THE Mg II h AND k LINES. I. ABSOLUTE CENTER AND LIMB MEASUREMENTS OF THE SOLAR PROFILES

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ABSTRACT

We report new measurements of the solar Mg II h and k lines with uncertainties in the absolute intensities at ±12 percent with smaller uncertainties for higher intensities. The spectral resolution, defined by the full width at half-maximum of the instrumental profile, was 0.028 Å, and the angular resolution element was 184" by US. Measurements were made for a quiet region near the disk center and for a quiet region at cos θ = 0.23. The measured profiles are suitable for detailed comparisons with theoretical solar and stellar profiles, as will be discussed in the paper by Ayres and Linsky (Paper II) that will follow in a later issue. Our measured minimum intensities and k₁ relative to the core intensities (k₂ and k₃) and to the average peak intensities (k₂ and k₃) are fainter than the corresponding intensities that were reported by Lemaire and Skumanich.

Subject headings: line profiles — Sun: spectra — ultraviolet: spectra

I. INTRODUCTION

The Mg II h and k lines are of great interest in solar and stellar physics. In the Sun, they, like the analogous Ca II H and K lines, can be used to investigate the structure of the upper photosphere, temperature minimum, and lower chromosphere. Measurements of the Mg II doublet emission in a number of F-M stars (Kondo et al. 1972; Doherty 1972; Moos et al. 1974; McClintock et al. 1975a, b; Evans, Jordan, and Wilson 1975; Bernat and Lambert 1975; and Kondo, Morgan, and Modisette 1975) and even possibly B-type stars (Kondo, Modisette, and Wolf 1975) imply the existence of chromospheric temperature inversions over a wide range of the H-R diagram. Also evidence for chromospheres appears at earlier spectral types in Mg II compared with the less opaque Ca II H and K lines. For example, the Ca II emission reversals are very weak in Procyon (F5 IV–V), whereas the Mg II emission cores are quite prominent (Kondo et al. 1972). This appearance of Mg II emission at earlier spectral types is due in part to the greater abundance and larger second ionization potential of Mg compared with Ca.

Kondo et al. (1972) have found a dependence of the Mg II k emission line width on the stellar absolute visual magnitude; this is analogous to the Wilson-Bappu effect for Ca II K (Wilson and Bappu 1957). Ayres, Linsky, and Shine (1975) have found evidence for a width-luminosity relationship for the wavelength separation of Mg II k₁₂ and k₃₁.

In this paper we present new observations of the intensity profiles of Mg II h and k for quiet regions at the center of the solar disk and near the limb (cos θ = μ = 0.23). The first observations and identifications of the Mg II doublet in the Sun were reported by Durand, Oberly, and Tousey (1949). More recently, consider-ably improved measurements with high angular and spectral resolution have been reported by Bates et al. (1969) and by Lemaire and Skumanich (1973). However, these measurements, although superior to earlier work, contain uncertainties that Milkey and Mihalas (1974) believed “are of sufficient magnitude to preclude the usefulness of an attempt to construct detailed chromospheric models based on the observed Mg II line intensity profiles.”

We believe that the measurements reported here are sufficiently accurate for detailed modeling (Ayres and Linsky 1975, henceforth Paper II) and will also be useful for comparisons with stellar Mg II h and k observations.

In this paper we refer to the center of the lines as h, and k₁, to the emission peaks as h₂ and k₂, and to the sides of the line outside the peaks as h₃ and k₃. The subscripts r and v refer to the long-wavelength and short-wavelength sides, respectively.

II. INSTRUMENTATION

a) Telescope-Spectrometer

The basic telescope-spectrometer combination used for the measurements was described by Parkinson and Reeves (1969). Several modifications were made to the instrument for the present set of observations. The spectrometer has an Ebert mounting with a 75 cm focal length and a plane diffraction grating, 3600 grooves mm⁻¹, that was holographically produced by Jobin-Yvon. The telescope system consists of an off-axis paraboloidal mirror of 93.0 cm focal length that serves as the main collector, and two additional plane folding mirrors. All mirrors were coated with aluminum and overcoated with the MgF₂ thickness to maximize the reflectance at 2300 Å. The entrance slit
was 0.830 mm long and 6.78 μ wide, resulting in an angular resolution element, independent of telescope aberrations, of 184″ by approximately 1:50. The spectrometer exit slit was 2.56 mm long and 6.84 μ wide, resulting in a passband of 0.0213 Å at 2800 Å. The slit lengths were determined with a measuring microscope, and the slit widths were determined from laser diffraction from several areas along the slits. Variations in width along the length of the straight slits were found to be less than 5 percent.

