ON THE ABSENCE OF A RELATIONSHIP BETWEEN THE PROPERTIES OF THE $T_e \geq 10^6$ K
AND THE PROPERTIES OF THE $T_e \leq 7 \times 10^5$ SOLAR PLASMAS

U. FELDMAN
E.O. Hulbert Center for Space Research, Naval Research Laboratory, Washington, DC 20375

AND

J. M. LAMING
SFA Inc., Landover, MD 20785

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ABSTRACT

Traditional solar upper atmosphere models assume continuity along solar upper atmosphere structures, from the $T_e \geq 10^6$ K corona to the $T_e \approx 10^4$ K chromosphere. Under such conditions a transition region with $3 \times 10^6 \leq T_e \leq 1 \times 10^6$ K should exist between the corona and chromosphere. According to such models, plasma properties of the corona could be inferred from plasma properties of the so-called transition region. Inherent in such models are assumptions that plasmas in such structures (most likely loops) are in hydrostatic equilibrium, and heat is distributed along them by thermal conduction. When accounting for coronal heat losses based on such models three mechanisms are mentioned: (1) radiation by coronal plasma; (2) thermal conductivity between the $10^6$ K corona and the $10^4$ K chromosphere and (3) mass motions, mostly into the solar wind. According to these models, thermal conductivity is the most efficient among the coronal heat loss mechanisms. In this paper, we describe studies of the relationships between structures having temperatures of $T_e \geq 1 \times 10^6$ K and those with temperatures of $T_e < 7 \times 10^5$ K. We show that effects of thermal conduction between the hot and the cold regions are not seen at the expected levels, implying that unimpaired continuity is not being maintained between the $10^6$ and $10^5$ K plasma regions. As a consequence of these findings, we stress that no conclusion on the properties of $T_e \geq 1 \times 10^6 K$ plasmas can be drawn from properties of the so-called transition region ($3 \times 10^6 \leq T_e \leq 7 \times 10^5 K$) plasmas.

Subject headings: plasmas — Sun: chromosphere — Sun: corona

1. INTRODUCTION

Traditional solar upper atmosphere models assume that continuity exists along solar upper atmosphere structures, from the $T_e \geq 10^6$ K corona to the $T_e \approx 10^4$ K chromosphere. Under such conditions, a transition region with $3 \times 10^6 \leq T_e \leq 1 \times 10^6$ K should exist between the corona and chromosphere. Thus, some authors have assumed that plasma properties of the corona could be inferred by studying the properties of the transition region, although this may not have been the original purpose of such models. Inherent in such models are the assumptions that distribution of plasmas in solar upper atmosphere structures (most likely loops) are dominated by hydrostatic equilibrium, and heat distribution along the structures is dominated by thermal conduction. When accounting for coronal heat losses based on such models three mechanisms are mentioned: (1) radiation by coronal plasma; (2) thermal conductivity between the $10^6$ K corona and the $10^4$ K chromosphere and (3) mass motions, mostly into the solar wind. The coronal radiation is measured to be $F_r \approx 1 \times 10^4$ ergs cm$^{-2}$ s$^{-1}$ for a typical coronal hole, $F_r \approx 1 \times 10^5$ ergs cm$^{-2}$ s$^{-1}$ for typical quiet regions and $F_r \approx 5 \times 10^6$ ergs cm$^{-2}$ s$^{-1}$ for the typical active regions. The conductive flux from coronal hole, quiet and active regions is estimated to be $F_c \approx 6 \times 10^6$ ergs cm$^{-2}$ s$^{-1}$, $F_c \approx 2 \times 10^7$ ergs cm$^{-2}$ s$^{-1}$, and $F_c \approx 6 \times 10^7$ ergs cm$^{-2}$ s$^{-1}$, respectively. Loss by mass motions in quiet and active regions is of secondary importance (Withbroe & Noyes 1977). Thus the conductive flux, if not inhibited, is the most important heat loss mechanism for plasmas in coronal holes, quiet regions, and, most likely, also in active regions. Thermal conductivity is also important for the thermal stability of loops.

