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SOLAR LIMB EMISSION LINES NEAR Ca II H & K AND THEIR SPATIAL INTENSITY VARIATIONS

R. J. RUTTEN (*) and R. E. STENCEL (***)

Sacramento Peak Observatory (**), Sunspot, New Mexico 88349, USA
NASA-Goddard Space Flight Center, Greenbelt, Maryland 20771, USA

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Summary. — We employ solar observations of high spatial and spectral resolution to identify emission lines seen in the extended wings of Ca II H & K near the solar limb. Emission lines in the wings of H & K represent valuable diagnostics of the atmospheres of cool stars, with a varying information content which depends on their particular formation mechanism. In solar spectrograms different emission line formation mechanisms can be distinguished by the character of the spatial intensity variation (SIV) apparent in the lines. We discuss various classes of H & K emission features, their spatial intensity variations and their formation mechanisms (of which some pose further problems).
We compile a new extended list of line identifications based on their formation class and compare the list with other line lists. We find evidence that stellar luminosity-sensitive lines tend to show large spatial intensity variation on the Sun.

Key words : Photosphere — Solar limb — Spectral line formation — Emission lines.

1. **Introduction.** — The existence of weak emission features in the extended wings of the solar Ca II H & K resonance lines has been known since Jewell's (1898) initial discovery of the 3 934.8 Å emission line observed near the solar limb. Since then their number has grown with the quality of the spectroscopic facilities : 4 lines in 1929 (Evershed), 9 in 1963 (Jensen and Orrall), 11 in 1973 (Engvold and Halvorsen) and 71 in 1973 (Stencel).

It has only recently been appreciated that these lines are of interest not only for their NLTE formation, but also for their potential as diagnostics of the atmospheric structure of cool stars. Stencel (1977, 1978) has reported on various characteristics of the weak lines superimposed on the H & K wings in a large sample of stars of spectral types F, G, K and M. They include lines that change from absorption into emission with increasing luminosity of a given spectral type. Several of these features exhibit a correlation between line width and stellar luminosity similar to the well-known Wilson-Bappu relation for the emission cores of Ca II H & K. In general, the variation of their width with the wavelength separation from the H and K line cores contains information on the depth-dependence of the non-thermal atmospheric motions.

The diagnostic value of these weak lines depends on their formation mechanism, which is different for the various classes of emission lines that exist. These classes are also distinct on spectrograms taken near the solar limb with high spatial resolution, because the differences in formation result in different sensitivities of the lines to small-scale inhomogeneities. We employ this property by using solar limb spectrograms of high spatial resolution as well as high spectral resolution. The observed spatial intensity variation (abbreviated to « SIV » hereafter) of a line then serves as an index of its formation class, and hence as an independent constraint on its identification. This enables us to ascertain the identifications of the majority of the emission features, notwithstanding the high line density in this spectral region, which has led to erroneous identifications in earlier work based on wavelength coincidences only.

Two types of H & K limb emission line have been discussed previously. The first type consists of the *rare earth ion emission lines*. These are very numerous due to the high line density of the rare earth ion spectra in the blue-violet wavelength region, and due to the predominance in the solar photosphere of the ions of the rare earths, which have typical first ionization potentials of 5.5 eV. The Ce II spectrum line density peaks in the 3 700-4 050 Å interval, at 10 lines per Å (Corliss, 1973).

Canfield (1971b) has explained the limb emission of the rare earth ion lines in the wings of H & K. The numerous levels and the many resonance-like transitions in the lanthanide spectra make the effects of *interlocking* important. Interlocking of the lines in the deep H & K wings with higher intensity lines outside H & K explains their emission over the local H & K background. In fact, the emission can be quite strong because the connecting rare earth lines outside the wings

(*) On leave from : The Astronomical Institute, Sterrewacht « Sonnenborgh », Zonneburg 2, 3512 NL Utrecht, The Netherlands.

(**) Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

(***) NAS-NRC Postdoctoral Research Associate.

Send offprint requests to : R. J. Rutten.

of H & K can also be limb emission lines, as in the case of Ce II. The latter have been explained by Canfield (1969, 1971a) as due to the importance of the scattering term in their source functions, which therefore follow the mean intensity outward, rather than the (in the blue) more steeply declining Planck function which describes the continuum. These formation mechanisms are perhaps the clearest example of effects of NLTE in weak photospheric lines.

For weak, optically thin lines such a formation mechanism through interlocking and scattering implies spatial averaging over a relatively large volume of line formation, resulting in low sensitivity of the line to small-scale inhomogeneities. Livingston and White (1974) noted a La II emission line without any SIV on a high-quality limb spectrogram that showed much finely-structured SIV in the other emission lines. Canfield and Stencel (1976) have confirmed that the Ce II 3 967.05 Å line near Ca II H shows only slight if any SIV in the solar spectrum.