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b) Instrumental Line Profile

The instrumental line profile for the wavelength of the 198Hg line at 2537 Å is given in Figure 1. The profile was determined by illuminating the telescope-spectrometer with a collimated beam from a microwave driven 198Hg lamp. In Figure 1a we see that the instrumental profile is nearly a pure Gaussian with a full width at half-maximum (FWHM) of 0.028 Å. Figure 1b compares the profile for the holographically produced grating used for this flight (crosses and dashed curve) with the profile of the same instrument equipped with a conventionally ruled grating (solid curve). The ruling ghosts are not present in the profile from the holographically produced grating, and its scattered light level appears to be slightly lower than the scattered light level from the particular ruled grating that we used for comparison.

Measurements of the profile shape preceding and following laboratory vibration tests, which subjected the instrument to vibration levels 1.5 times flight levels, have convinced us that the resolution would not degrade (because of vibration) during the rocket flight. The profiles were also measured as a function of temperature and were found to be constant for a range of greater than ± 3 K about the laboratory temperature at which the instrument was focused. The instrument temperature was monitored during the flight and found to be within this range. Our measured widths of many weak absorption lines are clear evidence that the instrumental resolution was 0.028 Å at 2537 Å throughout the rocket flight. For our Ebert spectrometer, the instrumental profile at the wavelength of Mg II h and k will not vary significantly from the profile shown in Figure 1.

c) Detection System

The photomultiplier used on this flight was an EMR type 541F-05M-14-03900 which was ordered from the manufacturer with the stipulation that it be aged at an anode current of 10⁻⁶ A for 200 hours, following which the electron gain must be greater than 10⁶ at 3000 volts and the time response should be such that for a step function of light the output of the photomultiplier must not vary by more than ± 5 percent from the value of the output 1 ms after the beginning of the step functions.

Upon receipt of the tube, it was set up on an optical bench and illuminated with a temperature-stabilized mercury pen ray lamp through a 2537 Å interference filter. Measurements were made in the direct current mode with the tube connected first as a photodiode and also as a photomultiplier. The current gain at 3000 volts was 5.3 x 10⁶. Time response was verified as being within the required specifications by displaying the anode current on a strip chart recorder and blocking and unblocking the light with an opaque screen.

The linearity of response was checked by inserting a series of neutral density filters calibrated at 2537 Å into the light beam, while recording the dc anode current.

At this point, the tube was tentatively deemed suitable for flight use, and was incorporated into the spectrometer and flight electronics system for final calibration.

The linearity of the flight detection system was determined in two ways. The double pulse resolution time (320 ns) of the electronics (not the photomultiplier) was measured, and a curve of the fraction of pulses counted versus input count rate was calculated. This result was compared with direct measurements of a similar curve when the full flight detection system, the temperature stabilized Hg lamp, and neutral density filters were used. The two curves are in agreement to within less than 5 percent. The fraction of input pulses counted was greater than 90 percent for input count rates up to 350 kHz and above 86 percent for count rates up to 600 kHz. Almost all of the flight data points for Mg II h and k had input count rates below 300 kHz and below 100 kHz for the emission centers.

III. OBSERVATIONAL CONDITIONS

a) The Flight

The instrument was launched on 1974 May 15 at 22:11:21 UT by an Aerobee 200 rocket from the White Sands Missile Range. The instrument reached a peak altitude of 281.2 km, and the data were accumulated for 396.5 s. The instrument made two full scans of the quiet Sun center spectrum between 2250 and 3200 Å and made nearly two full spectral scans for a region just inside the limb. The output of the detection system, the grating angle (as indicated by a shaft angle encoder), and other information such as the instrument temperature and pressure were fed to the rocket telemetry system and recorded at ground stations. An analog format of the data could be viewed in real time.