Theoretical models in which continuity exists between the $10^6$ K corona and the $10^4$ K chromosphere predict emission measure distributions with the functional form shown in Figure 1 (Mariska 1992). As can be seen from Figure 1, the radiation in the $3 \times 10^4 < T_e < 8 \times 10^5$ K temperature range should emerge from transition region layers which are only $\approx 100$ km wide. Using spectroscopic measurements mostly from near and above the solar limb, Feldman (1983, 1987) showed that most of the radiation in the $3 \times 10^4 < T_e \leq 5 \times 10^5$ K range does not originate from the predicted transition region. Feldman (1983, 1987) argued that the $3 \times 10^4 - 5 \times 10^5$ K radiation originates from plasma structures not associated with the adjacent $10^6$ K corona. He named those structures the "Unresolved Fine Structures."

In this paper we further investigate the relationship between coronal and lower temperature plasmas. We show that no relationship can be drawn on properties of the $T_e > 1 \times 10^6$ K plasmas from properties of the $T_e \leq 7 \times 10^5$ K plasma. We do so by searching for the signature that heat flux conducted from the corona will produce on the so-called transition region. The demonstration is based on the study of high-resolution monochromatic solar images in the 170–630 Å range. In § 2, we compare monochromatic solar images emitted by the plasmas in the $T_e \leq 7 \times 10^5$ K temperature range with those having a temperature of $T_e \approx 1 \times 10^6$ K. A search for the so-called transition region plasmas near the footpoints of $1 \times 10^6 < T_e < 3 \times 10^6$ K coronal loops is described in § 3. Conclusions from the investigation are given in § 4.
SOLAR PLASMAS

2. THE RELATIONSHIP BETWEEN \( T_e \approx 7 \times 10^5 \) STRUCTURES AND \( T_e \approx 1 \times 10^7 \) STRUCTURES IN QUIET AND CORONAL HOLE REGIONS

The S082a Naval Research Laboratory Spectroheliograph on Skylab (Tousey et al. 1977) recorded solar images in the 170–630 Å wavelength range. The spectroheliograph consisted of a 4 m radius of curvature spherical grating with 3600 lines mm\(^{-1}\). The spatial resolution of the spectroheliograph was \( \approx 2'' \) for images in the 170 < \( \lambda \) < 465 Å wavelength range, and it deteriorated to \( \approx 4'' \) at 550 Å. The solar diameter imaged by the spectroheliograph was 18.6 mm, and the dispersion of the spectroheliograph was 1.39 Å mm\(^{-1}\). Thus a wavelength band equal to a solar diameter corresponds to 26 Å.

The density of spectral lines in the solar spectra averages approximately one line per 1 Å. In the case where most lines are of equal intensity a significant overlap between adjacent solar images occurs. Several of the solar images in the spectral region under discussion are produced by very intense transitions. For such images it is expected that overlapping is less obstructing. Prominent among such images are those produced by the 465.22 Å Ne vii and 368.07 Å Mg ix lines which arise from the \( 2s^2 1S_0 - 2p^2 3P_1 \), Be i-like resonance transition. In actuality, the half of the Mg ix image which is directed toward shorter wavelengths is contaminated by images produced by shorter wavelength transitions among which the 360.76 Å Fe xvi is the most notable. The Ne vii image is also somewhat contaminated by a faint image of Ca ix at 466.23 Å. By using the less contaminated half of the Mg ix solar image together with the corresponding half of the Ne vii image, plasmas in the two temperature ranges could be compared.

Under steady state coronal equilibrium conditions, Mg ix transitions are most efficiently emitted from \( T_e \approx 1 \times 10^6 \) K plasmas. Most of the coronal plasmas in quiet regions have a temperature of \( T_e \geq 1 \times 10^6 \) K, while very little of the coronal hole plasmas reach \( T_e = 1 \times 10^6 \) K. As such, Mg ix images could be used to distinguish between coronal hole and hotter regions. Regions with little or no emission in the Mg ix images are defined as coronal holes. Ne vii transitions under steady state coronal equilibrium conditions are most efficiently emitted from \( T_e \approx 5 \times 10^5 \) K plasmas. Quiet region as well as coronal hole plasmas are well represented in Ne vii images.

