Magnetic Connections across the Chromosphere–Corona Transition Region

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Abstract

The plasma contributing to emission from the Sun between the cool chromosphere (≤10^4 K) and hot corona (≥10^6 K) has been subjected to many different interpretations. Here we look at the magnetic structure of this transition region (TR) plasma, based upon the implications of CLASP2 data of an active region recently published by Ishikawa et al., and earlier Interface Region Imaging Spectrograph (IRIS) and Solar Dynamics Observatory (SDO) data of quiet regions. Ishikawa et al. found that large areas of sunspot plages are magnetically unipolar as measured in the cores of Mg ii resonance lines, formed in the lower TR under low plasma-β conditions. Here we show that IRIS images in the line cores have fibrils that are well aligned with the overlying coronal loop segments seen in the 171 Å channel of SDO. When the TR emission in active regions arises from plasma magnetically and thermally connected to the corona, then the line cores can provide the first credible magnetic boundary conditions for force-free calculations extended to the corona. We also re-examine IRIS images of dynamic TR cool loops previously reported as a major contributor to TR emission from the quiet Sun. Dynamic cool loops contribute only a small fraction of the total TR emission from the quiet Sun.

Unified Astronomy Thesaurus concepts: Active solar corona (1988); Solar corona (1483); Quiet solar corona (1992); Stellar coronae (305); Solar transition region (1532)

1. Introduction

Ultraviolet emission from features formed between the ≈6000 K and 10^6 K plasmas of the chromosphere and corona of the Sun have been studied quantitatively for over half a century (e.g., Detwiler et al. 1961; Pottasch 1964; Burton et al. 1967). The underlying chromosphere spans many pressure scale heights; it is a thermostat in that an increase in heating there leads largely to the increased energy of latent heat of ionization of hydrogen, and the accompanying freed electrons lead to rapid radiation losses through inelastic collisions with atoms and atomic ions. In contrast, the overlying corona conducts heat more efficiently to lower temperature plasma than it can radiate, because abundant ions (particularly of H, He, C, N, and O) are fully ionized, or belong to H- or He-like ions. Radiative losses from these ions are modest, because almost as much energy is required to excite radiative transitions, requiring a change in principal quantum number, as it does to ionize them (Gabriel & Jordan 1971, reviewed by Judge 2019). Therefore, any coronal heating that would otherwise raise coronal temperatures is instead rapidly ducted to plasma at lower temperatures. The radiation losses per particle peak near the middle of the transition region (TR) close to 10^6 K, where transitions with no changes of principal quantum number, such as O vi and other members of, for example, Li-, Be-, B-, and Na-like ions, efficiently emit UV radiation.

Increased heating in the corona therefore leads to larger TR radiative losses predominantly at UV wavelengths, with minor increases in coronal temperature (Woolley & Allen 1950). This physical scenario leads to well-known “scaling laws” for coronal loops close to equilibrium conditions, which are nonlinear in electron temperature (McWhirter et al. 1975; Rosner et al. 1978).

The solar TR plasmas, when in thermal contact with both chromosphere and corona, are therefore sandwiched between two stable thermal reservoirs, but in itself tends to be unstable to modest perturbations. Consequently, little plasma can exist for long at intermediate temperatures near 10^5 K (Mariska 1992). For example, in 1D empirical models, TR plasma spans of order 100 km in height, compared with 1500 km for the stratified chromosphere and many thousands of kilometers in the corona (e.g., see the review by Jordan 1992). Further, it has been known for 7+ decades that static equilibria are impossible by consideration of radiative and classical conductive energy transport alone (Giovanelli 1949).

TR radiation generally emerges in the vacuum UV (λ > 1100 Å) where normal incidence optics can be used, and in this region many space-based instruments have operated since the 1960s. As a consequence of the above considerations, the TR has been a natural focus of observers to focus on the dynamics and overall behavior of TR plasma as it spectacularly reacts to modest changes in conditions above and below. To the observer then, the TR appears very dynamic, akin to the motions at the end of a whip, in response to drivers above and below. The dynamic spectra of TR lines (e.g., Dere et al. 1989) have received an unusual amount of attention compared with their relatively benign chromospheric and coronal counterparts (Mariska 1992).

1.1. The Purpose of the Present Work

In the light of new results of magnetic field measurements above the active corona reported by Ishikawa et al. (2021), we reopen an old debate concerning the magnetic and thermal structures that lead to TR emission. There are two camps of thought.

1. The TR plasma’s bright emission is caused by magnetic field-aligned transport processes, including but not limited to classical heat conduction down from the corona.
2. The TR plasma’s bright emission comes from an “unresolved fine structure” (henceforth “UFS”) in which the coronal energy flux does not contribute significantly to the emission, at least for plasmas below ≈2 × 10^4 K. Instead the energy is supplied by upward directed
mechanical energy, deposited locally and advected and radiated away.

