A PRELIMINARY STUDY OF THE EXTREME ULTRAVIOLET SPECTROHELIOMETERS FROM SKYLAB


E. O. Hulbert Center for Space Research, Naval Research Laboratory, Washington, D.C. 20375, U.S.A.

(Received 19 October, 1973)

Abstract. Some of the first observations obtained with the Naval Research Laboratory’s Extreme Ultraviolet Spectrograph (S082A) during the first Skylab mission are presented and compared with magnetograms and other ground-based data. The instrument is a slitless objective-type grating spectrograph covering 170–630 Å and described in Solar Phys. 27, 251 (1972). Chromospheric network, loop prominences, active regions, a flare, limb brightening, XUV bright points, and ‘coronal holes’ are among the phenomena shown and discussed.

The First Skylab Mission, SL/2, May 14 to June 22, 1973, was highly successful scientifically, in spite of engineering problems that reduced the time available for operation of the instrument. In this first brief paper we present some particularly interesting results obtained with experiment S082A, the Extreme Ultraviolet Spectroheliograph that was one of the six major instruments in the Apollo Telescope Mount (ATM). Our current involvement with the continuing missions has left time to do little more than examine the images and derive obvious conclusions. The instrument is a photographic slitless objective type grating spectrograph covering the range 170–630 Å. The radius 4 m, and ruling density, 3600/mm, resulted in solar images of 18.5 mm diameter dispersed so that the solar diameter covered 25 Å. For more detail see Reeves et al. (1972).

Figure 1 illustrates the form in which the extreme ultraviolet spectroheliograms were obtained. This figure shows spectroheliograms in the wavelength range from roughly 200 Å to 400 Å. The 200–300 Å section is shown at the top of figure and the 300–400 Å section is shown at the bottom. In each case, wavelength increases to the right. This figure was made from sections of two original film strips which span the ranges 170–350 Å and 300–630 Å, resp. The solar diameter is 18 mm on the original film strips, corresponding to approx. 25 Å along the direction of dispersion. Thus, images from spectrum lines differing by more than about 25 Å do not overlap. The appearance of these solar images ranges from solid disks such as the chromospheric He II 304 image to the images showing emission from only the hot active regions and coronal loops such as the coronal Fe xv 285 and Fe xvi 335, 361 images. Intermediate in appearance is the conspicuously limb-brightened image Mg ix 368. Images showing emission from only the very hottest active regions and from flares are characteristic of lines of still higher stages of ionization, and some can be seen in Figure 1 at wavelengths shorter than 304 Å.
Fig. 1. Spectroheliograms of the 200-400 Å region obtained on June 15, 1973 (14:13:05 GMT) during a solar flare. In the upper picture, images are visible from the He II continuum near 323 Å through the Lyman series of He II to the Lyman image at 304 Å. In the lower picture (14:14:53 GMT) the Fe xvi continuum through the Fe xvi images at 335 Å and 351 Å to well beyond the full disk image of N IX at 386 Å.
These spectroheliograms were obtained during the flare of June 15, 1973. The flare intensity in He II 304 was so great that the film 'solarized' at this location resulting in a decrease in film density rather than the usual increase. Thus, in He II 304, the flare image appears dark rather than bright.

Although many other features are visible in these spectroheliograms, we shall close our general description of the data format by pointing out the Lyman series of He*, converging from He II 304 to its continuum at 228 Å. From an inspection of the print, we can resolve the first 13 lines of this series corresponding to a wavelength resolution of 0.19 Å between the 12th and 13th lines and 0.15 Å between the 13th line and the violet edge of the remaining unresolved lines. A rough estimate of the size of the flare ribbon is 5", corresponding to 0.06 Å at the dispersion of 25 Å/solar diam. This is the amount by which one might expect the 18th and 19th members of this Lyman series to differ according to the simple Rydberg series relation. Thus, in principle, one might expect a careful measurement of the original negatives to resolve a few more lines of this series.