b) Pointing

The excellent pointing stability of the SPARCS 201 was better than ± 0.5 in pitch and yaw and about ± 0.1 in roll angle for 2 s time periods. Since the telescope axis was coaligned (within a small angular offset) with the axis of the pointing control, the absolute coordinates for center pointing could be determined from the laboratory measurements of the offset and the programmed pointing coordinates. The programmed projection of the spectrometer entrance slit on the Sun (see Fig. 2 [PL 11]) had coordinates for the center of the slit of 30 ± 60° north and 9 ± 60° east with respect to the disk center and the projection of heliocentric
Fig. 1.—(a) Instrumental line profile at $\lambda 2537$ Å. (b) Comparison of the instrumental line profile at $\lambda 2537$ Å using the holographically ruled grating of this flight (crosses and dashed line) with the line profile of the same instrument equipped with a particular grating that was conventionally ruled (solid line).
were completed, the SPARCS pointing control was from the north-south line so that the north tip of the north on the disk. The straight slit was rotated 4°5 from the north-south line so that the north tip of the slit was 7° east of the slit center position.

After two full spectral scans of the center region were completed, the SPARCS pointing control was commanded to point the slit center to 849° east, 7°8 north (shown by the dot-dash line in Fig. 2). The actual coordinates for limb pointing differed substantially from the programmed coordinates because of the uncertainty in the coalignment of the pointing control and the telescope, and because of the uncertainty in the value of the bias voltage that was required for the offset pointing maneuver. To determine our coordinates for near limb pointing, we measured the limb-to-center ratio for wavelengths near 3190 Å and determined \( \mu \) by comparing our measurements with the ground-based measurements of Peyturaux (1955). The ratio for six structureless regions of the spectrum between 3186.8 Å and 3175.7 Å gave a value of 0.305 ± 0.026 and a value of 0.298 ± 0.009 was found for the average limb-to-center ratios for 5 Å intervals between 3187.5 and 3167.5 Å. This results in a most probable value for \( \mu \) of 0.230 ± 0.008 where the error does not include the uncertainty of the measurements of Peyturaux.

The value of \( \mu \) is determined from the ratio of the average intensities along the slit projection so that the values of \( \mu \) along the slit projection can vary from about 0.184 to 0.249 for the case where the slit center is on the east-west line. The value of \( \mu \) could vary from 0.177 to 0.271 in the worst case where the slit was at the extreme north limit of the pointing uncertainty. Since the intensity ratio is expected to vary linearly over these ranges of \( \mu \) for wavelengths in the range 2250 Å to 3200 Å (Bonnet 1968), the observed spectrum should be very representative of \( \mu = 0.23 \) at all flight wavelengths.

c) Spectroheliograms

The pointing coordinates were selected by choosing quiet regions on the solar disk from neutral line drawings and verbal descriptions of solar activity from the National Oceanographic and Atmospheric Administration's solar forecast service. Following the launch, Sacramento Peak Observatory furnished us with the spectroheliograms for the launch date, which are shown in Figure 2. The projections of the spectrometer entrance slit for observations of the disk center were located within the area indicated by the dash line. The programmed slit projection for near limb pointing is shown as a dot-dash line; the indicated area in Figure 2 for observations near the east limb encloses the possible projections of the slit for \( \mu = 0.23 \) where the pointing uncertainties have been included. It is clear from Figure 2 that both areas of observation are very free of activity for heights in the solar atmosphere that correspond to the four spectroheliograms. Therefore, the observed Mg II h and k profiles should be characteristic of the average quiet Sun in the wings and in the emission centers.

