EMISSION LINES IN THE WINGS OF Ca II H AND K. I.
INITIAL SOLAR OBSERVATIONS AND IMPLICATIONS

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ABSTRACT

We apply solar observations to the problem of proper identification of the atomic species and
the mechanism of formation of emission lines in the wings of the Ca II H and K lines. Emission
lines of both rare earths and metals appear to be present in the Sun. Their behavior in the solar
spectrum implies that emission lines of metals will be useful in studies of chromospheres of other
stars in which they are observed.

Subject headings: line identifications — Sun: chromosphere — Sun: spectra

I. INTRODUCTION

Emission lines appear in the extended absorption
wings of the Ca II H and K lines in spectra of a variety
of stars, including the Sun. Solar observations afford
the advantages of higher spectral and spatial resolu-
tion. In this paper we present new solar observations
and discuss their bearing on the identification of these
emission lines and the consequent implications con-
cerning the mechanism of their formation and the
nature of stellar atmospheres in which they are
observed.

Jewell (1898) discovered the first of these emission
lines in the K line, at λ3934.8, near the solar limb.
Many observers subsequently have reported additional
lines; the most complete list presently available
(Stencil 1973) includes more than 70. Workers as
recent as Jensen and Orrall (1963) have identified
these lines with rare earths. Hart (1962) suggested
that these identifications might be chance coinci-
dences, due to the high density of possible rare-earth
identifications. Although this suggestion is not sub-
stantiated by better spectral observations (Canfield
1968), the fact remains that the probability of chance
coincidence between any given line and a laboratory-
observed rare-earth line is higher than that for most
other elements. Hence it is not surprising that Engvold
and Halvorsen (1973) found that earlier rare-earth
identifications of three of the stronger lines were
incorrect; they contended that proper identification
lay with ionized metals. These identifications were
confirmed by Stencil (1973), who tentatively identi-
fied nine of 71 lines with neutral or ionized metals,
and the rest with rare earths.

In recent years emission lines have been discovered
in spectra of stars other than the Sun. Fosbury (1971)
identified Jewell’s (1898) line in the spectrum of
Arcturus. Stencil (1975) found five other emission
lines near the core of K in nine late-type stars. Stencel
(1976, hereafter Paper II), has sampled a wider variety
of spectral types on high-dispersion coudé plates
from Hale Observatories (see, e.g., Wilson and Bappu
1957; Wilson 1976). This study indicates the presence
of emission lines, tentatively identified with both rare
earths and metals, in essentially all low-gravity stars
having strong H and K features.

Engvold and Halvorsen (1973) suggested that the
formation of ionized metal lines is different from that
of the rare earths, which seems quite reasonable.
Canfield (1969, 1971a, b) has shown that lines of rare
earths in the solar spectrum can be understood in
terms of radiative interlocking with other weak lines,
all radiatively controlled. On the other hand, Lites
(1974) showed that the solar Fe II λ3969.4 line is
excited by interlocking with a single strong ultraviolet
line and behaves more like a chromospheric line,
in contrast to the rare-earth lines, which in the Sun
are of photospheric origin. In general, one would
not be able to account for the appearance of metal
lines in emission by the same mechanism as that of the
rare earths, since the atomic structures of the metals
do not exhibit the extreme complexity that provides
the many opportunities for radiative interlocking
found in most rare earths.

There is then an important reason to determine
proper identifications for the observed emission lines:
the interpretation of metal lines in emission in the
solar atmosphere, and probably also in late-type
atmospheres, involves the existence of chromospheres,
while the interpretation of rare-earth emission lines
does not. For this reason, we show that one can use
spatially resolved solar observations to aid in the
identification, since such observations allow one to
distinguish between mechanisms of formation by the
extent of variability of emission from point to point
on the solar disk.