The Atlas of Extreme Ultraviolet Spectroheliograms From 170–630 Å, Volume 3 (Feldman, Purcell, & Dohne 1987) contains a large sequence of Ne vii and Mg ix images simultaneously recorded by the S082a spectroheliograph. Figure 2 shows the less contaminated half of two of the Ne vii and Mg ix images. In the images displayed in Figure 2 the Sun's north pole is on the right. Notice the appearance of the northern polar coronal hole in the Mg ix images. Ne vii images are characterized by an intense limb-brightening ring which is well observed in both quiet and coronal hole regions. When compared with quiet regions, the limb-brightened ring over coronal holes appears slightly brighter and somewhat stretched (Huber et al. 1974; Bohlin, Sheeley, & Tousey 1975). Away from the limb coronal hole and quiet regions images in the 465.22 Å Ne vii line look quite similar.

A comparison of the image pairs in Figure 2 reveals that a one-to-one correlation between the brightness of the \( T_e \geq 1 \times 10^6 \) K plasmas and the \( T_e \approx 5 \times 10^5 \) K plasmas does not always exist. As seen from the images in Figure 2, the coronal hole plasmas represented by the Ne vii image are as bright as and sometimes even brighter than the quiet region plasmas. On the other hand, the amount of \( T_e \geq 1 \times 10^6 \) K plasmas in coronal hole regions when compared with those in quiet regions is significantly reduced. It appears that the brightness of plasma in the \( 5 \times 10^5 \) region is independent of the plasma brightness in the much higher temperature region. This observation contradicts the notion that, if continuity exists, the \( 5 \times 10^5 \) K plasmas are formed by heat conduction between the corona and the lower temperature regions. More likely the observations indicate that thermal continuity between the corona and the chromosphere is not being maintained in the solar upper atmosphere.

The above observations support the conclusions of Feldman (1983, 1987) which stated that the so-called transition region, if it exists, is of minor importance in contributing to the \( T_e \approx 5 \times 10^5 \) K radiation.

3. A SEARCH FOR THE FOOTPOINTS OF HOT (\( 2 \times 10^6 \leq T_e < 3 \times 10^6 \) K) CORONAL LOOPS IN LINES EMITTED BY \( T_e < 1 \times 10^6 \) K PLASMAS

According to theoretical models, if inhibited, heat conduction from \( 1 \times 10^6 \leq T_e \leq 3 \times 10^6 \) K bright coronal loops should produce a \( T_e \leq 1 \times 10^5 \) K transition region. The signatures of the colder layers should be visible in lines of Ne vii, Mg viii Fe ix, and Fe x. In this section the relationship between properties of the hot loop tops and the footpoints are investigated using images obtained by the NRL S082a spectroheliograph on Skylab. The images of the coronal loop to be discussed were acquired by scanning, with a PDS microdensitometer, the original Skylab photographic plates.

Coronal loops discussed, for example, by Rosner, Tucker, & Vaiana (1978) are predicted to be largely isothermal due to the high thermal conductivity of coronal plasma, with the transition to \( T_e \leq 1 \times 10^6 \) K temperatures occurring over a short distance, known as the loop upper transition region. Athay (1981) has calculated the differential emission measure distributions one would expect from various loop models. In his models he assumed a plasma in steady state coronal equilibrium, maintaining constant pressure conditions. Flow-driven models, in which transition region heat losses which were assumed to be by thermal conduction and radiation were balanced by enthalpy and gravitational potential energy flux, appear to be the most successful in reproducing the observed differential emission measure above \( 3 \times 10^5 \) K. Figure 3 shows

