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RECENT EXTREME ULTRAVIOLET SOLAR SPECTRA

AND SPECTROHELIOGRAMS†

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Talk presented: COSPAR Meeting, Vienna, Austria -- May 10-19, 1966

To be published in Proceedings of the Meeting

† Supported, in part, by the National Aeronautics and Space Agency.

‡ Sponsored jointly by the Office of Naval Research and the National Science Foundation

(7140-PRR-9/66:RT:mgw; 1570-1077:HWO:mmc, 15 Feb 1966)

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ABSTRACT

Extreme ultraviolet spectroheliograms obtained on October 20, 1965, February 1, 1966, and with 10" spatial resolution on April 28, 1966, show that the chromospheric coarse mottling and network are characteristic of He II 304 Å; high chromospheric lines such as Mg IX 368 Å are emitted mostly from the limb and plages; coronal lines like those from Fe XV and XVI come only from plages and the corona above them. Spectra obtained on February 1, 1966 show that Fe XV 284 Å and Fe XVI 335, 361 Å are of low intensity in the quiet sun, by comparison to September 20, 1963 when the sun was active. In the new spectrum all three lines of Fe XIV $3p\,^2P^o - 3d\,^2D$ are resolved, but the identification of Fe XIV $3s\,^2P^o - 3p\,^2P$ remains questionable. The range 70 - 105 Å was photographed using a filter of indium instead of aluminum. Many new lines are present, including lines of Fe IX, X, and XI.

INTRODUCTION

During the year since the last meeting of COSPAR we have flown three Aerobee rockets each containing a spectroheliograph that was larger than the instruments flown earlier (Tousey, Austin, Purcell, and Widing, 1965). The grating was of 1 M instead of 40 cm radius, thus producing 4.6 mm diameter images whose resolution was not limited by emulsion grain. In the laboratory this instrument resolved 10", but in two of the flights this resolution was not

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attained because of noise in the solar pointing control. Spectroheliograms were obtained on October 20, 1965 and February 1, 1966 when the sun was very quiet, and on April 28, 1966 when it was active. On February 1, 1966, two grazing incidence spectrographs were flown along with the spectroheliograph. They were of the type flown on September 20, 1963 (Tousey, Austin, Purcell, and Widing, 1965), but were adjusted to different wavelength ranges. Each employed a 2400-line/mm 40-cm radius grating at 5° from grazing incidence. The long wavelength spectrograph covered the range 160–410 Å and employed a thin aluminum filter to eliminate long wavelength stray light. The short wavelength spectrograph was adjusted to cover the range 150 Å nearly to the central image at 0 Å. One-half of the slit of the latter instrument was covered with a thin aluminum filter and the other half with a filter of indium. The transmittance of indium, as reported by Hunter and Tousey (1964), extends in the longward direction at least to 105 Å, whereas aluminum cuts off at about 70 Å.

CONCLUSIONS

(1) The extreme ultraviolet spectra, photographed with the radiation from the entire sun, show that coronal lines such as Fe XV 284.15 Å and Fe XVI 335.39, 360.75 Å were much weaker on February 1, 1966 when the sun was quiet and had few centers of activity, than on September 20, 1963 when it was very active. Chromospheric lines showed the same difference, but to a lesser degree. This was of assistance in distinguishing and identifying lines of Fe XIV.

(2) The spectroheliograms show conclusively that the emission from Fe XV, and XVI comes from the centers of activity and the corona, but not from the quiet disc, to within the sensitivity attainable with this spectroheliograph.

(3) Lines from ions produced at lower temperatures than Fe XIV, XV, and XVI, for example Mg IX 368.07 Å, and Ne VII 465.2 Å are radiated from centers of activity which appear larger and more diffuse; they are emitted also from the limb, especially in the neighborhood of the equator, and weakly from the disc.

(4) The low chromospheric lines He II 303.78 Å, and He I 584.33 Å, come from the entire disc and show the chromospheric network and coarse mottles. They are also radiated from centers of activity. The pattern of the quiet sun, recorded at a spatial resolution of 10" - 20", appears very similar in He II 303.78 Å and CaK. He II shows a narrow limb-brightened ring, except over the poles; traces of this ring are present in He I 584.33 Å.

The general conclusion is that the pattern of emission over the sun depends very greatly on the particular extreme ultraviolet line observed; a series of spectroheliograms made in lines requiring greater and greater temperature for their production, permits mapping the chromosphere and corona and the centers of activity in three dimensions.

THE SPECTRA

In Fig. 1 the x-ray spectra obtained on September 20, 1963, and February 1, 1966 are compared, to show the dependence of certain lines on the degree of solar activity. The upper half of the new spectrum, taken through the aluminum filter, can be compared directly with the earlier spectrum. All lines are much weaker with a quiet than with an active sun; part, but not all of this difference may be instrumental.

The lower half of the new spectrum was photographed through the indium filter which transmitted much more than the aluminum filter at long wavelengths, but about equally at C VI 33.7 Å. The resolution in the new spectrum is not as great as in the earlier exposure because of a small departure from best focus; however, all the lines present on September 20, 1963 can be distinguished, though not all are resolved. In addition, many new lines are visible at long wavelengths.

With the quiet sun, there is a change in the relative intensities of many of the lines. Most conspicuous is the weakness of Fe XVI 63.72 Å compared to the nearby lines of Mg X and IX; on September 20, 1963 its intensity was equal to that of Mg IX 62.75 Å, whereas on February 1, 1966 it was much less.