We conclude that the formation of the H & K limb emission lines due to rare earth ions is well understood, and that these lines show no spatial intensity variation (SIV).

A line of a wholly different type that has received attention is the Fe II 3 969.4 Å doublet line (multiplet 3, a^4P-z^6D^0). Discovered by Evershed (1929), it was first attributed to Eu II or the wing of a nearby Fe I line (Thackeray, 1935, 1936) and later to Er II (Jensen and Orrall, 1963). Engvold and Halvorsen (1973) and Stencel (1973) re-identified it as due to Fe II multiplet 3. Lites (1974) suggested that this doublet is in emission near the limb due to pumping through the *UV* Fe II a^6D-z^6D^0 resonance lines (2 611.9, 2 617.6, 2 585.9, 2 598.4, 2 631.0 and 2 631.3 Å), with which it shares its upper levels. Canfield and Stencel (1976) found that its SIV is extremely large, and so confirmed that it cannot be due to a rare earth ion.

The question still remains of whether the *UV* photons that do the pumping are chromospheric or photospheric in origin. Lites (1974) found that they are downward diffusing chromospheric photons, but the strong emission cores that his model predicts for the *UV* resonance lines have not been observed in the solar spectrum (cf. Kohl *et al.,* 1978). This difficulty will be examined in another paper (Cram *et al.*).

A parallel study of the SIV in solar limb emission lines *outside H & K* has been made for the near-*UV* wavelength region 3 400-3 526 Å by Canfield *et al.* (1978). They found that the emission lines in this spectral region show SIV only when the lower-level population density is sufficiently high, and interlocking via radiative excitation through other lines is not important. The occurrence of SIV therefore depends generally on element abundance, spectrum complexity and lower excitation energy. Lines that show more SIV are also more locally controlled, and hence are more useful diagnostics of stellar atmospheric structure. These conclusions will hold as well for H & K wing emission lines.

2. **Methods.** — 2.1 OBSERVATIONS. — The spectrograms that we have used in this study were obtained by J. M. Beckers with the Echelle Spectrograph of the Vacuum Tower Telescope at the Sacramento Peak Observatory on 4 June 1976, on Eastman Kodak 5375 film. A 316 line/mm grating was used, yielding a dispersion of 11 mm/Å. The curved entrance slit, matching the solar limb, was opened to 110 μm and was placed a few seconds of arc inside the limb. Its width corresponds to 0.4 arcs, or 294 km on the Sun, or 10 mÅ in the spectrum. A time series was obtained consisting of sequences of three exposures, of 10, 20 and 30 seconds duration, of the spectrum between 3 919.5 and 3 983.5 Å.

The quality of the atmospheric seeing varied during the observing run ; the best spectrograms were selected. Their spatial resolution along the slit is about 1 arcs, or 750 km on the Sun, at a spatial scale of 287 μm/arcs on the film. A selection from the spectrograms is shown in figure 1.

2.2 MEASUREMENTS. — On photographic prints of the selected spectrograms we — i.e. each author independently — measured the positions of all discernable emission features, and derived wavelengths from the prominent absorption lines, using the tabulation of Moore, Minnaert and Houtgast (1966 : henceforward abbreviated to MMH). The line strengths and the degree of SIV were visually estimated, selecting for each line the print on which it was best exposed. The lines were identified from the usual sources for atomic laboratory wavelengths : Moore (1959, RMT), Meggers, Corliss and Scribner (1975, NBS145) and MMH. In addition to wavelength coincidence and multiplet membership, we used the solar SIV, and the appearance and strength of the lines in the laboratory as extra constraints on the identifications.

3. **Results : Catalogue of H & K limb emission lines.** — 3.1 EMISSION LINE CLASSES. — The limb emission features superimposed on H & K are found to be *observationally* distinguishable in three different classes :

(a) *rare earth emission lines ;*
(b) *metal ion emission lines ;*
(c) *self-reversed lines.*

In addition to these classes, there is of course also emission present in the cores of H & K and — near the solar limb — in the Balmer H_ε line at 3 970 Å and in the He I 3 964.8 Å (multiplet 5) line. These lines (shown in figure 1) represent separate classes of their own, but will not be discussed here in detail.

The first two classes (a, b) together contain all *pure* emission lines, with or without SIV. They are listed together in table I. The second class (b) consists of the Fe II 3 969.4 Å line discussed above, and various similar lines found to be present.