Figure 2 shows a He II 304 spectroheliogram taken on May 30, 1973. For comparison, we also show a magnetogram and spectroheliograms in Hz 6563 and Ca II K 3934 taken on the same day. The He II 304 spectroheliogram appears similar to the Ca II 3934 spectroheliogram in many respects. Both show the bright chromospheric network. Both show even brighter emission from the active regions. However, there are some striking differences that can not be accounted for by variations in the appearance of Ca II spectroheliograms with wavelength or bandpass. A number of these differences are listed in the following paragraphs. We are continuing to find interesting results every day, so this list is by no means complete.

An obvious result is that the 'coronal holes' that one sees in coronal and X-ray images are also visible in the He II 304 images. A comparison between the He II 304 pictures and the broadband (170–650 Å) coronal images, obtained by the Naval Research Laboratory's XUV Monitor on board Skylab, shows the close correlation between a 'coronal hole' and the depression of the He II network. This is not a new result since these He II 304 'holes' have been observed in rocket spectroheliograms obtained over the past decade (Tousey et al., 1965). However, the high spatial resolution with which these He II 304 'holes' can now be observed is new. This resolution helps one to study the sharpness of the boundary of the 'hole'. In particular, comparison between the photospheric magnetogram and the He II 304 and Ca II 3934 spectroheliograms allows one to identify specifically which magnetic field structures are in the hole and which are outside.

A second difference between the He II 304 spectroheliograms and the Ca II K spectroheliograms is the detailed appearance of the network. In general, the network in He II 304 is much coarser than that in the K line. In fact, sometimes the network in He II 304 becomes so wide that it fills in the center of a network cell. Although we realize that this sometimes happens to the K line in an active region, we are referring especially to non-active regions where we can see that the K line does not fill in the cells. This filling in of the network cells by especially wide network appears to be a
characteristic of the large unipolar magnetic regions, rather than regions of weak or mixed polarity, as one can see by comparison between the magnetogram and the He II 304 spectroheliogram. A third difference between the He II 304 and Ca II K spectroheliograms is that the He II spectroheliograms show the partitioning of the solar disk into large-scale unipolar magnetic regions much better than the Ca II spectroheliograms. This is shown clearly in the southern hemisphere on the May 30, 1973 He II 304 spectroheliogram. A small coronal hole lies at the south polar cap. Just farther from the pole is a band of thick network associated with a large unipolar magnetic region of negative polarity. (It is not possible to recognize this region of negative polarity on the single magnetogram which is reproduced in Figure 2. But a careful inspection of several magnetograms taken on subsequent days has convinced us that this unipolar magnetic region band does exist.) A dark channel separates this negative polarity region from a unipolar region of positive polarity northward of it. This dark channel contains only remnants of a filament in Hz, and it is the He II 304 analogue of a filament channel.

In addition to the active regions, and the regions of thick network in the He II 304 spectroheliograms, there are small areas of emission scattered more or less uniformly on the solar disk that appear somewhat brighter than the He II network. These features are especially visible in the large coronal hole in the south polar region shown on the He II 304 spectroheliogram of June 18, 1973 in Figure 3. While the wide He II 304 network 'fades out' significantly in the coronal hole, the small, brighter areas remain bright right into the 'coronal hole'. This effect is even more striking in the Mg IX 368 spectroheliograms. In the past we have referred to such feature as 'XUV bright points', and noted that in many cases they correspond spatially to the location of small bipolar magnetic features (Tousey et al., 1971).

In Figure 3 we compare a Kitt Peak magnetogram and spectroheliograms obtained in Ne VII 465, and in He II 304 and Fe XV 285. Compared with He II 304, the Ne VII image seems less of a 'solid' disk, and shows considerable limb brightening. As previous rocket observations have shown, gaps in the limb brightening occur where Hz and He II 304 disk filaments cross the limb to become prominences. Filament channels and coronal holes are visible in the Ne VII spectroheliogram, although apparently with less contrast than in the He II spectroheliogram. The large coronal hole near the south pole is visible in both the He II and Ne VII images. In fact, one can see from the location of the south pole in these two images that these spectroheliograms were taken with different orientations between the dispersion direction and the solar rotation axis. (The streaks across the Ne VII 465 image are produced by the He I 504 continuum and show the direction of dispersion.) The chromospheric network is visible in Ne VII. In addition, several brighter-than-average features appear in the Ne VII spectroheliograms. Many of these small emission features are the foot points of loops in active regions. This is particularly clear when these active regions occur near the limb. In these cases, the loops can be seen extending well beyond the limb.