In Fig. 2, the long wavelength end of the spectrum photographed with the indium filter is reproduced. It is compared with the spectrum obtained on March 30, 1964 by Hall, Schweitzer, Heroux, and Hinteregger (1965) and with the spectrum produced by the high temperature plasma of Zeta published by Gabriel and Fawcett (1965). The multiplets of Fe IX, X, and XI near 105, 95, and 88 Å, respectively, are present in both solar spectra; other emissions from Zeta do not match the solar spectrum at all closely, but this would not be expected since the strongest solar lines from 80 Å to shorter wavelengths are produced by Mg and Si, elements not present in the Zeta discharge.

We have compared the photographic solar spectrum with the new photoelectric spectrum described by Manson in the previous paper. The agreement is very good indeed, and the resolution of the two spectra is about the same. The relative intensities of the lines are not greatly different; this is reasonable since the sun was quiet on both days. Identification of the new lines is in progress but not complete.

The identification in the sun of the three lines of the Fe XIV multiplet $3s^2\ 3p\ ^2P^\circ - 3s^2\ 3d\ ^2D$ seems now to be established. Laboratory wavelengths have been determined by Peacock, Cowan, and Sawyer using an Fe-loaded theta-pinch, and by Gabriel and Fawcett (1965) for two of the lines, as emitted by Zeta. The wavelengths for the transitions Δj $3/2 \rightarrow 1/2$, $3/2 \rightarrow 3/2$, and $5/2 \rightarrow 3/2$ are respectively, 211.32, 220.09, and 219.13 (± 0.03 Å) as given by the former authors. The relative intensity of 211.32 to 220.09 Å is given by the ωf ratio, 3.8; but 210.13 Å may be still weaker because of the difficulty in populating the $j = 5/2$ upper level by collisions from the ground term. This problem has been discussed by Stockhausen (1965), and by Jordan (1965).

In the spectrum of September 20, 1963 lines were reported by Tousey, Austin, Purcell, and Widing (1965) at 211.32, 220.16, and 219.04 Å. In the April 28, 1966 spectrum obtained with the long wavelength instrument which has improved resolution, 211.32 Å is present with no suggestion of blending. Faint lines are present at 220.05 Å and 220.35 Å (± 0.03 Å); they are well separated and are identified as Fe XIV 220.09 Å and O V 220.35 Å, respectively; in the 1963 spectrum they were blended and reported as a single line. There is also a pair of lines at 219.09 Å and 218.09 Å (± 0.03 Å). The former appears to be Fe XIV 219.13 Å, and the latter is unidentified. In 1963 they were blended and reported as a single line. In support of this identification, all three lines were weak relative to other lines on February 1, 1966 when compared with September 20, 1963, as was true of the lines of Fe XV and XVI.

Identification of the four lines in the multiplet $3s^2\ 3p\ ^2P^\circ - 3s\ 3p^2\ ^2P$ is not yet satisfactory because of the lack of laboratory wavelengths, and because of masking and possible blends with S X, Fe XV, and Fe XVI. Fe XIV $3s^2\ 3p\ ^2P^\circ - 3s\ 3p^2\ ^2S$, however, seems to be satisfactorily identified as the solar line at 274.23 Å, which is not confused by blends, and whose intensity was observed to be lower on February 1, 1966 than on September 20, 1963, much like Fe XV 284 Å. No laboratory wavelength is available.

SPECTROHELIOGRAMS

The extreme ultraviolet spectroheliograms shown in Figs. 3 - 7 are spectra formed of images of the entire sun, produced by a normal-incidence spectrograph having a dispersion of 8.3 Å/mm or 1.2 Å/arc min. Thus each solar image covers a wavelength range in Angstroms that is 20 percent greater than its diameter in arc minutes.

A portion of the February 1, 1966 spectroheliogram is shown in Fig. 3. This illustrates best the differing characters of spectroheliograms made with emission lines which originate from different levels in the sun's atmosphere.

Low chromospheric He II 304 Å is emitted from the entire quiet sun, and in this image the resolution permits distinguishing details in the range 20" - 40". Emission also takes place from the centers of activity; two were present on the east and west limbs respectively, and a third lay somewhat inside the east limb. For the quiet sun there is no apparent increase in intensity toward the limb when recorded with a resolution of the order of 40". The lines emitted from the high chromosphere or low corona, such as Mg IX 368 Å, produce little or no emission from the quiet disc as a whole, but appear as a ring with strongest emission in the neighborhood of the equator; the centers of activity are intense. The purely coronal emission lines Fe XV 284 Å, and Fe XVI 335, 361 Å are emitted only from centers of activity and from the region of the corona above them. They are smaller and relatively brighter than for Mg IX. From these lines no emission is detected around the limb except in the neighborhood of centers of activity, and no emission is detected from the disc as a whole, within the sensitivity of the instrument.

It should be noted that in preparing Fig. 3, an He II 304 Å image from a short exposure was combined with the other images from a long exposure; this was necessary because the helium image was so intense compared to the others that they could not all be printed from a single exposure.