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II. OBSERVATIONS

We report observations of two types; both use the echelle spectrograph of the vacuum tower telescope of Sacramento Peak Observatory (Dunn 1969, 1971).

a) Spectra

The spectra were obtained by Beckers et al. (1972) in the vicinity of the Ca II H and K lines with a 300 line mm\(^{-1}\) grating in the 15th order, 144 \(\mu\)m entrance-slit width, dispersion 12.10 mm Å\(^{-1}\) on 70 mm Eastman Kodak 5375 film, as part of their Program D. The image scale along the spectrograph slit is 287 \(\mu\)m \(^{-1}\) on 70 mm East slit width, dispersion 12.10 mm Å\(^{-1}\), with 500 \(\mu\)m entrance and exit slit. Line-continuum pairs were obtained 450 seconds apart, the minimum possible temporal separation consistent with adequate exposure on Eastman Kodak 5375 film and a temporal separation of an integral half-period of the photospheric 300 second oscillation (in retrospect, 600 seconds might have been still better). We then subtracted photographically, using the usual \(\gamma = 1\) positive-negative pairs, the continuum observations from their corresponding lines, in order to cancel to some extent the photospheric contribution to the lines, insofar as the seeing and lack of ideal simultaneity permit. We are aware, of course, that this procedure is only a partial cancellation, since it is a subtraction of densities, not intensities.

Figure 1 (Plate 8) shows a spectrum taken with the center of the slit located at the solar limb. The two strongest emission lines are identified by Stencel (1973) and Engvold and Halvorsen (1973) as \(\lambda 3969.40\), Fe II multiplet 3; and \(\lambda 3967.048\), Ce II multiplet 84, in Moore’s (1945) multiplet table. Both identifications are reasonably secure and agreed upon among these investigators. One can readily see that the Fe II line shows considerable variation in intensity along the slit; the Ce II line does not. We note that previous observations of spicular spectra by Pasachoff, Noyes, and Beckers (1968) did not reveal this distinction, which we attribute to the improved spatial resolution of the present spectra. The fact that rare-earth lines show no spatial variation at 1" resolution has been reported previously by Livingston and White (1974). In our spectra, they do show slight variation. We also note in Figure 1 that the weak emission line \(\lambda 3967.173\), Ce II (indicated by the dashed arrow), shows little spatial variation. Similar spectra in the vicinity of the K line reveal that \(\lambda 3927.109\) (Nd II), \(\lambda 3931.358\) (Ce II multiplet 61), \(\lambda 3631.526\) (Dy II?), \(\lambda 3931.823\) (Ce II), and Jewell’s (1898) line at \(\lambda 3934.80\) also show little spatial variation. On the other hand, spatial variation is evident in \(\lambda 3934.128\) (Zr II), although its weakness and proximity to the K\(_2\) feature complicate the picture (we do note that this line definitely does exhibit more spatial variation than comparable weak lines whose identification as rare earths seem certain). The identification of all but Jewell’s line is in accord with Engvold and Halvorsen (1973) and Stencel (1973).

The evidence at hand suggests the hypothesis that emission lines of ionized metals show distinct intensity variation in observations of a sufficiently high spatial resolution (1"), whereas emission lines of ionized rare earths do not.

Application of this hypothesis and our observations of the line at \(\lambda 3934.8\) imply that it is indeed a rare-earth line, in accord with the identification in terms of Nd II by Jensen and Orrall (1963) and others. However, Engvold and Halvorsen (1973) and Stencel (1973) identified this line with Zr II. This identification is supported by the strengthening of the line during flares (Öhman 1969; Grossi Gallegos, Molnar, and Seibold 1971), as well as the presence of the other members of multiplet 43 in Pierce’s (1968) atlas. It therefore seems likely that both Nd II and Zr II contribute to this line, which is of considerable interest in the spectra of giants and supergiants. Fosbury (1971) finds it in \(\alpha\) Boo (K2 IIIp) and Stencel (Paper II) finds it in emission in \(\alpha\) Per (F51b), \(\xi\) Cyg (G8 II), \(\alpha\) Hyd (K3 II), and several other stars.

The enhanced emission in the line \(\lambda 3969.40\) in flare spectra (Öhman 1969; Grossi Gallegos, Molnar, and Seibold 1971) also supports the identifications of that line in terms of Fe II.

