Hersé (1979) from a balloon-borne experiment imaging the Sun near 2000 Å.

Three distinct types of features are apparent in the top image of Figure 6: very bright points and clusters of points within the main active region, the bright plage constituting the active regions, and the overall network everywhere on the disk. However, the difference between plage and network appears to be one of spatial extent rather than brightness, in that the active region plage appears to be simply a larger concentration of network-like emission. Slightly longer exposure manifests an entirely new component, however, as shown in the bottom of Figure 6. The spatial resolution of the image is on the order of 1"; the countless “cell bright points” inside the network (supergranule cells) are real, and have been studied in detail by Foing and Bonnet (1984a, b) and, using a different data set of slightly lower resolution, by Cook, Brueckner, and Bartoe (1983).

The intensity ratios of these structures to the general UV temperature minimum background (cf. Foing and Bonnet 1984a) are approximately ~ 6, for the very bright points; ~ 3, for the network/plage; and ~ 1.5, for the cell bright points. We now estimate the fractional coverage of the solar disk for each of these features. Active region plage plus network is on the order of 10%, whereas the active region very bright points are certainly less than, say, 0.1%. The cell bright points appear to cover about 15% of the quiet surface according to Cook, Brueckner, and Bartoe (1983), which is consistent with the Foing and Bonnet observation that typical grain widths are ~ 1.5 Mm and average distances between grain edges are ~ 2 Mm; we note that Cook, Brueckner, and Bartoe attempt to correct for the fact that they are not resolving the cell bright points when they estimate a 4% surface coverage; however, in our context this is not relevant since we will combine intensity with area, and that product is independent of resolution. Table 8 summarizes the contribution to the disk-integrated UV temperature minimum flux of these various observed components.

The plage and network emission on the Sun is clearly related to magnetic structure, and Foing and Bonnet (1984a, b) are able to account for this using the simple approximation that the temperature distribution is the same inside and outside magnetic flux tubes, but that the density inside flux tubes is less than in the external atmosphere; this then implies that a given optical depth will occur at a deeper level in the flux tube, and hence, with an outwardly decreasing temperature gradient, a higher temperature will be seen inside the flux tube. The simplifications inherent in this “model” are questionable, but the empirical fact remains that regions of known magnetic flux concentration coincide with increased emission at the temperature minimum level of the atmosphere in the network.
TABLE 8

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Background</th>
<th>Cell Bright Points</th>
<th>Plage/Network</th>
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<tr>
<td>Intensity (arbitrary scale)</td>
<td>1</td>
<td>1.5</td>
<td>3</td>
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<tr>
<td>Surface coverage</td>
<td>-0.75</td>
<td>-0.15</td>
<td>-0.10</td>
</tr>
<tr>
<td>Disk-integrated</td>
<td>~0.58</td>
<td>~0.18</td>
<td>~0.24</td>
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</table>

The origin of the cell bright points inside the network is still unknown. Foing and Bonnet argue that too high a magnetic field strength at the photospheric level is implied by a flux tube model of cell bright points, i.e., a bright point being a single flux tube; the implied field strengths are not seen on photospheric magnetograms. Again, however, the simplifications of the model make this a weak argument; in fact, very small magnetic field concentrations have recently been observed inside supergranule cells (Title 1984; Topka 1984; Martin 1984). The similarity of these bright points to those seen in Ca II K, is striking, and Sivaraman and Livingston (1982) claim to have demonstrated the cospatiality of these Ca II K bright points with weak magnetic elements (near-simultaneous very high resolution magnetograms and spectroheliograms are necessary owing to the short lifetime and the motion of these features), although this result is not universally accepted at present. It has been proposed instead that there is local energy dissipation somehow related to coherent oscillations within supergranules (cf. Damé, Gouttebroze, and Malherbe 1984; Cram and Damé 1983); the bright points may be nodes in a standing-wave system.