The long wavelength range of the February 1, 1966 spectroheliogram is reproduced in Fig. 4. Here, the second order images of the short wavelength lines such as He II 304 Å are present together with the first order of lines within the range 450 - 650 Å. The vertical, picket-like structure was caused by the screen on which the aluminum filter was mounted and is spurious. The horizontal bars of the screen did not cast shadows.

A rough analysis of these images is indicated in the Figure. Emission from the plages is strong in Si XII 499, 522 Å, and can be distinguished in Mg X 610, 625 Å. The plages produced by the second order of Fe XV 284 Å are also present. All these lines are emitted by the centers of activity only, and not from the limb or disc as a whole. He I 584 Å and the second order of He II 304 Å are strong from the plages and show also much detailed structure over the entire disc. The second and third members of the He I series can be distinguished, and the He I continuum accounts for the diffuse blackening from roughly 515 Å to 475 Å. In the He I series there is no suggestion of enhancement at the limb. The high chromospheric line Ne VII 465 Å is emitted strongly from the limb, to some extent from the centers of activity and from the disc as a whole with low intensity. In this region are present the strongest lines of O III, O IV, and O V, at 508 Å, 554 Å, and 630 Å, respectively. These are low chromospheric, but O IV and O V and perhaps O III show enhanced emission at the limb.

In Fig. 5, the He II 304 Å spectroheliogram obtained on October 20, 1965 is compared with the corresponding CaK spectroheliogram. Jitter of the pointing control in azimuth doubled the 304 Å image details in the direction perpendicular to the dispersion; since the elevation jitter was negligible, there was no doubling along the direction of dispersion and the resolution was of the order of 20". The detail correlates reasonably well with the detail in CaK. Looked at from the point of view of the relative intensity of emission over wide areas of the quiet sun, however, the 304 Å image appears to be quite different from the CaK; indeed, there seems to be an anticorrelation. For example, in the region somewhat east of the North Pole the He II image is weak, and this is also true of a large region extending from the center toward the southeast. The CaK image shows no suggestion of the weak region at the north, and the central region is the most strongly emitting portion of the entire disc. Three or four centers of activity are visible in CaK and also in He II. Superimposed upon the latter, however, are several of the centers of activity produced by the overlapping images of Fe XV and XVI.

The short wavelength spectroheliograms of October 20, 1965 are reproduced in Fig. 6. A key shows the particular images of the central plage which are believed to be produced to a large extent by Fe XIV. The conspicuous ring centered at about 257 Å is caused by one or more of the components of the blend of three lines -- He II 256.32 Å, S X 257.29 Å, and Si X 258.29 Å. Perhaps the most interesting feature is the emission present in Fe XV 284.15 Å. The position of the center of the disc in this line is just on the limb of the He II 304 Å image. Two active regions on the east limb are indicated with arrows. The one at the left was from a center of activity which appeared on the limb two days later, as observed in CaK; the one on the right did not appear until three days later. Therefore Fe XV emission must extend high up into the corona above strong centers of activity.

On April 28, 1966, a new set of spectroheliograms was obtained with 10" resolution, the limit attainable with the instrument. One He II 304 Å image is reproduced in Fig. 7. The sun was quite active, but large regions were free from plages and show the pattern of the quiet sun. The fine detail in He II correlates well with that present in CaK, and the network and coarse mottles are clearly present. In all other lines except He I, however, the network and mottles are absent or of too low contrast to detect, just as on February 1, 1966. At 10" resolution limb brightening can be seen in He II, and also in almost all the emission lines. A prominence shows clearly in the southwest, but what appears to be a tremendous prominence in the northeast is a plage from Fe XVI 335 Å. Alongside this feature there is present a fine thread, which is believed to be part of a loop prominence in He II 304 Å. Another loop prominence is present on the east limb a little south of the equator.

The absence of the coarse mottles and chromospheric network in O III, IV, and V, and all lines of still higher ionization potential leads to the conclusion that these structures are confined to the rather low chromosphere. Since they are well developed in He II 304 Å, they must extend at least to the region where the temperature has reached 40 000 °K, where this line is emitted, according to Athay (1965). Above the 140 000 °K level, however, where O IV has its maximum concentration (Jordan, 1966), these structures seem to be absent. Therefore it is unlikely that they are involved in the process which transfers energy into the upper chromosphere and corona.

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C. Jordan (1966), Private Communication.

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CAPTIONS

Fig. 1. Solar x-ray spectra photographed with a spectrograph using a 2400-line/mm 40 cm-radius grating at 5° from grazing-incidence. On September 20, 1963 the slit was covered with a filter of aluminum 1000 Å thick; on February 1, 1966 the upper half of the slit was covered with an aluminum filter and the lower half with a filter of indium. The sun was active on the first flight and quiet on the second.

Fig. 2. The long wavelength end of the spectrum photographed on February 1, 1966 using a filter of indium. Presented for comparison are: (a), the spectrum of the high temperature plasma produced by Zeta (Gabriel and Fawcett, 1965); and (b) - the photoelectrically scanned spectrum obtained on March 30, 1964 by Hall, Schweitzer, Heroux and Hinteregger (1965).

Fig. 3. Extreme ultraviolet spectroheliograms photographed on February 1, 1966 with an objective-type single-concave-grating spectrograph.

Fig. 4. Spectroheliograms photographed on February 1, 1966. The picket-like structure was caused by shadows cast by the vertical bars of the mesh supporting the aluminum filter. He II 304 Å and Fe XV 284 Å, are present in second order.