b) Spectroheliograms

We made spectroheliograms on 1975 December 7 with a 79 line mm\(^{-1}\) grating in the 56th order, dispersion 13.5 mm Å\(^{-1}\), with 500 \(\mu\)m entrance and exit slits, corresponding to 1.74 spatially and 0.037 Å spectrally. Observations were obtained near disk center and near the limb, using image scan speeds of 12" and 9" per second, respectively. Spectroheliograms were made in Fe II \(\lambda 3969.40\) and Ce II \(\lambda 3967.048\), as well as at nearby continuum positions \(\lambda 3966.950\) and \(\lambda 3969.540\). The half-widths of these lines are approximately a factor of 2 greater than the spectral size of the exit slit. Line-continuum pairs were obtained 450 seconds apart, the minimum possible temporal separation consistent with adequate exposure on Eastman Kodak 5375 film and a temporal separation of an integral half-period of the photospheric 300 second oscillation (in retrospect, 600 seconds might have been still better). We then subtracted photographically, via the usual \(\gamma = 1\) positive-negative pairs, the continuum observations from their corresponding lines, in order to cancel to some extent the photospheric contribution to the lines, insofar as the seeing and lack of ideal simultaneity permit. We are aware, of course, that this procedure is only a partial cancellation, since it is a subtraction of densities, not intensities.

Figure 2 (Plate 9) compares the subtracted spectroheliograms in the Ce II line and the Fe II line, near the center of the solar disk. We note that the well-known bright chromospheric structure (the “coarse network” easily observed in Ca II H or K) is evident in the Fe II line, but barely perceptible in the Ce II line.

III. CONCLUSIONS

We conclude that both the spectral and spectroheliographic observations support the emission-line identifications of Engvold and Halvorsen (1973) and Stencel (1973) (with the exception of Jewell’s line) in terms of both rare earths and metals, and the theoretical work of Canfield (1971a, b) and Lites (1974) on the rare-earth and Fe II \(\lambda 3969.4\) emission lines. As would be expected, the rare-earth lines show relatively little spatial variation due to their radiative excitation by optically thin lines. This means that their source functions are controlled by the photospheric mean intensities in weak lines, a quantity that is a considerable spatial average. In contrast, the intensity of the Fe II line is controlled by a moderately strong ultraviolet line (Lites 1974) whose source
function at the height of formation of the weak Fe II line is locally controlled, and will therefore show local temperature and density variations.

In addition to source-function differences, optical-depth differences also lead to spatial variation of line profiles. The same effects will be present in the latter case as in those discussed above. The atomic populations, and hence the optical depths, of a species controlled by optically thin radiation fields will tend to vary less than those of a species or line that is locally controlled.

Finally, both our observations and Lites's calculations show that the Fe I λ3969.4 line has a chromospheric contribution. Since solar chromospheric structures tend to have a coarser scale than photospheric structures, one would expect to be able to more easily resolve the larger-scale spatial variations of chromospheric lines. However, our observations are quite sufficient to resolve photospheric structures. The observations thus support the contention that the variations in rare-earth lines are indeed of smaller amplitude, not just smaller scale.

The implication of both the solar observations and the theoretical work is that emission lines of metals show greater temperature and density sensitivity than those of rare earths. In the atmospheres of certain stars, the emission lines of metals would then be expected to be good indicators of temperature and density in the upper photosphere and low chromosphere, whereas those of rare earths bear more strongly on the T(r) relationship in the middle photosphere. Lites has shown that in the solar atmosphere, the line λ3969.4 of Fe II does not appear in emission without a chromospheric temperature rise. This leads us to expect that in our later analyses, certain emission lines of metals will require the existence of stellar chromospheres, whereas lines identified with rare earths will not. Because of this difference in the mechanisms of line formation, the distinction between identifications with rare earths or metals is important. Hence the information secured from solar studies has important bearing on the results from other stars, since it aids both in identification of species responsible for observed lines and in determination of the mechanism of line formation.

Our observations suggest that further work is appropriate in the areas of (1) observational confirmation of the identifications of the emission features in the Sun, based on the hypothesis proposed in the present paper, and (2) modeling of the atmospheres of cool stars in terms of the formation of emission lines from both metallic and rare-earth ions. Observational and theoretical work presently under way along these lines will be reported in later papers of this series.

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Fig. 1.—Spectrogram illustrating the different spatial variation of Ce II $\lambda$3967.048 and Fe II $\lambda$3969.40 (solid arrows). The dashed arrow indicates Ce II $\lambda$3967.173. The length of the spectrum along the slit is 140 arc seconds.

Canfield and Stencel (see page 619)
Fig. 2.—Subtracted spectroheliograms in the lines Ce II 3967.048 and Fe II 3969.04. The dimensions of the spectroheliograms are 60 by 120 arc seconds.

Canfield and Stencil (see page 619)