The third observational class (c) consists of *self-reversed* lines, which have cores in absorption and wings in emission. These are due to both neutral and singly-ionized metals. The formation of their emission wings inside the solar limb has not been discussed yet : we will indicate a mechanism in section 4.3. They are listed separately in table II.

A representative selection of these different classes in shown in figure 1.

3.2 PURE EMISSION LINES. — In table I we list all observed pure (i.e. non-reversed) emission lines, in the following notation :

Column 1 : feature number ;
Column 2 : measured solar wavelength in Ångstrom, accuracy 0.01 Å ;
Column 3 : estimated intensity, on a subjective scale from 1 (barely discernable) to 10 (strongest emission present) ;
Column 4 : spatial intensity variation (SIV) ;
 – = no SIV present
 0 = some SIV present
 + = very strong SIV
 d = diffuse line ;
Column 5 : identification : element, ionization stage and RMT multiplet number when present in RMT.
 + = transition without RMT multiplet number, but identified in NBS145 (part 1) by the excitation energies of its upper and lower levels. Their designation is given in the Atomic Energy Levels (Moore, 1949-1958) or in the literature compiled in NBS145 (part 1) ;
 ? = wavelength coincidence, but identification is questionable ;
Column 6 : laboratory wavelength in Å, taken from NBS or RMT ;
Column 7 : number referring to the notes below.

3.3 SELF-REVERSED LINES. — In table II we list the observed self-reversed lines, i.e. the lines with emission wings and absorption cores. The Ca II H & K and H_ε lines are included. The notation is as follows :

Column 1 : feature number ;
Column 2 : solar wavelength (Å) of line center, taken from MMH ;
Column 3 : identification, taken from MMH ;
Column 4 : intensity of emission wings, on a subjective scale from 1 to 10 ;
Column 5 : type of line ; number refers to notes below.

3.4 COMPARISON WITH OTHER COMPILATIONS. — Table I represents an improvement over the earlier lists of H & K limb emission lines, both in the number of features, which has now grown to 125, and in the reliability of the identifications. To this improvement have contributed : the superiority of the new Sacramento Peak Observatory observations, the availability of the NBS145 laboratory line list, and the independent constraint of spatial intensity variations.

We first compare our list to Stencel's (1977, Table II) list of *stellar H & K wing emission lines* in table III. The column « class » specifies the stellar behaviour (cf. Stencel, 1977), « W-B » the presence of a stellar Wilson-Bappu effect and « SIV » the presence of solar spatial intensity variation.

Stencel's list contains 13 emission features (his classes a and b), of which 7 lines are also on our list. Of the latter, the two lines that show most clearly a Wilson-Bappu type relation between line width and luminosity (Ti II, nr. 113 and Fe II, nr. 30) are lines of our class (b), due to metal ions. They show SIV in the Sun. However, the stellar 3 935.94 Å feature which has the most pronounced Wilson-Bappu character, is not seen in emission in our solar spectra. Finally, the rare earth line at 3 937.5 Å (nr. 27) is also present in the stellar list, with a Wilson-Bappu relation of its own.

We next compare our list with the compilations of the *solar chromospheric spectrum*. Most of our rare earth lines are not present in the extensive flash-spectrum list of Dunn *et al.* (1966) of chromospheric lines observed at the 1962 eclipse, except for the strongest ones and three weak lines (Eu II 3 930.5, Nd II 3 951.1 and Sn II 3 963. Å). Some other lines of table I are present : Zr II 3 934.78, Fe II 3 938.30 Å and our unidentified lines nrs. 71 and 72, identified by Dunn *et al.* as Ti I 13 and Zr II 16 respectively. Of table II all lines are present, except Ti II 3 932.0 Å which may have been swamped by the Ca II K_{23} core emission. This comparison shows that only the strongest rare earth lines extend into the chromosphere.

Many more lines of our list are also present in Pierce's (1968) tabulation of the chromospheric spectrum « *outside of eclipse* ». His observations were made with the spectrograph slit placed tangentially to the solar limb, and so they are intermediate between the truly chromospheric eclipse flash spectrum and our spectrograms which were taken with the slit inside the limb. Pierce's list presents indeed a mixture of the flash spectrum tabulation by Dunn *et al.* (1968) and our tables I and II. His list contains many rare earth lines that are present in our list but not in the flash spectrum, and on the other hand various metal lines that do appear in the latter but not in our list. Even so, there are many more coincidences with our list than with the list of the flash spectrum. There are also numerous entries in Pierce's list, attributed to rare earths as well as to metals, that are not present in either our list or in the Dunn *et al.* compilation. Some of these must be regarded as questionable (cf. Livingston and White, 1974).