Fig. 5. The He II 304 Å spectroheliogram of October 20, 1965 compared with a CaK spectroheliogram made on the same day.

Fig. 6. The short wavelength spectroheliograms obtained on October 20, 1965. The vertical picket-like structure was caused by the bars of the mesh which supported the aluminum filter. The scale and key at the bottom refer to the images of plage having the McMath No. 8032. The orientation of the images is the same as for Fig. 5.

Fig. 7. An He II 304 Å spectroheliogram photographed on April 28, 1966. The resolution is of the order of 10". At the center of the disc can be seen two plages caused by the overlapping image of Fe XV 284 Å.

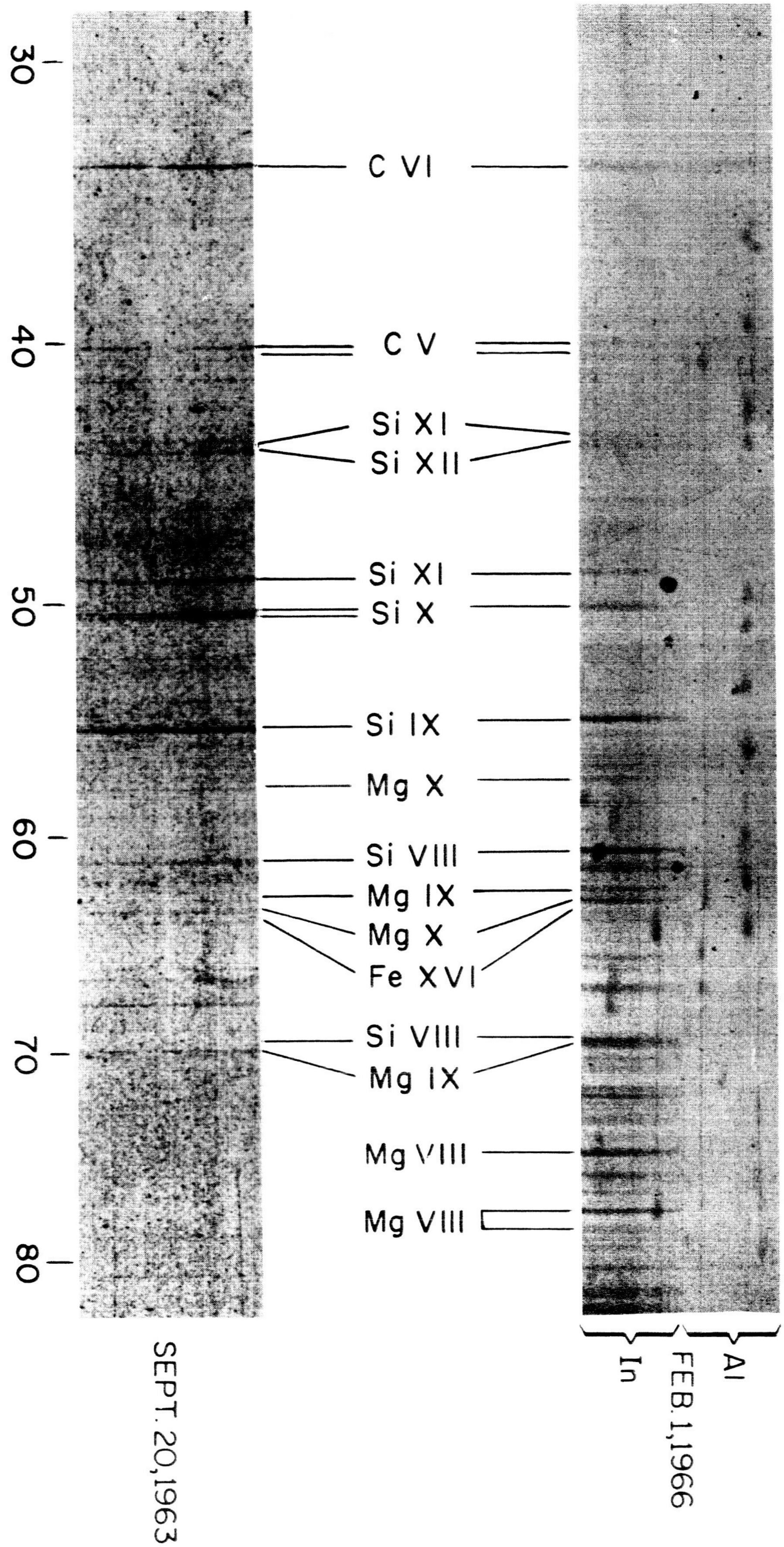
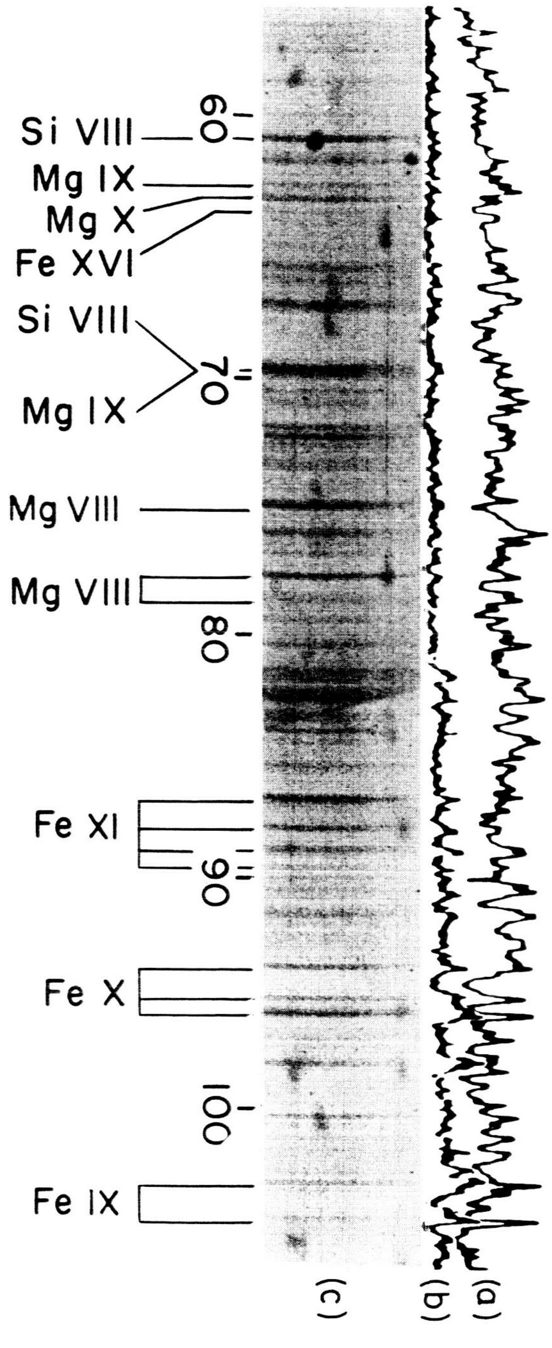