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Fig. 2b—Solar images in the lines of Ne vii (T_e ≈ 5 × 10^5 K) and Mg ix (T_e ≈ 1 × 10^6 K) reproduced from the Atlas of Extreme Ultraviolet Spectroheliograms from 170–630 Å (Feldman 1987). In each of the images the solar north pole is on the right.
the flow-driven model most successful in this respect, with $n_e \times T = 6 \times 10^{14}$, a constant heat flux of $5 \times 10^5$ ergs cm$^{-2}$ s$^{-1}$ and a flow velocity of 3.2 km s$^{-1}$. Using such models we can estimate the intensity ratio between coronal lines ($T_e \geq 2 \times 10^6$ K) emitted from the main top portion of the loop and upper transition region lines that should be emitted from the footpoints. In Table 1 we give atomic data for all the spectral lines that will be discussed. The columns give the following data: (1), the line; (2), its log temperature of formation; (3), the log of the differential emission measure at this temperature from Athay's models; (4), the log of the number of emitted photons per unit emission measure; and (5), the log of the relative spectroheliograph efficiency. The main source for the atomic data in this table is Feldman et al. (1992), supplemented by Dufon (1991) for Fe xiv 417.25 Å, Bhatia & Kastner (1980) for Ni xvi 249.18 Å, and our own HULLAC (Klapisch et al. 1988) computations for Si xi. For all these transitions, abundances were taken to be the coronal abundances of Feldman et al. (1992), and ionization balances came from Arnaud & Rothenflug (1985). Tables 2, 3, and 4 are to be compared with Figures 4, 5, and 6. We give the ratios (in photons, though to one significant figure this is the same as the intensity ratios in energy units) for various pairs of transitions. For each pair, a transition that may be considered to be coming from the loop upper transition region is specified at the top of each column, its intensity being divided by that from a coronal transition specified at the left-hand side of each row. Each intensity ratio includes the factors listed in Table 1, and a geometrical factor corresponding to the exposed area on the photographic plate that the coronal and transition region sections of the loop project. The loop area is approximately 20" x 2" in angular size. The upper transition region angular size is much smaller than the instrument spatial resolution, which is 2" x 2". We take this as the upper transition region projected area, giving a factor of 10 enhancement of the incident photon flux of radiation in the upper transition region image over that of the coronal part.

The images in Figures 4, 5, and 6 are reproduced according to their photographic density. While this makes quantitative comparisons difficult, it is certainly possible to judge whether loop footpoints or a complete loop is visible in a particular line. In the first example (Fig. 4), the main loop is visible in the light of Ni xvii ($T_e \approx 2.5 \times 10^6$ K) and Fe xv ($T_e \approx 2.0 \times 10^6$ K). According to calculations the footpoints of the loop seen in the light of 171.07 Å Fe ix and 174.53 Å Fe x lines should be 4 times, and 3 times, respectively, as bright as the Fe xv image and approximately equally as bright as the Ni vii image. In reality, no footpoints are visible even at a much reduced brightness. As in images produced by the Fe xv and Ni xvii,

### Table 1

<table>
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<tr>
<th>Transition (Å)</th>
<th>log (T)</th>
<th>log (DEM)</th>
<th>log [(I/ng)]</th>
<th>log [σ(λ)]</th>
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<td>Ne vii 564.22</td>
<td>5.7</td>
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<td>26.71</td>
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<td>27.95</td>
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<td>-14.33</td>
<td>-4.89</td>
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<td>Ni xvi 249.18</td>
<td>6.4</td>
<td>28.29</td>
<td>-14.19</td>
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* See text for explanation of columns.

### Table 2

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<th>Transition Pair Ratios (photons) for Loops in Figure 4</th>
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<tr>
<td>Fe ix 171.07 Å</td>
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<tr>
<td>Fe xv 243.78 Å</td>
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<tr>
<td>Fe xv 262.98 Å</td>
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<td>Ni xvi 249.18 Å</td>
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### Table 3

<table>
<thead>
<tr>
<th>Transition Pair Ratios (photons) for Loops in Figure 5</th>
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<tr>
<td>Ne vii 465.22 Å</td>
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<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Si xii 520.67 Å</td>
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<tr>
<td>Fe xv 417.25 Å</td>
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### Table 4