Finally, we compare our list to Svestka's (1972) list of emission lines of the same spectral region as seen in *solar flare spectrograms*. Of table I only a small number of lines, all non-rare earth, are seen in flares : Zr II 3 934.8 (nr. 25), Fe II 3 938.3 (nr. 30), Fe II 3 945.2 (nr. 44) and He I 3 964.8 Å (nr. 83). Several of these are among the strongest stellar H & K emission lines as well (Stencel, 1977). Of table II, all lines are seen in emission in flares, except for the two Y II lines (nrs. 117, 125) and V II 3 952.0 Å (nr. 118).

4. **Discussion : line classes and formation mechanisms.** — 4.1 EMISSION LINES OF RARE EARTH IONS. — Rare earth lines constitute the majority of the emission features seen near H & K in the Sun. In order of decreasing frequency, lines of Ce II, Nd II, Sm II, Pr II, Dy II, Eu II, Gd II, La II and Er II are present. Only the strongest of these lines show a hint of SIV, and only these extend into the chromosphere. Their pre-

sence and their properties are fully in agreement with the Canfield (1971a, 1971b) formation mechanism of radiative interlocking through optically thin lines.

4.2 EMISSION LINES OF METAL IONS. — Of the non-reversed emission lines that show large SIV, only the identifications of nrs. 30, 44, 86, 95 and 104 are certain. These lines are all due to multiplets 3 and 29 of Fe II, and are well explained by the Lites (1973) formation mechanism of upper level pumping through the strong Fe II resonance lines in the *UV* — although the source of the *UV* photons remains to be settled, as mentioned above. This question is of obvious importance to stellar diagnostic applications.

For the other emission lines with pronounced SIV (nrs. 37, 51, 71 and 72) we found only questionable identifications, if any. In addition, some metal ion lines are probably present without SIV (nrs. 16, 18, 25 ; cf. Canfield *et al.,* 1978).

4.3 SELF-REVERSED LINES. — As shown by their appearance (notes 9-14), the self-reversed lines of table II are of varying character. We first discuss the Fe I 4 and Al I 1 lines described in note 9. The reversal pattern — a wide dark core and narrow emission wings — of these resonance lines indicates a similar origin as for the similar pattern near the limb of the Ba II 4 554 Å resonance line (Rutten, 1977). This line has partially coherently scattered wings, of which the source function decouples from the line core source function at a height where collisional redistribution becomes infrequent, and shows a suprathermal frequency-dependent fishbone pattern outwards. The high wing source function produces observable emission near the limb (Rutten, 1978 ; Rutten and Milkey, 1979).

Although the Doppler width of the Fe I and Al I resonance lines is larger than the barium Doppler width, resulting in a larger width of the redistributed line *core,* the frequency-dependence of the Fe I and Al I *wing* source functions is enhanced by the background H & K wing opacity, which raises the height of formation of the line wings to a lower density where collisional redistribution occurs less frequently. The result near the limb is the typical pattern of a wide, dark core and narrow emission wings that is observed.

On the basis of this tentative mechanism we predict that the Fe I 3 920.27 Å line (nr. 109 : maximum polarization possible = 100 %, cf. Beckers, 1974) will show linear polarization near the limb, and that the other Fe I lines of multiplet 4 may show some polarization (maxima 15-30 %). (The Al I doublet lines may serve as an observational check since they are not polarizable.)

The extra brightenings that are superimposed on the average reversal pattern point to local changes in the atmospheric structure in inhomogeneities that similarly affect the weaker subordinate lines described in note 10. These lines show only emission knots, and no underlying average reversal.

A similar difference between emission in fine structure and in underlying average reversals is also shown by the chromospheric emission lines. As described in notes 13 and 14, the Ca II H & K emission consists exclusively of these fine structure elements, while H_ε shows an average underlying reversal pattern. This difference illustrates the local collisional control of H & K and the non-local photoelectric control of H_ε (cf. Ayres and Linsky, 1975).

Finally, there are only three lines that show the flash spectrum pattern of an emission line with a self-absorbed core : a weak absorption core present in a wider emission line. This is the pattern expected very close to the limb for *normal* lines, with source functions that are thermal or nearly thermal up to the temperature minimum (cf. discussion in Rutten and Milkey, 1979, for Ba II 5 854 Å). The line of Ti II 34 (nr. 113, note 12) is the only example present of a weak line. The lines of Y II 6 (nrs. 117, 125 ; note 11) are very bright, and they show large and peculiar SIV. They are not present in Svestka's (1972) flare emission line list. We could not find a simple pumping mechanism for these lines.