30
40
50
60
70
80
C VI
C V
Si XI
Si XII
Si XI
Si X
Si IX
Mg X
Si VIII
Mg IX
Mg X
Fe XVI
Si VIII
Mg IX
Mg VIII
Mg VIII
SEPT. 20,1963
In
FEB. 1,1966
Al

Figure 1



Si VIII
Mg IX
Mg X
Fe XVI
Si VIII
Mg IX
Mg VIII
Mg VIII
Fe XI
Fe X
Fe IX
60
70
80
90
100
(c)
(b)
(a)

Figure 2

X-UV SPECTROHELIOGRAMS FEB 1, 1966
U. S. NAVAL RESEARCH LABORATORY

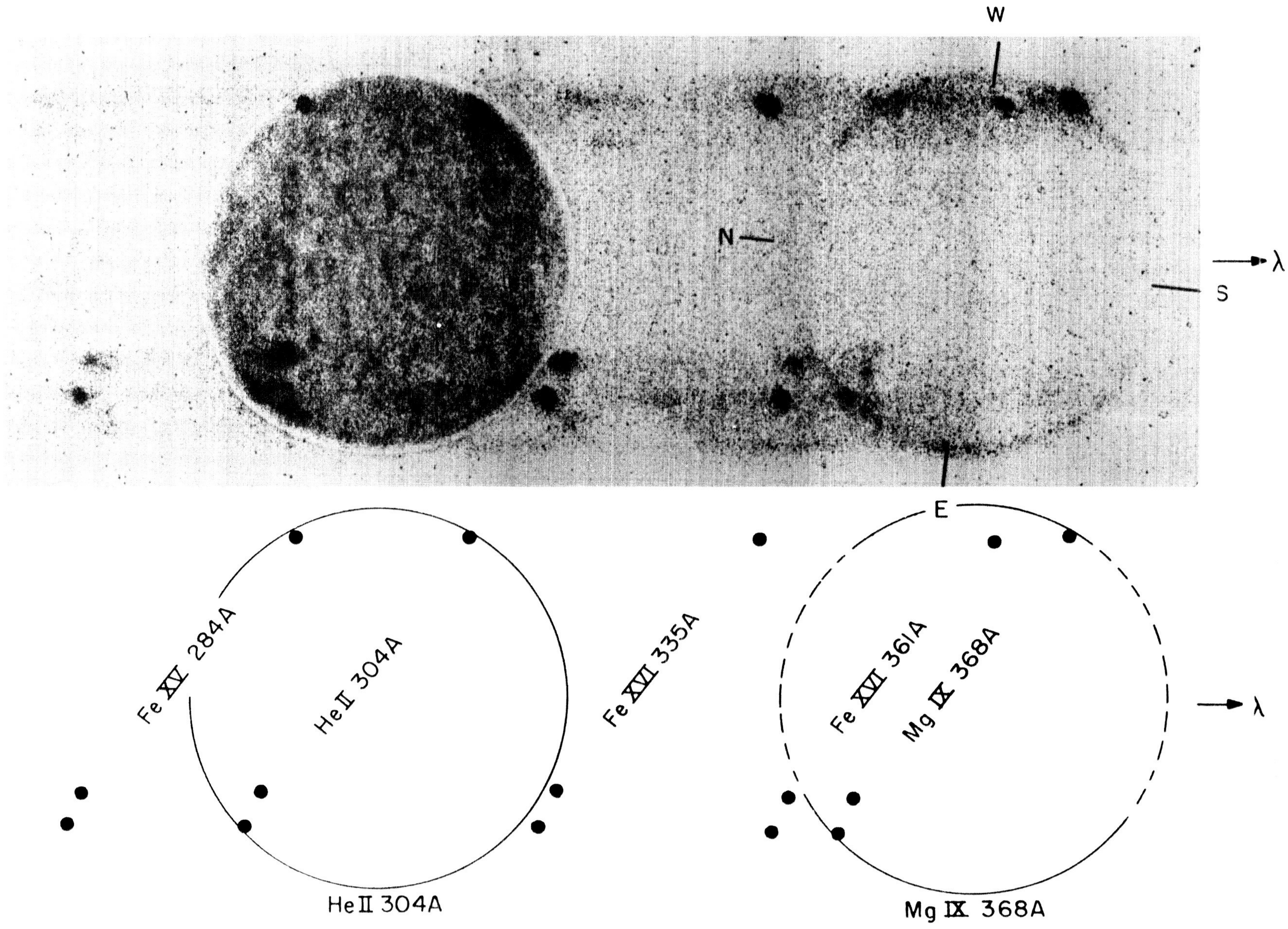


Figure 3

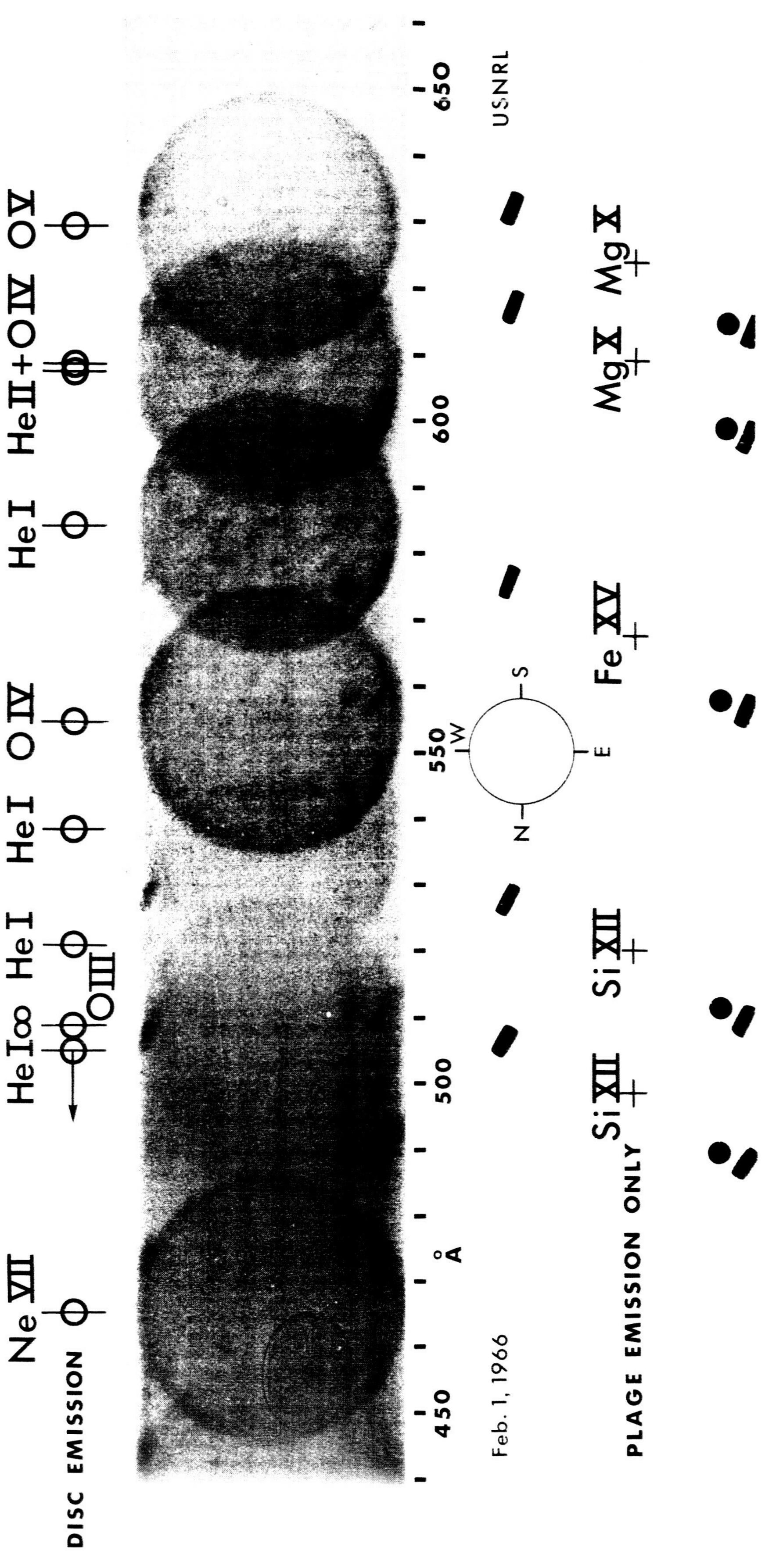

DISC EMISSION
Ne VII
He I
He I
O III
He I
O IV
He I
He II + O IV
O V
450
Å
500
550
600
650
Feb. 1, 1966
US NRL
S
W
E
N
PLAGE EMISSION ONLY
Si XII
Si XII
Fe XV
Mg X
Mg X