The consequences of resolving this debate extend beyond studies of the TR. There is intense interest in understanding coronal physics as it pertains to the irradiation of interplanetary space with variable UV and X-ray radiation, as well as to the ejection of plasma and magnetic fields. Lines known to form in TR plasma formed under scenario 1. can be used to infer magnetic energy, configurations, and evolution in the overlying corona. TR emission arising from scenario 2 can say nothing about evolving magnetic properties of the corona.

1.2. Field-aligned Transport Models

In favor of models within camp 1, are two facts related to the differential emission measure. This well-known quantity, derived by inversion of observations, can be related to the energy balance, including its transport, across the TR (Jordan 1980). First the shape of this function derived from observations of quiet Sun, coronal holes and active regions is remarkably constant (e.g., Noyes et al. 1970; Jordan 1980; Feldman et al. 2009). This suggests a connection in the transport of energy across the chromosphere–corona transition (Jordan 1992). Second, above \(10^5\) K, the emission measure derived from observations varies as \(T_e^{5/2}\) with \(T_e\) the plasma electron temperature. This result is expected when energy is dominated by field-aligned heat conduction downwards (i.e., a constant conductive energy flux downwards, e.g., Jordan 1980). However, the emission measure structure below \(10^5\) K leads to TR emission that is far brighter than classical models, based on heat conduction, could predict (Kopp & Kuperus 1968). In principle this problem might be partly resolved in “funnel-like” expansion of the magnetic field Gabriel (1976). But in strong field concentrations where expansion has occurred below in the chromosphere, some have asked the question as to where the excess conducted energy goes (e.g., Kopp & Kuperus 1968; Athay 1990). The lack of static solutions identified first by Giovanelli (1949) has suggested to some that the excessively steep temperature gradients implied in classical models leads to dynamical instabilities (e.g., turbulence) which can then transport the conductive heat flux across the atmosphere in a quasi-steady manner. The elementary plasma physics of the consequences of the high conductive flux has been carefully discussed by Ashbourn & Woods (2001). A phenomenological formalism based on eddy diffusion was given by Cally (1990) in which the observed emission measures were used to find parameters of turbulent energy transport downwards to \(10^4\) K. An alternate picture involving steady flows has been invoked by Fontenla and colleagues who added neutral-ion diffusion processes (“ambipolar” diffusion) to develop sophisticated models in a plane-parallel configuration (Fontenla et al. 1990, 1993, 2002). Some have suggested that spicules might arise from effects of this heat flux (Kuperus & Athay 1967; Kopp & Kuperus 1968; Athay 2000).

Athay (1990) proposed that field-aligned transport of conductive energy, when it reaches cool plasma, may account for the emission measures below \(10^5\) K. Athay invokes a highly corrugated (non-horizontal) thermal interface, generated perhaps by the interface between the corona and embedded spicules. In this fashion, large cross-field temperature gradients may transport heat from hot coronal ions into those in the cooler plasma via ion-neutral collisions or anomalous crossfield transport processes (see also Ji et al. 1996; Judge 2008).

1.3. Models for the TR “Unresolved Fine Structures”

In an intriguing series of papers, Feldman has argued that the bright TR emission observed is from structures that are energetically disconnected from the corona (Feldman 1983, 1987, 1998). Given that the thermal conductivities along the magnetic field are many orders of magnitude greater than cross-field values at coronal temperatures, any bundles of magnetic flux that never reach coronal temperatures will remain thermally protected from coronal plasma in which they may be embedded. Qualitative physical interpretations by Dowdy et al. (1986) proposed that much of the quiet solar TR emission we see is not the result of downward energy transport. Instead the structures are a population of “cool loops,” with temperatures up to ca. \(10^5\) K, near the peak of the radiative loss function, in which local mechanical heating from below leads to the observed TR radiative losses. Antiochos & Noci (1986) were able to relate the ideas to definite physical models based upon physical force and energy balance. They argued that cool loops could, under reasonable conditions, explain long-recognized problems associated only with classical heat transport along hot loops. Various authors studied the stability of such solutions (e.g., Cally & Robb 1991; Sasson et al. 2015), raising questions as to the viability of the model. However, this picture received support from the high resolution UV observations from the Interface Region Imaging Spectrograph (IRIS) spacecraft, revealing dynamical closed loop-structures at the solar limb in spectral features formed in the lower TR of the quiet Sun (Hansteen et al. 2014, henceforth “H2014”). The thermal evolution of the loops observed by Hansteen et al. (2014) appears to vary on timescales of a minute or so, comparable to sound crossing times. Thus these emitting structures are not static and instability may not be an issue. In fact these structures are perhaps akin to the proposal of Sasso et al. (2015) in which populations of quasi-static models (those with subsonic speeds) might account for a variety of important observations.