4.4 OTHER EMISSION FEATURES. — The only remaining emission line is He I 5 (nr. 83). It is the only non-reversed emission line of a neutral element ; it appears as a weak feature of large width (0.24 Å), due to the small atomic mass of helium (cf. Fig. 1).

4.5 DISCUSSION OF OTHER COMPILATIONS. — The comparison with Stencel's (1977) *stellar list* poses several questions (Table III). The pumped metal ion lines, such as Fe II 3 938.3 Å seem to be the most pronounced of the stellar emission features, and to exhibit the clearest Wilson-Bappu relations. This indicates that *large solar SIV and stellar luminosity dependence correlate.*

However, the stellar 3 937.5 Å line has as its solar counterpart only a rather weak rare earth line, which is formed quite differently. Jewell's line at 3 934.8 Å shows no solar SIV, and the strong stellar 3 935.9 Å line is wholly absent in the solar emission spectrum. Emission mechanisms for the various stellar lines identified as due to neutral metals are not clear in the context of the present solar data. Probably part of this difficulty arises from the much lower spectral resolution of the stellar data, and we anticipate improvement in the wavelengths and identifications when stellar spectra of higher spectral purity become available.

The comparison of our list with the Dunn *et al.* (1968) *list of the flash spectrum* and the list of the chromospheric spectrum « *outside of eclipse* » (Pierce, 1968) leads us to conclude that most of the solar limb emission lines are *photospheric* in origin, and that these appear in emission inside the limb because of special NLTE formation mechanisms. Only the strongest lines extend into the chromosphere.

Therefore the list by Pierce is to a large extent a list of *disk emission lines* : it may be viewed as a catalogue of lines with NLTE source functions in the high photosphere, rather than as a list of truly chromospheric flash spectrum lines, for most of the lines that are not present in the Dunn *et al.* tabulation.

5. **Conclusions.** — We have presented a new list of solar limb emission features near Ca II H & K based on new observations of high spatial and spectral resolution. Solar spatial intensity variation (SIV) is found to be a useful diagnostic in the classification of these lines.

Of the various classes of emission lines that are observationally distinguishable, only the lines of rare earth ions pose no further questions. For the other classes there remain unsolved problems, which include the identification of various emission lines with large SIV, and the correspondence with similar emission lines in stellar spectra.

Also of interest for further study are the NLTE formation mechanisms of the various types of self-reversed lines, and of the strong Y II emission lines.

A final conclusion is that Pierce's (1968) list of the chromospheric spectrum *outside of eclipse* may in many cases be interpreted as specifying *photospheric* lines with suprathermal NLTE line source functions. This list may therefore often serve as an empirical check on NLTE effects for *normal* photospheric lines.

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TABLE I. — *Non-Reversed Emission Lines near Solar Ca II H & K.*

Nr.	Solar Wavelength	Int.	Spatial Int. Variation	Identification		Notes
1	3919.62	2	- d	Pr II ?	3919.63	
2	19.80	5	-	Ce II 60	19.81	
3	19.92	3	-	Nd II +	19.92	
4	20.96	6	0	Nd II +	20.96	
5	21.91	3	- d	V I 42 ?	21.90	3
6	22.40	4	-	Sm II 38	22.40	
7	23.12	4	-	Ce II 191	23.11	
8	24.65	6	0	Ce II 190	24.64	
9	24.80	2	-	Ce II +	24.80	
10	24.99	1	- d	Nd I + ?	24.98	
				Pr I ?	24.99	
				Nb I + ?	25.00	
11	25.43	2	- d	Tb II + ?	25.45	
				Pr II 11	25.47	
12	27.11	5	-	Nd II +	27.10	
13	27.39	1	-	Ce II 43	27.39	
14	28.29	2	-	Sm II 17	28.28	
15	29.27	4	-	Nd II +	29.26	
16	29.73	2	- d	V II 10 ?	29.73	4
17	30.53	1	-	Eu II 5	30.48	
18	30.67	2	-	Y II 16	30.66	
19	30.81	1	-	Ce II +	30.81	
20	31.09	2	-	Ce II 49	31.09	2
21	31.38	2	-	Ce II 61	31.37	
22	31.54	4	-	Dy II +	31.52	
23	31.84	1	-	Ce II +	31.83	
24	32.14	1	-	Ce II +	32.15	
25	34.78	5	-	Zr II 43	34.79	1,8
26	36.22	3	-	La II 13	36.22	1
27	37.58	2	-	Nd II 19	37.57	1
28	37.81	1	- d	Ce II +	37.81	
29	38.09	4	-	Ce II 205	38.09	
30	38.30	10	+	Fe II 3	38.30	1
31	38.64	4	-	Er II + ?	38.63	3
32	38.86	3	-	Nd II +	38.86	
33	39.55	2	-	Tb II + ?	39.52	1
				Ce II + ?	39.52	
				Nd II + ?	39.52	
34	39.67	2	-	Ce II +	39.66	
35	40.34	7	0	Ce II 50	40.34	
36	40.96	3	-	Ce II +	40.97	
37	41.54	3	+	Re I + ?	41.54	
				Eu II ?	41.56	
38	41.88	2	-	Sm II + ?	41.87	
39	42.15	8	0	Ce II 37	42.15	
40	3942.26	2	-	Pr II ?	3942.27	
41	42.75	8	0	Ce II 57	42.75	
42	43.25	4	-	Sm II 9 ?	43.24	
43	44.68	7	0	Dy II +	44.68	
44	45.22	9	+	Fe II 3	45.21	
45	46.51	4	-	Sm II +	46.51	
46	47.98	4	-	Ce II +	47.97	
47	48.34	3	-	Nd II +	48.32	
48	49.07	8	0 d	La II 41	49.10	
49	49.41	3	-	Pr II 16	49.43	
50	51.13	3	-	Nd II + ?	51.16	
51	51.17	2	+	?	-	5
52	51.21	3	-	?	-	
53	51.32	2	-	Eu II ?	51.33	
54	52.11	2	-	Ce II +	52.11	
				Pr II ?	?	
55	52.20	7	0	Nd II 23	52.20	
56	52.57	6	0	Ce II 113	52.54	
57	52.84	2	-	Mn I + ?	52.84	
58	53.40	1	-	Nd II +	53.40	
59	43.54	2	-	Nd II +	53.52	
60	53.66	4	-	Ce II 141	53.66	