Figure 4

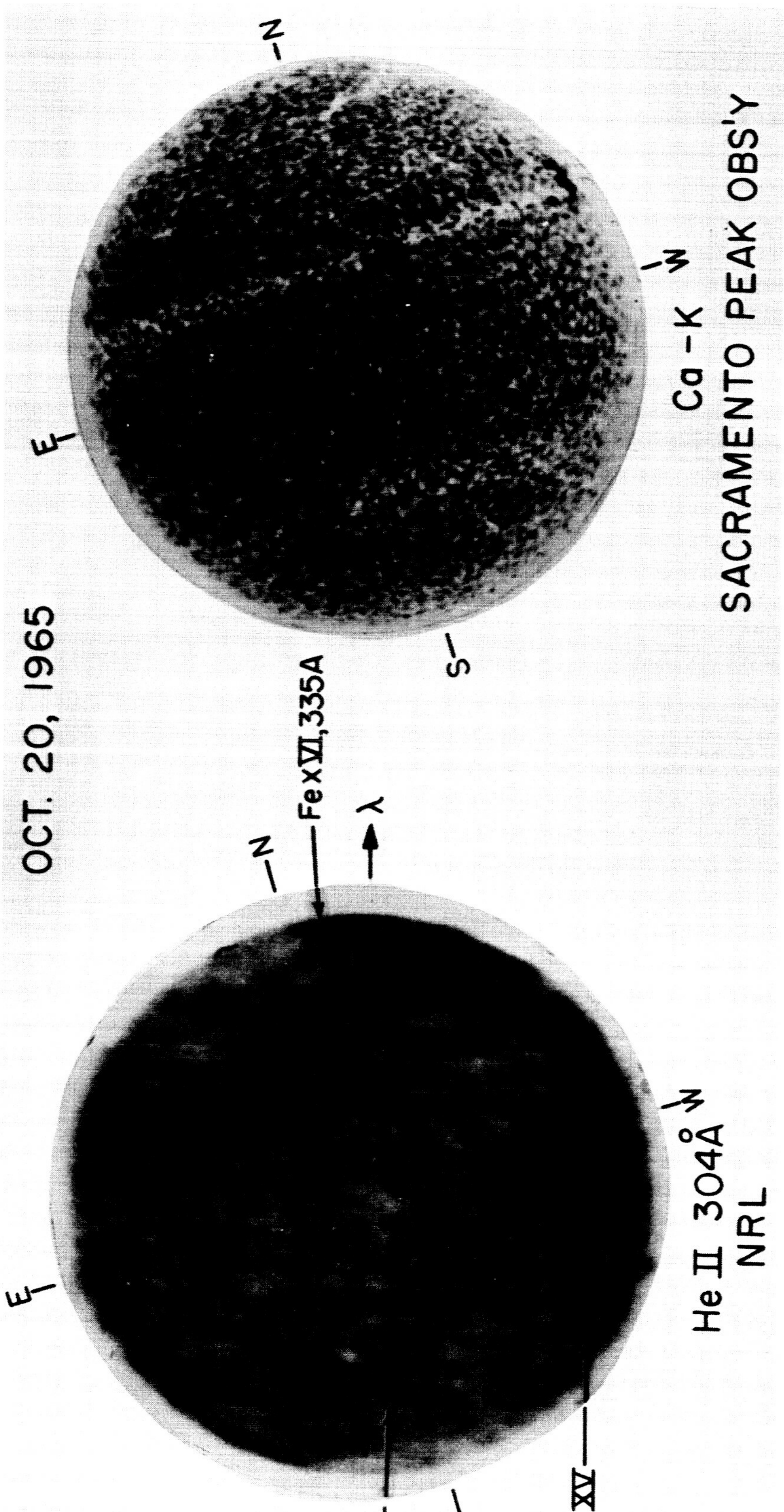

OCT. 20, 1965
E
N
S
W
Fe XVI, 335A
λ
Fe XV
284A
Fe XV
He II 304Å
NRL
E
N
S
W
Ca - K
SACRAMENTO PEAK OBS'Y

Figure 5