The Fe XV 285 image in Figure 3 shows emission from only the active regions and
loop structures. (These loop structures are shown much better in Figure 4 where the exposure of the original film was more suitable for the Fe xv 285 image.) A number of features of this Fe xv 285 image are evident. The emission from the active regions comes primarily from bright loops. In some cases small bright points are evident. These seem to be associated with small bipolar magnetic regions or with magnetic features having a polarity opposite to most of the surrounding magnetic fields. In the southeast quadrant of the disk, a number of bright loops are visible in Fe xv 285 just over the place where a disk filament occurs in the He II 304 image. Comparison with the Kitt Peak magnetogram in Figure 3 shows that the foot points of the loops have opposite magnetic polarity and that the filament separates these general areas of opposite magnetic polarity.

The active region just south and east of the disk center looks something like a ‘fountain’ in Fe xv 285 with many loops rising from a central area and looping back to the surface some distance away. Comparison with the magnetogram shows that a strong negative polarity magnetic field occurs in the center of this loop system and that the brightest loops stretch across a supergranular cell to connect with foot points of opposite polarity. The weaker loops stretch in the opposite direction and connect with positive-polarity foot points of an apparently older region to the east of this active region. This behavior of the weaker loops was entirely unexpected. In many years of interpreting photospheric magnetograms, we have become accustomed to supposing that in a bipolar magnetic region of relatively simple structure, the areas of leading polarity are all ‘connected’ to the areas of following polarity by magnetic loops. That some of the areas of one polarity may be connected to an entirely different magnetic region is a surprise that appears relatively frequently in our coronal observations. The small bright point just south of this loop system is associated with a small bipolar pair of magnetic points on the magnetogram. An enhanced bright area is visible in the He II 304 spectroheliogram at this location. The Ne vii 465 image also shows an enhanced bright feature at this location, and in addition shows a loop extending from it.

Another group of such bright points appears in association with the active region just north and west of the disk center. Several bright points occur in the Fe xv 285 image, and a number of bright loops extend about 100,000 km northward of these points. Comparison with the magnetogram shows that these loops are connecting with another magnetic region to the north. The loops are also visible in the He II 304 image, and look like the fibril structures seen on high spatial resolution, narrow-band Hα filtergrams. Although the footpoints are bright in Ne vii 465, the loops themselves are not visible in this spectroheliogram. They are, however, in the Mg ix 368 image as well as the Fe xvi 335 and 361 images obtained simultaneously. In each case, however, a different number of loops is visible, suggesting that spectroheliograms of this type will provide an excellent probe of this magnetic loop structure.

Figure 4a shows an Fe xv 285 spectroheliogram exposed to show the faint loops against the disk. Comparison with the magnetogram in Figure 4b shows that several faint loops from the active region north-east of the disk center stretch out to ‘connect’
Fig. 2a. A comparison of observations taken on May 30, 1973. Left: He ii 304 at 14:14 GMT (Skylab). Right: Magnetogram at 17:45 GMT (Kitt Peak National Observatory). In each photograph, solar north is up and west is to the right.
Fig. 2b. A comparison of observations taken on May 30, 1973. Left: Ca II 3934 at 20:06 GMT (Institute for Astronomy – Haleakala Observatory). Right: Hα 6563 at 11:28 GMT (Ramey Air Force Base Solar Observatory). In each photograph, solar north is up and west is to the right. (The Hα image is rotated slightly clockwise relative to the other images.)
Fig. 3a. A comparison of observations taken on June 18, 1973. Left: Fe xv 285 (overlapping He ii) at 16:31 GMT. Right: He ii 304 at 16:31 GMT.

In each case, solar north is to the left and west is up.
Fig. 3b. A comparison of observations taken on June 18, 1973. Left: Ne vii at 21:38 GMT, Right: Magnetogram at 15:55 GMT (Kitt Peak National Observatory). In each case solar north is to the left and west is up. In the magnetogram, lighter-than-average features correspond to a positive line-of-sight polarity in the sense that the magnetic vector is directed outward from the Sun. Darker-than-average features represent negative polarity.
with small bipolar magnetic regions more than 100000 km away. The numerous observations made during the first Skylab mission show that such connections between active regions are frequent. This suggests that apparently remote active regions may interact more strongly and more often than we have previously suspected.