Nr.	Wavelength	Int.	S I V	Identification		Notes
61	53.95	4	- d	Ce II +	53.95	
62	54.40	2	-	Nd II ?	54.41	
63	55.10	1	-	Nd II + ?	55.09	
64	56.05	2	-	Ce II +	56.06	
65	56.28	5	-	Ce II 202	56.28	
66	56.90	3	-	Ce II 176	56.90	
67	57.46	4	- d	Nd II +	57.45	
68	57.68	4	-	Gd II 19	57.67	
69	57.80	3	- d	Dy II +	57.79	
70	58.01	6	-	Nd II 25	58.00	
71	58.17	2	+	Ti I 13 ?	58.21	5
				Zr II 16 ?	58.22	
72	58.25	8	+	Pr II ?	58.22	
				Ce II ?	58.27	
73	58.87	5	-	Ce II +	58.?	
74	59.53	3	-	Sm II +	59.53	
75	$9.62	2	-	Ce II +	59.62	
76	59.80	1	-	Ce II +	59.80	
77	60.38	1	-	Ce II +	60.38	
78	60.93	5	-	Ce II 84	60.91	
79	61.03	3	-	Re I + ?	61.04	
80	62.20	3	-	Nd II +	62.21	
81	63.00	2	-	Sm II +	63.00	
82	63.91	4	- d	Nd II +	63.90	
83	64.82	1	- band	He I 5	64.73	1
84	3967.03	4	-	Ce II 84	3967.05	
85	67.16	2	-	Pr II ?	67.15	
				Ce II + ?	67.18	
86	69.39	10	+	Fe II 3	69.39,.40	1
87	70.53	1	-	Sm II +	70.53	
88	70.61	1	-	Ce II +	70.64	
89	71.40	2	-	Sm II 43	71.40	2
90	71.68	3	-	Ce II 133	71.68	
91	71.75	2	-	Gd II 49	71.75	
92	71.97	6	- d	Eu II 5	71.96	6
93	73.27	7	0	Nd II 19	73.30	
94	73.99	4	-	Gd II 50	73.98	
95	74.17	5	+	Fe II 29	74.17	1
96	75.07	3	-	Ce II +	75.07	
97	76.28	5	-	Sm II 9	76.27	
98	78.56	7	-	Dy II +	78.57	
99	78.86	2	-	?	-	
100	79.02	1	-	Nd ?	79.03	
101	79.19	5	-	Sm II 51	79.20	
102	80.89	7	-	Ce II 194	80.88	
103	81.19	1	0	?	-	
104	81.62	5	+	Fe II 3	81.62	
105	81.94-82.09	3	- d	Pr II 38	82.05	7
106	82.38	5	-	Nd II +	82.36	
107	82.92	5	- :	Ce II +	82.89	
108	83.29	4	-	Ce II +	83.29	