In the UPS picture, the question remains as yet unanswered: how can the emission measure distributions both below and above \(10^5\) K be correlated, as observed, in this “cool loop” picture? Presumably some kind of statistical averaging is invoked. It is certainly true that the cool loops of H2014 are small, effectively below the resolutions of data used for most emission measure analyses, suggesting large numbers of small features will contribute over large areas. The question remains open.

Another question pertains to the nature of TR structures in active regions. In plages surrounding sunspots, the TR emission is on average several times brighter than in quiet regions (e.g., Brueckner & Bartoe 1974). Cool loops seen during the SKYLAB era in active regions (reviewed by Jordan 1976) might suggest that these structures again dominate the TR emission. These appeared most prominently under post-flare conditions. Later results from the VAULT Lo imager (Patsourakos et al. 2007) appeared to show cool loops associated with plages surrounding active regions. However, plages are known to be largely unipolar (Giovanelli 1982). Thus Judge & Centeno (2008) examined the underlying magnetic fields and the morphology of the Lo images, concluding instead that these cannot be cool loops because plages underlying VAULT images are indeed unipolar, as measured using sensitive magnetographs. The authors suggested instead that the TR over plages forms through energy transport from both the chromosphere and corona.
2. Implications of Data from the CLASP2 UV Spectropolarimeter

The first published results from the CLASP2 mission (Ishikawa et al. 2021) focus on the Stokes V profiles of the resonance lines of Mg II as observed primarily in plages. Their results are important for our study of the TR, to include both active and quiet regions. While the bulk of the radiation in the opacity-broadened Mg II h and k lines is emitted from the chromosphere (Ayres 1979), the very cores form in plasma close to $2 \times 10^4$ K in 1D models of Fontenla et al. (1993; P. Judge et al. 2021, in preparation). These line cores can therefore probe magnetic conditions in the lower TR plasma. The calculations of line core formation heights in the 3D dynamical snapshots of Leenaarts et al. (2013) are unfortunately not plotted as a function of electron temperature $T_e$. But when the h and k lines become optically thin because of increased ionization to $\text{Mg}^{2+}$ by electron collisions and not simply the drop in opacity when $\text{Mg}^+$ is the dominant ion, then the $\tau = 1$ surface must occur close to $2 \times 10^4$ K. The contours of the $\tau = 1$ surfaces of Mg II k in Figure 1 of Leenaarts et al. (2013) lie close to the $2 \times 10^4$ K temperature cutoff shown, seeming to confirm this picture.

Judge & Centeno (2008) studied the morphology and the underlying photospheric magnetic environment of VAULT $\alpha$ data. They argued that the cool loop solutions cannot be important as active region TR contributors for several reasons. First, the photospheric magnetic fields underlying the bright and curious $\alpha$ structures in the images appear unipolar. The unipolar fields measured using the Kitt Peak Vacuum Telescope (KPVT), had an average flux per resolution element of $\approx 1.4 \times 10^{18}$ Mx. In contrast, the smallest detectable flux concentrations of opposite sign to the major polarity were $1.3 \times 10^{16}$ Mx ($2\sigma$ statistical level). Although it is possible to hide the magnetic footpoints of loops if they are below this level, to do so the Sun would have to arrange such that essentially no flux of opposite polarity could be detected over an entire plage. One might expect, based upon the disorder associated with magnetoconvection, that patches of opposite polarity, if present with sufficient flux, should be visible.

Judge & Centeno (2008) also argued that the morphology and spatial alignment of the $\alpha$ “fibrils” arranged themselves more like little comets, with tails somehow aligned over large areas. This situation is anything other than that envisaged for the quiet Sun (Dowdy et al. 1986).

The CLASP2 data sample magnetic fields directly at the base of the solar TR. Such plasma is many orders of magnitude lower in pressure than, and $\approx 2$ Mm above, the photosphere where previous magnetic measurements have been made. The Stokes V profiles detected using CLASP2 in the observed plages and active network are all of the same sign. In any model of the Zeeman effect (Ishikawa et al. 2021 interpreted the data quantitatively using the weak field approximation), this can only mean unipolar line-of-sight (LOS) fields. The CLASP2 results are consistent with the physical picture of magnetic field decreasing in strength from their origins beneath the solar surface.

Following Judge & Centeno (2008), in Figure 1 we attempt to reveal possible alignments between the comet-like Mg II fibril structures at the edges of the plage and in the network to the west, with overlying coronal structure. A 1:1 correspondence between the two is not seen, but this is as expected given the disparate lengths and heights of the two kinds of structures. The Mg II “fibrils” are seen only at the edges of the plages. This is perhaps due to the dimmer background intensities over the quieter regions, and/or the denser populations and hence confusion expected over the central area of plages. Nevertheless, given the different projections of the chromospheric and coronal structures, the overall alignment is remarkable in the underlying organized directions along which magnetic structures can be traced.