Before concluding our necessarily brief description of a few selected XUV spectroheliograms obtained during the first Skylab mission, we shall consider two further aspects of these observations. One of these concerns the spectral properties of various solar features. The other concerns the way that various solar features change with time.

Certain features on these spectroheliograms seem to vary in their appearance when the relative orientation between the solar axis and the dispersion direction is changed. Several examples appear in Figure 5 which shows a pair of Ne VII 465 spectroheliograms taken only a few minutes apart with their roll axes perpendicular. The long, but narrow, loop in the active region just north of disk center appears sharper in Figure 5a when the solar axis is parallel to the dispersion direction than in Figure 5b when the axis is perpendicular to the dispersion direction. That is, the width of the
principal part of the loop appears smaller in Figure 5a when it is measured perpendicular to the dispersion than in Figure 5b when it is measured parallel to the dispersion. Similarly, the nearly vertical loops on the east limb appear sharper in Figure 5b where their widths are measured perpendicular to the direction of the dispersion than in Figure 5a where their widths are measured parallel to the dispersion direction. Such observations presumably result from the fact that measurements perpendicular to the dispersion reflect the physical size of a feature, whereas measurements along the dispersion reflect its Ne vii 465 line width as well as its physical size. For example, a point source having a 0.1 Å line width will be stretched for approximately 7” along the dispersion direction but not at all in the perpendicular direction. Since our spatial resolution is approximately half this value, if small features having profiles of 0.1 Å are present, we should expect to see them stretched along the dispersion.
Fig. 5a–b. A comparison between Ne vii 465 spectroheliograms obtained on June 13, 1973 with perpendicular roll angles. In each picture, solar north is up and west is to the right. (a) 01:19 GMT with the direction of dispersion parallel to the solar rotation axis. (b) 01:28 GMT with the direction of dispersion perpendicular to the solar rotation axis.
The width of the Ne vii limb brightening also seems to vary with the roll angle between the solar rotation axis and the direction of dispersion. In Figure 5a the width of the limb brightening appears to be much larger at the north and south poles where it is measured along the dispersion than at the east and west limbs where it is measured perpendicular to the dispersion. At first we thought that this was another example of the effect described in the previous paragraph – namely, that perpendicular to the dispersion, the limbs reflect their physical width whereas along the dispersion they reflect both their physical width and the Ne vii 465 line width. Reference to Figure 5b shows that this can not be the complete explanation. Otherwise, in Figure 5b the widths of the east and west limbs would be larger than the widths of the polar limbs, and in general they are not. A clue in resolving this puzzle was the observation from these and other Ne vii spectroheliograms that along the limb the transition from an extra-wide limb to a normal limb coincides with the boundary between a coronal hole at the limb and a normal limb. We concluded that the extra-wide limb occurs over a coronal hole, and it is widest when it is measured along the dispersion. Preliminary measurements suggest that the Ne vii 465 line width does not change from the normal limb to the limb over a coronal hole, but that the physical width of the limb brightening nearly doubles its value over a coronal hole. A possible explanation for this is that the thermal gradient with height is less over a coronal hole than over the normal atmosphere, as proposed by Munro and Withbroe (1972). If so, a given narrow range of temperature at which this transition region Ne vii 465 line is formed would correspond to a wider range of height of formation over a coronal hole than over the normal atmosphere.

Finally, we shall consider briefly how various solar features in our spectroheliograms change with time. We begin with the evolution of the coronal loops of an active region as it is carried across the disk by solar rotation. Although such loops are evident in many XUV lines, we shall illustrate this process with Ne vii 465 spectroheliograms which show the fine-scale nature of the loops especially well, perhaps due to the relatively narrow range of temperature over which this line is formed. Figure 6 shows a sequence of Ne vii 465 spectroheliograms of an active region (McMath plage 379) taken daily during the period from June 8 to June 19, 1973. This region is the same one that Figure 1 shows flaring on June 15. Numerous long bright features are visible extending several tens of thousands of kilometers above this active region, especially during its passage around the west limb. While this region was near the central meridian on June 12, 13, and 14, the bright arches appear connected into complete loops suggesting that they delineate magnetic field lines. A comparison of these Ne vii spectroheliograms with magnetograms supports this suggestion by showing that these loops join fields of opposite magnetic polarity.