1. Also present in the list of Stencel (1977, Table II) for F, G, K and M stars ;
2. Emission line present near this wavelength in the list of Stencel (1977, Table II) for F, G, K and M stars, but with another identification ;
3. Other members of this multiplet in the range 3 919-3 984 Å are not observed ;
4. Nr. 16 : very diffuse ; not in NBS145. Other member of this multiplet (nr. 118) is self-reversed ;
5. Large SIV, with emission only present in knots of typical size 700-1 500 km ;
6. Also wide in laboratory spectrum ;
7. Nr. 105 : very wide Pr II line, in agreement with complex laboratory line, which probably has large hyperfine structure (Pr is odd-numbered). Superimposed is Ti II with faint emission knots in its wings ;
8. Nr. 25 : Jewell's (1898) line.

TABLE II. — *Self-Reversed Emission Lines near Solar Ca II H & K.*

Nr.	Wavelength	Intensity	Identification	Notes/types
109	3920.27	3	Fe I 4	9
110	22.92	3	Fe I 4	9
111	27.93	4	Fe I 4	9
112	30.31	4	Fe I 4	9
113	32.02	2	Ti II 34	12
114	33.68	>10	Ca II 1 (K)	13
115	44.02	5	Al I 1	9
116	49.96	2	Fe I 72	10
117	50.36	9	Y II 6	11
118	51.96	1	V II 10	10
119	56.69	2	Fe I 278	10
120	61.54	6	Al I 1	9
121	68.49	>10	Ca II 1 (H)	13
122	70.08	>10	H I (H_ϵ)	14
123	77.75	2	Fe I 72	10
124	81.78	2	Fe I 278	10
125	82.60	9	Y II 6	11

9. Line with very dark, wide, flatbottomed absorption core and narrow emission wings. Superimposed on average emission wings are knots of extra emission, of size 700-1 500 km and average spacing of 3 000-8 000 km. These knots are shown similarly by all lines of types 9 and 10 ; the knots on the red and the blue side of each line are also well correlated ;

10. Line with dark core ; emission in the wings *only* in the form of the knots mentioned for type 9 ;

11. Nrs. 117 and 125 : line of Y II 6 (a^3D-z^1D^0). The only lines of this type : very bright, wide emission lines, with weak absorption cores and large SIV on 700-1 500 km scale ;

12. Nr. 113 : the only line of its type. A weak, self-reversed line with a weak absorption core and weak, but generally present emission wings. Variable from exposure to exposure, with varying ratio of emission over absorption. Slight SIV present in the emission. This line is one of Stencel's (1977) Wilson-Bappu lines ;

13. Nrs. 114 and 121 : Ca II H & K. The H_3 and K_3 absorption cores are very wide (0.6 Å). The H_2 and K_2 emission peaks consist *exclusively* of bright knots of size ~ 1 500 km and average spacing 3 000 km and with large variation in (Doppler ? −) shift from line center ;

14. Nr. 122 : H_ε. Very strong emission line, with a wide, weak absorption core, and an average reversal pattern of wing emission with only slight SIV. Clusters of brighter knots of emission are superimposed ; these correlate well with the brightest features in H_2 and K_2, at average separations of 15 000-30 000 km.

TABLE III. — *Comparison of Solar and Stellar Line Lists.*

Wavelength	Stellar I.D.	Class	W-B	Solar I.D.	SIV
3931.1	Fe I 565	a		Ce II 49	-
3932.0	Ti II 34	b	+	Ti II 34	note 12
3934.8	Zr II 43	b	+	Zr II 43	-
3935.9	Fe II 173?	a	+	-	
3936.2	La II 13	b		La II 13	-
3937.5	Nd II 19	a	+	Nd II 19	-
3938.2	Fe II 3	a	+	Fe II 3	+
3939.5	Sc II? Nd II?	a		?rare earth?	-
3966.6	Fe I 562,282	a	+	-	
3969.4	Fe II 3	a		Fe II 3	+