IV. Radiometric Calibration

a) Calibration Based on a Standard Photodiode

Although we measured the efficiency of most of the elements of the rocket instrument individually, the total spectrometer, telescope, and detection system were finally calibrated as a unit. This radiometric calibration was divided into two wavelength ranges. For the shorter wavelengths (2250–2528 Å) the calibration was based on Spicer diode Serial No. 127, a special photodiode that has a magnesium fluoride window and a cesium telluride cathode. This detector was calibrated at the U.S. National Bureau of Standards (NBS) by direct comparison of photocurrents with an NBS calibrated standard photodiode. Our method of calibration for the short wavelength range was almost identical to the methods we used for earlier flights and has been described fully (Kohl and Parkinson 1974).

b) Calibration Based on a Standard Lamp

For wavelengths between 2516 Å and 3200 Å, the radiometric calibration is based on the calibration of a Philips tungsten ribbon standard of spectral radiance. The lamp current was measured with a Weston model 1971 dc ammeter that was calibrated before and immediately after the calibration of the rocket instrument. The brightness temperature of the lamp was determined originally by Philips Research Laboratories and then recalibrated at Eppley Laboratories and periodically at Harvard by a direct comparison with another Philips lamp that is used as a laboratory standard (Huber and Parkinson 1972). The values for the emissivity of tungsten that are also required were taken from De Vos (1954).

For this calibration, the telescope system was removed and a calibrated portion of the tungsten ribbon lamp was focused directly onto the spectrometer entrance slit. The solid angle was defined by a circular aperture that was placed against the focusing lens on the side nearest the standard lamp. The size of the aperture stop was set to just underfill the spectrometer grating. Smaller apertures were also used to check for spatial nonuniformities. The system calibration was found to be independent of the part of the optics used. Another consistency test was to use more than one lamp current for the calibration at a given wavelength. The calibration was found to be independent of the lamp current within 1–2 percent.

c) System Calibration Function

The solar data are reduced by use of our basic calibration equation,

\[
\int_{\lambda_1}^{\lambda_2} I_\odot(\lambda) d\lambda = S(\lambda) \int_{\lambda_1}^{\lambda_2} \frac{K(\lambda', t) d\lambda'}{\Delta \lambda t} \sqrt{R_s A_s \Omega_s},
\]

where \( \int I(\lambda) d\lambda \) is the integrated intensity in photons s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\) for any wavelength interval \( \lambda_2 - \lambda_1 \), \( R_s \) is the reflectance of the telescope objective, \( A_s \) is the area of the entrance slit, \( \Omega_s \) is the solid angle subtended by
§ VI). The wavelength scale is based on the laboratory wavelengths (in air) of lines identified in the wings of Mg $\Pi \ h$ and $k$ and at shorter and longer wavelengths. The wavelength scale was not corrected for the solar wavelength shifts.

The intensity structure in Figure 4 is due to the solar spectrum, not to statistical fluctuations, which have about a 5 percent standard deviation for observations of the line wings. The observations were subject to an occasional electronic noise burst that appeared as an increase in intensity, and, less often, there were short interruptions (1–5 ms) of the signal. These sections of the data could be identified because they were not consistent for the two scans of the spectrum at the center or at the near limb pointing coordinates.

We could almost always determine which scan was in error by examining the data after they had been filtered by Fourier transform techniques. We found that the power spectrum of the noise bursts and signal interruptions contained large high-frequency components that, when filtered out of the data, tended to move the smoothed points outside the statistical error bars of the noisy data and toward the correct values. A few such areas were removed from Figure 4.

b) Background Noise

A definitive measurement of the intensity of Mg $\Pi \ h$ and $k$ that includes the absolute values of the $h$ and $k$, minima must take account of the instrumental background level that should be accurately known. One source of background noise that is completely negligible in our case is the continuous electronic and photomultiplier noise (about 0.006 counts are accumulated during the time to scan 0.01 Å). The noise bursts discussed in § Vb are not a problem, since they do not repeat from scan to scan.

Instrumental scattered light can be a serious problem for measurements of this kind, but it was not a problem for this work. The amount of scattered light due to wavelengths well away from the wavelength of interest was determined from measurements made during the flight for center pointing and again for limb pointing. The measurements were made by quickly scanning the full wavelength range, while an absorption filter covered the entrance slit. To reject lower wavelengths, a quartz window was always present between the exit slit and the detector. The scattered light for this flight was found to be independent of the wavelength setting of the spectrometer and changed by only 1 percent between center and limb. We have attributed the measured scattered light level to light leaks near the detector.