On a shorter time scale, a large number of frames of XUV spectroheliograms were obtained on June 15, 1973. This was primarily due to the occurrence of a flare and the consequent operation of the high frame-rate flare mode. In addition to spectroheliograms in many coronal lines, a sequence of He ii 304 spectroheliograms of the entire solar disk was obtained with spatial resolution in the 2′′–5′′ range. This sequence
Fig. 6. A sequence of daily Ne VII 465 spectropheliograms showing the evolution of an active region (McMath plage 379) as it is carried across the disk by solar rotation during the period June 8 to June 19, 1973. In this figure, north is up and west is to the right. Upper row: June 8 through June 14. Lower row: June 15 through June 19.
spanned more than 15 hr with a sub-sequence having 10 min time resolution over nearly a 2 hr period.

Several different kinds of change were observed. The flare varied in a manner similar to its familiar behavior in Hz. Although we have not yet had time to trace its behavior carefully, the He II 304 network seems to behave much like the chromospheric network observed in Ca II 3934 and CN 3883 with significant positional changes occurring during a 9 hr interval but relatively few significant positional changes during a 2 hr interval.

The formation and disappearance of an enhanced bright point was observed during this 15 hr sequence. It was not visible on the first frame, but was clearly visible at the start of the flare sequence 9 hr later. Tracing its behavior through the flare and post flare period, we found that after one hour this bright point separated into 2 distinct points. (In retrospect, one might easily interpret its initial form to consist of two almost-resolved points.) This resolving of an enhanced bright point into two bright features may be significant if these features correspond to small bipolar magnetic regions, as we have often observed.

Two and one half hours after its initial appearance, it was still visible as two distinct points, but 6 hr afterward it had faded into a single point only slightly brighter than the network of which it seemed a part. Half an hour after that, it was not distinguishable from any other fragment of the He II 304 network. Its total lifetime was somewhere between 6 and 15 hr. We expect further study to reveal that this behavior is typical of many such bright points.

In addition to the changes of these bright points, significant changes in off-limb He II 304 loop structures were observed during this 15 hr time period. Furthermore, the nearby Fe xv 285 spectroheliograms showed appreciable changes in the active region loops on the solar disk.

Acknowledgements

The size of the Apollo Telescope Mount project and the seven years of its life make it impossible to name all the persons who have contributed to its success. We thank all people at the Naval Research Laboratory who have worked on the many aspects of the program. We are particularly indebted to our colleagues who are or once were members of the ATM team: O. K. Moe and K. G. Widing participated in the scientific planning; the NRL console in the Mission Control Center was manned by C. C. Cheng, D. L. Garrett, R. N. Mason, T. Mikes, K. Nicolas, and D. Schneible; W. R. Crockett was responsible for the extensive test program and for the telemetry, and W. R. Hunter for contamination monitoring during thermal vacuum tests; the early development of ATM mission planning of observing programs and the coordination with other groups was done by T. C. Winter, Jr., Lt. Col. USA during his three-year term of duty at NRL.

We thank the Ball Brothers Research Corporation most sincerely for their devotion to the construction and perfection of the NRL instruments, and also for their engi-
engineering support at MSFC and JSC during the mission. Particularly we wish to thank M. W. Frank, Program Manager and W. R. Siddle. To NOAA we are indebted for invaluable advice on current solar conditions.

It has been a pleasure to work with the many Centers and individuals of the NASA, who provided the support and overall direction for ATM – OSS and OMSF at Headquarters; MSFC, the Engineering Development Center; KSC, where ATM Skylab and the vehicle were mated and launched, and JSC where the actual operation of the mission was conducted.

Special appreciation is due to N. Paul Patterson, who was responsible as observing program instructor for the training of the astronauts that resulted in their enthusiastic and expert operation of the instruments.

Lastly, and with the greatest admiration we single out Pete Conrad, Joe Kerwin, and Paul Weitz, the astronauts. With great courage they saved the crippled Skylab Space Station and then went on to carry out all the solar observations with utmost perfection.

References