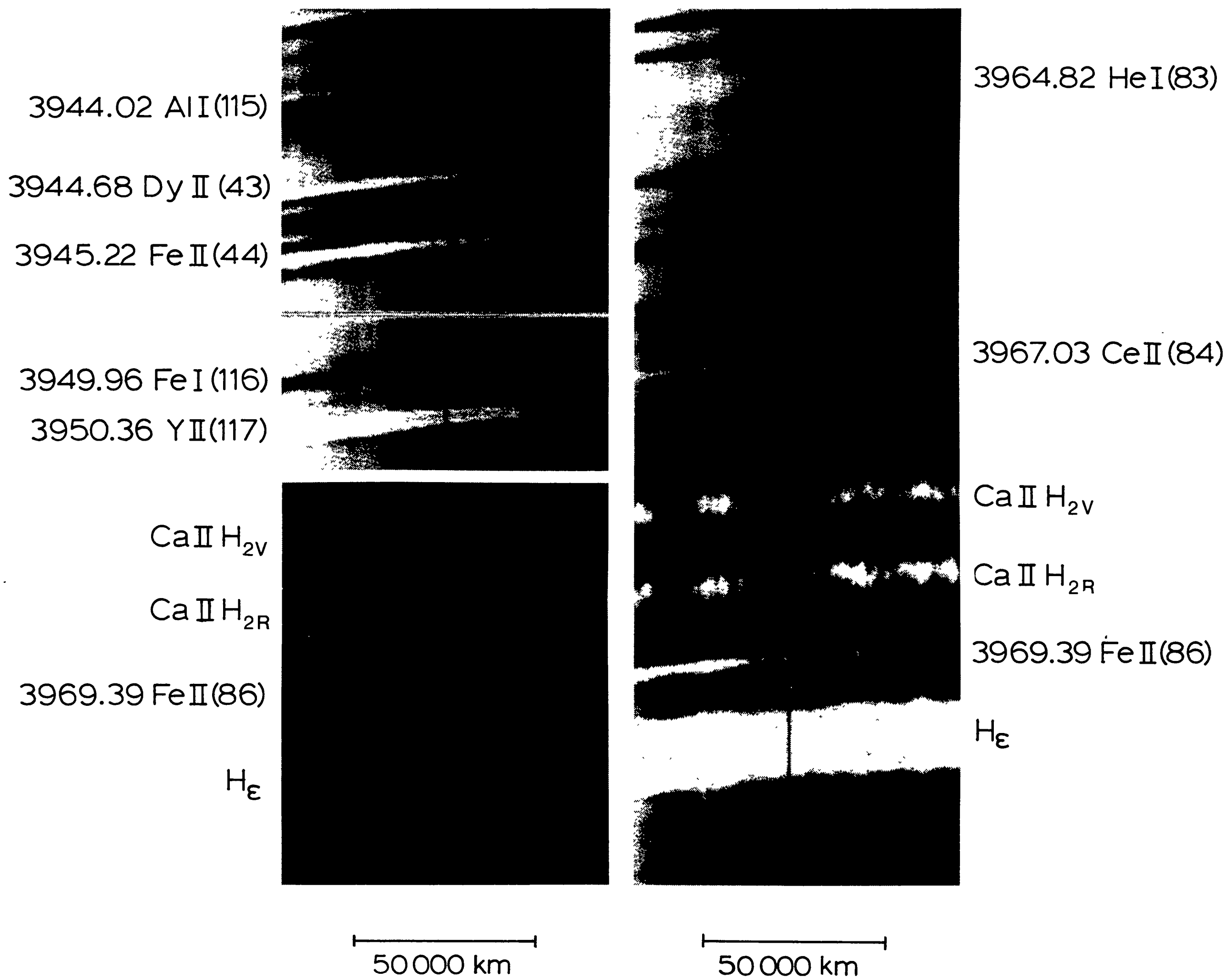

FIGURE 1. — *Examples of limb emission lines*. The part of the spectrum with Ca II H and Balmer H_ε is shown twice : a normal exposure on the lower right side, a weak exposure on the lower left side. The latter shows the weak reversal of H_ε.
The emission lines shown are identified in the margins by their wavelength, spectrum and the number given in tables I and II. They show different amounts of spatial intensity variation (SIV). Examples of the various classes discussed in the text are :

Nr. 84 — Ce II 3 967.0 Å : rare earth line of class (a) without SIV, in emission through the Canfield mechanisms of interlocking and scattering ;
Nr. 43 — Dy II 3 944.7 Å : one of the strongest rare earth lines (class (a)), showing slight SIV ;
Nr. 86 — Fe II 3 969.4 Å : metal ion line of class (b) with large SIV, in emission through the Lites mechanism of pumping by *UV* resonance lines ;
Nr. 44 — Fe II 3 945.2 Å : other member of the same multiplet, showing identical behaviour ;
Nr. 115 — Al I 3 944.0 Å : strong self-reversed resonance line, with a very wide, dark core and narrow wings in emission through partially coherent scattering ;
Nr. 116 — Fe I 3 950.0 Å : weaker metal line, with fine structure emission knots but no underlying reversal pattern as nr. 115 ;
Nr. 117 — Y II 3 950.5 Å : one of only three lines present with a weak self-absorbed core ; in very strong emission which is not understood.