Another source is scattering inside the spectrometer of light with wavelengths near the wavelength being scanned. We did not expect this to be a problem for this flight because the spectrometer, with the holographically produced grating, has an exceptionally low scattered-light level and no detectable ruling ghosts. In Figure 1b, we see that the efficiency of the instrumental profile at 1.0 Å from line center is about $5 \times 10^{-5}$ of the peak efficiency. As an upper limit, we

V. RESULTS

a) General

An overall view of our measurements of Mg $\Pi \ h$ and $k$, for observations at Sun center and near the solar limb, is shown in Figure 4. The ordinates represent the spectral intensities on an absolute scale that we believe is accurate to better than ±12 percent (see
have assumed that the efficiency remains at this level for ± 30 Å where the efficiency falls to zero. With this assumption, we estimate an uncertainty in the $k_1$ and $h_1$ minimum intensities of -8 to 0 percent due to scattered light. Further evidence for a low scattered-light level can be found from the observed minimum intensities of lines near Mg II $h$ and $k$. For example, we have identified all three members of the Mn i (ultraviolet multiplet No. 1) lines at 2801.084 Å, 2798.270 Å, and 2794.817 Å in the solar spectrum. Two of the lines are indicated in Figure 5. The line at 2794.817 Å, which is located very near the $k_1$ minimum, has an intensity at line center that is well below the measured minima of $h_1$ and $k_1$.

c) Mg II $h$ and $k$ Centers

Our observations of the emission centers of Mg II $h$ and $k$ are shown in Figure 5. The data points are the raw data intensities for 0.01 Å intervals. For convenience, every third data point has been plotted. Triangles and crosses represent the individual scans and the solid lines represent the average intensities of two scans that have been smoothed with a Gaussian filter with a full width of 0.02 Å. A few points that have been identified as noise (see § Va) were removed from the data before the final filtering operation. Noise was not removed from the raw data points of Figure 5. The values of the smoothed average intensities are given in Table 1.

Since we have used a scanning spectrometer, the statistical fluctuations of the data depend on the wavelength interval for each data point. The error bars for the raw data (shown in Fig. 5) represent one standard deviation for wavelength intervals of 0.01 Å. The Fourier filtering process used to produce the solid line curve in Figure 5 reduces the statistical uncertainty, as would an increase in the data point wavelength interval.

d) Features of the Profiles

In order to facilitate comparisons of our measurements with other experimental data and with theoretical models (see Paper II), we have used the data in Table 1 to determine the wavelengths and spectral
Fig. 5.—The emission centers of solar Mg II h and k. The raw data (triangles and crosses) are given for two scans at $\mu = 1$ (upper) and two scans at $\mu = 0.23$ (lower). The average data (solid line) for each set of scans after Fourier smoothing are also shown.
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**Table 1:** Absolute Spectral Intensities of Mg ii h and k

- **(A)** units are ergs cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) cm\(^{-1}\)
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\* \( \lambda(\lambda) \) units are ergs cm\(^{-2} \) s\(^{-1} \) sr\(^{-1} \) cm\(^{-1} \)

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intensities of the inflection points in the Mg II h and k profiles. These results are given in Table 2. Because of
the presence of the Mn i line (2794.817 Å) near k1v, the information for k1v is ambiguous and was omitted
therefore from Table 2. For μ = 1, our measured wavelength separations relative to line center Δλ of the
h1 and k1 minima are slightly larger than the values determined by Milkey and Mihalas (1974) from the
measurements of Lemaire (1971). Our corresponding Δλ's for the profiles at μ = 0.23 are larger than our
values of Δλ for the center profiles.

In Table 3, we compare our relative intensities and
wavelength separations to the "k reference profile" of
Lemaire and Skumanich (1973). The agreement is
good for the separation of the peaks and for the
FWHM. Their value for the ratio of the mean peak
intensity to the core intensity is outside our estimated
error limit (see § VI). The major differences in the two
sets of measurements are the respective values for the
ratio between the core intensity and the minimum
intensity. Their value for k1r lies well outside our error
limits. Their corresponding ratio for h is 1.86 com-
pared with our ratio of 3.59. The ratios between the
average peak intensity and the minimum intensity for
the k line at μ = 1 are 6.36 for this work and 5.14 for
Lemaire and Skumanich (1973). In Figure 6, we
compare h to k for the center and for the near limb
spectra. We have not considered the k1r minimum in
detail because of the ambiguity introduced by the
Mn i line. We find (1) h is more intense than k for any
Δλ beyond 0.50 Å for μ = 1, and beyond 0.55 Å for
μ = 0.23; (2) h lies below k throughout the core for
both μ = 1 and 0.23; (3) the ratio of the k1 and h1
intensities is 1.14 and 1.21 for μ = 1 and 0.23, respec-
tively; (4) the absolute spectral intensities of h1 and
k1r are almost equal, although h1r appears to be
slightly fainter than k1r at the disk center and slightly
stronger at μ = 0.23.