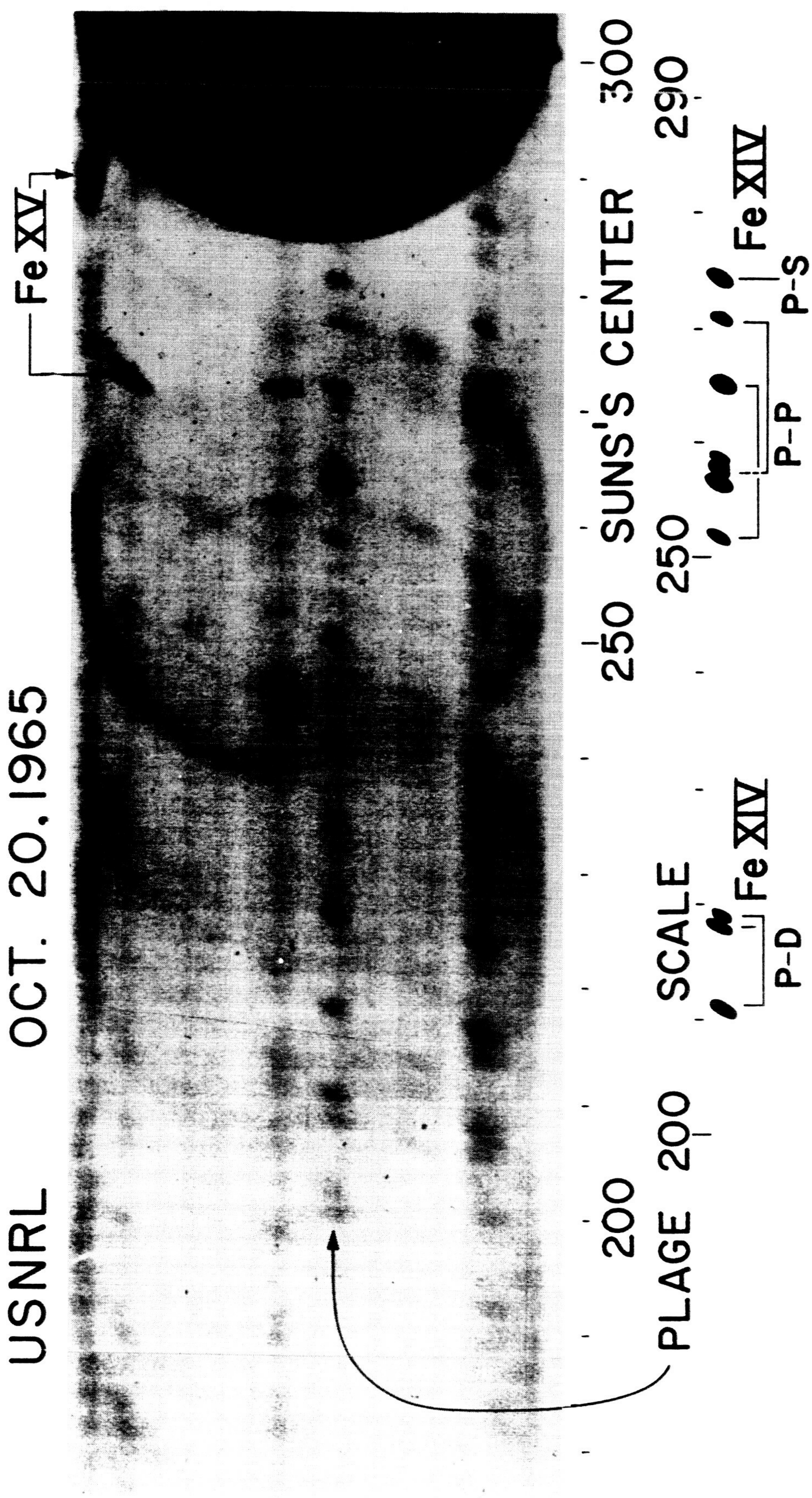

USNRL
OCT. 20, 1965
Fe XV
PLAGE
200
200
200
SCALE
Fe XIV
P-D
250
250
SUNS'S CENTER
P-P
P-S
Fe XIV
290
300

Figure 6

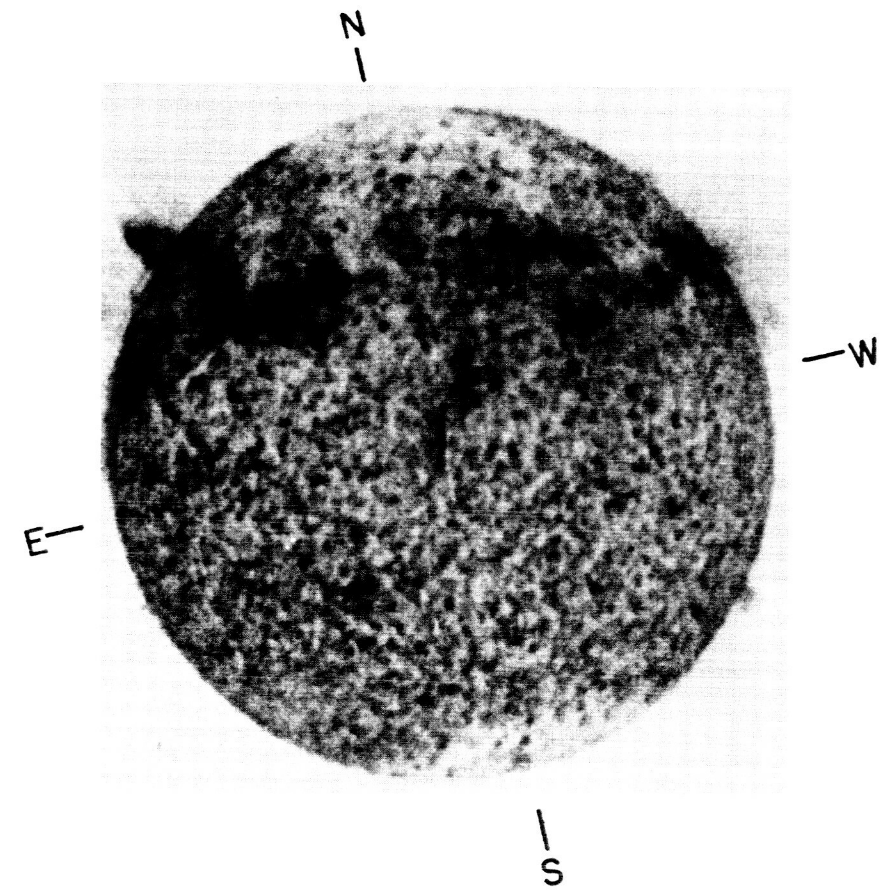


Figure 7