An obvious question to ask is, What is the lowest $T_{\text{min}}$ and what is the highest $T_{\text{min}}$ for stars like the Sun, consistent with atmospheric structure basically analogous to that of the Sun? We have just demonstrated that in fact ~40% of the solar UV flux is due to excess emission from plage, network, and cell bright points, and if we were to replace that excess emission with the lower overall UV background, the best-fit blackbody would be ~100–200 K lower. Nevertheless, within the approximation of the blackbody representation and the uncertainty in calculating a non-LTE Cayrel mechanism minimum, it is clear that the general background solar UV continuum is close to the theoretical minimum. The only star that appears to be significantly cooler than this in our sample is of slightly later spectral type than the Sun (HD 20794 at G5 V); we thus find no anomalies regarding a temperature minimum that is too low for any of our stars.

At the other extreme, if the Sun were covered entirely by plage, the disk-integrated flux would be ~2–3 times higher, and this translates into an apparent temperature increase of ~150–250 K. The star HD 63077 appears to have an effective temperature somewhat lower than the Sun, $T_{\text{eff}}$ ~5620–5660 K, yet we find that $T_{\text{min}}$ is ~400 K higher than the Sun; this star is classified as spectral type G0 V, but if the effective temperature is correct, this poses a problem in accounting for the apparent UV flux.

The star HD 1835 may be an example of a star like the Sun (G2 V) almost entirely covered by plage, since its Ca II K index is ~6 times solar and we find $T_{\text{min}}$ ~150 K higher than the Sun. Campbell and Cayrel (1984) propose that ~3% of the stellar surface of HD 1835 is covered by starspot umbrae (compared with ~0.1% for the Sun with, say, 10 average-sized spots on the visible hemisphere; Unsold 1969); this is consistent with our suggestion that the surface is entirely covered by plage, since on the Sun the ratio of plage/umbral area is ~50 for a typical active region.

VII. SUMMARY

1. The UV continuum longward of ~1600 Å in IUE short-wavelength spectra is a diagnostic of the temperature minimum. Differential intercomparison of the temperature minima of solar-like stars can be done by fitting blackbody radiation functions to such stellar surface fluxes, and this procedure is not sensitive to scattered-light contamination of IUE low-dispersion spectra.

2. There is a considerable range of $T_{\text{min}}$ for stars of similar $T_{\text{eff}}$ and spectral type. Evolutionary effects (i.e., age-dependent activity) appear in the strength of the temperature minimum emission which are correlated with the degree of chromospheric, transition region, and coronal emission in the sense that "active stars" have hotter temperature minima.

3. For stars like the Sun there appears to be a qualitative decrease in the degree of activity at around 1–2 billion years (with the caveat that this could be an artifact of the small sample).

4. The temperature minimum of the Sun is highly structured on spatial scales of ~1". Cell bright points inside the supergranulation network contribute significantly to the disk-integrated flux (in our example ~18%); enhanced network and plage emission contribute about the same (in our example ~24%); the remainder comes from the general quiet-Sun background.

5. It is possible to explain the observed range in temperature minimum emission for solar-like stars by having the stellar surface covered almost entirely by solar-like plage, or conversely by having the stellar surface consist of only quiet-Sun-like background.

6. Interesting qualitative differences are apparent in the UV spectra of stars that are near solar twins in the photospheric spectrum. We provide a compendium of stellar data to further this approach to the study of stellar activity. It is apparent from our compendium that there are discrepancies in determinations of basic stellar parameters that need to be resolved.

Part of this work has been done under the Lockheed Independent Research Program. This work was also supported in part by the National Aeronautics and Space Administration through grant NAG5-69 to the University of California Space Sciences Laboratory. We wish to acknowledge the help of Dr. E. W. Brugel and the staff of the IUE Regional Data Center at the University of Colorado, and in particular Mr. T. Armitage. We also wish to thank Dr. G. J. Rottman and Dr. T. R. Ayres at LASP for freely sharing data and analysis programs with us. We thank the staff of the NSSDC for their expedient delivery of archival IUE data. We thank Dr. L. W. Acton for carrying out some of the IUE observations.
REFERENCES


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