We have attempted to determine the absolute
intensity profiles that are representative of the Mg II h
and k wings. This was done by selecting sections of the
observed spectra that are apparently free of absorption
lines. The results for μ = 1 and 0.23 are given in
Figure 7.

In Figure 8 we give the limb-to-center intensity
ratio as a function of wavelength. The intensity
values used for the wings are those plotted in Figure
7, and the values used for the center emission
features are the intensities of the inflection points
from Table 2.

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<td>0.680</td>
<td>0.530</td>
<td>0.56</td>
</tr>
<tr>
<td>Ratio between mean peak intensity and core intensity</td>
<td>2.18</td>
<td>1.86</td>
<td>2.07</td>
<td>1.82</td>
<td>2.2</td>
</tr>
<tr>
<td>Integral intensity × 10^-5 (ergs cm^-2 s^-1 sr^-1)</td>
<td>1.48</td>
<td>1.72</td>
<td>2.04</td>
<td>2.24</td>
<td>...</td>
</tr>
<tr>
<td>Ratio between core intensity and average minimum intensity</td>
<td>3.45</td>
<td>3.59</td>
<td>4.04</td>
<td>3.49‡</td>
<td>2.38§</td>
</tr>
<tr>
<td>Ratio between average peak intensity and average minimum intensity</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>6.36</td>
<td>5.14§</td>
</tr>
</tbody>
</table>

* This work.
† Quiet Sun reference profile (Lemaire and Skumanich 1973).
‡ Using k1r only.
§ Measured from Fig. 3 (Lemaire and Skumanich 1973).

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VI. EXPERIMENTAL UNCERTAINTY

The sources of uncertainty in the absolute intensity measurements are due to the radiometric calibration and data reduction, the background noise including scattered light, and the statistical uncertainty due to the count rate. Treating the errors in the individual quantities as independent, we determined a most probable error of 11 percent in the radiometric calibration and data reduction. The background noise (see § VIb) is negligible over most of the profiles but is large enough to impose an uncertainty of —8 to 0.0 percent in the absolute intensities of the $k_1$ and $h_1$ minima. The statistical uncertainty depends on the integration time of the scanning spectrometer and therefore on the spectral width of the feature of interest. For example, the standard deviations for a 0.03 Å bandpass at the peak of the emission features or for a 0.1 Å bandpass at $k_1$, are less than 6 percent.

Our measurements of the absolute spectral intensities of Mg II $h$ and $k$ should be accurate to within ± 12 percent for intensities that are much larger than the minima and to within —20 to +12 percent at the $k_1$ and $h_1$ minima.

The relative intensities which are independent of the calibration errors should be accurate to between —13 and +6 percent for the minima and to within ± 6 percent for higher intensities.

VII. SUMMARY

We have presented our high spectral resolution measurements of the absolute spectral intensity of the solar Mg II $h$ and $k$ lines at the center of the disk and at $\mu = 0.23$. The measured profiles are suitable for detailed comparisons with theoretical profiles (Paper II). Our profiles for the center of the disk are similar to the observations of Lemaire (1971) but have fainter minimum intensities relative to the core intensities.

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Fig. 7.—Representations of the Mg II h and k wings that were determined from regions of the spectrum that are apparently free of absorption lines.
REFERENCES


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Fig. 2.—Spectroheliograms, courtesy of Sacramento Peak Observatory, for the launch data in (a) Hα, (b) Hα + 0.5 Å, (c) Ca K, and (d) Ca K + 0.38 Å. The area of observation is enclosed by the dashed line for center pointing and by the solid line for near limb pointing. The programmed limb pointing is also shown (dot-dash line).

Kohl and Parkinson (see page 600)