<table>
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<th>Transition Pair Ratios (photons) for Loops in Figure 6</th>
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<td>Ne vii 465.22 Å</td>
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<tr>
<td>Si xii 520.67 Å</td>
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<tr>
<td>Fe xv 417.25 Å</td>
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the entire loop rather than the footpoints is seen in the light of Fe xv and Fe x. The pattern seen in Figure 4 is repeated in Figure 5. The footpoints of the loop in the light of 244.91 Å Fe ix are expected to be half as intense as the Fe xv and Fe xvi images (Table 2). In reality, the Fe ix image is significantly less intense, and no trace of the footpoint can be found.

In Figure 6, the loop's images seen in the light of Si xi (2.0 × 10^5 K) and Fe xv (2.0 × 10^6 K) are compared with images seen in the light of Ne vii (5.0 × 10^5 K) and Mg viii (7.9 × 10^5 K). Again, no footpoints of the 2 × 10^6 K loop are observed in the light emitted by the upper transition region plasmas. A similar conclusion was also reached by Widing & Cook (1987).

In general, then models of hot loops do not predict as much emission in the transition region at temperatures up to 3 × 10^5 K as is observed from the complete solar disk, which necessitates something like the cool loop model of Antiochos & Noci (1986). But when images of individual loops are investigated, their study shows that too much transition region radiation is predicted to come from the loop footpoints.

In Figures 7 and 8 we show solar images of a group of active regions in the light of He ii 303.79 Å, Ne vii 465.22 Å, Mg ix 368.07 Å, and Fe xv 284.17 Å. Figure 7 shows the active regions as they appeared on the solar disk, and Figure 8 shows their appearance 5 days later when they had reached the solar limb. Contours calculated for the Fe xv emission are reproduced on each image to enable one to see how closely bright features at the different temperatures line up. Figure 7 shows a very good correspondence, particularly between Fe xv and He ii. The Ne vii emission even shows what might be interpreted as footpoints to the Fe xv loops, but close inspection shows that these “footpoints” are not quite at the precise locations where one would expect them, relative to the Fe xv loop. However, as this active region complex progresses to the solar limb, one sees the correspondence disappear to a certain extent. Distinct loops are now visible in Ne vii, in conflict with what one would expect to see based on the considerations of Antiochos & Noci (1986). Such loops are not clearly visible in the other images, although some structures can be made out.

The images suggest that while coronal lines may reasonably be assumed as coming from large loops, the origin of the Ne vii and He ii emission is less clear. Theoretical possibilities like cool loops (Antiochos & Noci 1986) may account for some, but clearly not all, of the emission, as the large loops in Ne vii show.

4. CONCLUSIONS

Some solar and stellar researchers are under the impression that there is a one-to-one correlation between $T_e < 1 \times 10^6$ K and $T_e \geq 10^6$ K plasmas in the solar atmosphere. Our studies indicate that no conclusion either on the shape of the emitting structures, their intensity distribution, or any other plasma property can be drawn from one type of plasma about the other. The $T_e \leq 1 \times 10^6$ K plasmas and the $T_e \geq 2 \times 10^6$ K plasmas are mostly disconnected from each other. In § 2 we...
have shown that bright emission in the $5 \times 10^5$ K temperature range has no bearing on the brightness of the $T_e \geq 1 \times 10^6$ K coronal plasmas. In § 3 we have shown that the bright footpoints predicted by theories, in which the uninhibited conduction from the corona plays a major role, are generally not present. Often it appears as if the same spatial location is occupied by cold and hot loops, while in other cases the hot and cold loops emerge from different locations.

We would like to thank Katherine A. Abbott for her help in scanning the Skylab plates and recreating the computer images.
**Fig. 6**.—The morphology of a bright coronal loop recorded by the S082a spectroheliograph on Skylab and traced on a PDS microdensitometer. The loop seen in the light of 

**Fig. 7**.—The morphology of a group of active regions in the light of 

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Fig. 8.—As for Fig. 7. The active region complex has now moved to the solar limb

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