We conclude that the evidence for the connection of bright plages and associated bright network emission in TR lines to the corona is definitive.
Let us transform the limb loops to disk center in a statistical sense. The geometry at the limb means that features of median height $h$ will be visible if it lies within a line-of-sight length

$$\ell \approx \sqrt{2R_s h} \approx 50 \text{ Mm.}$$

The equivalent area observed at disk center in the quiet Sun containing just 1 dynamic loop is then $\ell \cdot s \approx 700 \text{ Mm}^2$. The area of a single supergranule is roughly $700 \text{ Mm}^2$. We should expect to observe one of these bright loops per supergranule at any given time.

The total radiative flux from these features, assuming they are optically thin, is independent of viewing angle. Using the reported median intensity of UFS at the limb of $I = 40 \text{ DN s}^{-1}$ (H2014), we would compute a mean disk center intensity $\bar{I}$ distributed over area $\ell \cdot s$ of

$$\bar{I} \approx AI/(\ell \cdot s) \approx 0.003I.$$

H2014 give a physical conversion of 215 erg cm$^{-2}$ sr$^{-1}$ s$^{-1}$ for each DN per second, so that $\bar{I} \approx 8600 \text{ erg cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$. Taken together, we find that the summed intensity of all the limb cool loops when viewed at disk center in the 1400 Å channel of the SJI is then

$$\bar{I} \approx 26 \text{ erg cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1},$$

which includes both lines of Si IV. Perhaps some of the limb emission is hidden behind the extra opacity near 1400 Å along such long lines of sight. In the Discussion section below, we relate the limb lines of sight to disk center and address attenuation by bound-free opacity of neutral silicon.

What might these structures then contribute to the quiet Sun intensities seen at disk center? To avoid intercalibration issues, we examined disk center data from IRIS acquired with the 1400 Å SJI channel listed in Table 1. These sample various levels of sunspot activity from nearly maximum sunspot number of over 100 down to four per month. Clearly the mean disk center intensities vary greatly depending on the magnetic flux at disk center, for which the monthly SSN is a crude measure. Even though Sun center is often used to observe disk center, for which the monthly SSN is a crude measure. Even though Sun center is often used to observe disk center, for which the monthly SSN is a crude measure.

We will require two more statistical quantities—the number of cool loops visible at any time per unit arc length along the limb, and their apparent area in the plane of the sky. These quantities are not specified in the original paper but inspection of the limb and inside-limb images (their Figure 1) indicates to us that there are at most three such loops visible over the quiet Sun limb every arcminute of arc length (i.e., one such loop every length $s \approx 14 \text{ Mm}$). While this number is subject to large uncertainties given the published analysis, movie S1 of H2014 seems to confirm this rough number. Certainly in the data shown, the number cannot be twice this value for the regions shown. The loops shown in their Figure 1 indicate a median loop area $A$ of $\approx 4 \cdot 0.5 = 2 \text{ Mm}^2$. 

IRIS observations prove that a large fraction of the solar TR emission is due to low-lying, relatively cool, loops having no thermal contact with the corona.

First we examine the actual data analyzed by H2014, listed along with other data listed in Table 1. The data of H2014 were data taken at the solar limb, from 2013 October to December, a period near the maximum of solar cycle 24. From histograms of properties of these dynamic loops (their Figure 2), we adopt the following numbers for analysis. The median values of apparent length, height above limb, and intensity (in DN s$^{-1}$) are 4 Mm, 2 Mm, and $\approx 40 \text{ DN s}^{-1}$, respectively. A distribution of lifetimes is not shown, but we assume that the time series shown in Figure S1 are typical, and estimate median lifetimes of order 60 s. This number is mentioned in their text as

... loops appear to be lit up in segments, with each segment only being visible for roughly a minute.

Table 1
IRIS 1400 Å Slitjaw Image Sequences

| Start Time UT | $\mathcal{N}_{exp}$ | $X$ | $Y$ | Exp. | Cadence | $\text{DN s}^{-1}$ | $\bar{I}$ | SSN |
|---------------|---------------------|-----|-----|------|---------|-------------------|--------|-----|
| 2013-10-02 06:47:23.5$^a$ | 100 | 1 | 948 | 2.0 | 11.8 | 19.5 | 2093 | 107 |
| 2013-12-09 23:33:46.8$^a$ | 128 | 970 | 30 | 8.0 | 18.9 | 75.8 | 2038 | 108 |
| 2013-09-13 06:36:51.6 | 300 | -2 | 7 | 2.0 | 3.8 | 24 | 2560 | 105 |
| 2013-12-01 00:42:38.7 | 550 | -3 | 3 | 2.0 | 3.8 | 15.3 | 1643 | 108 |
| 2017-04-03 07:40:01.0 | 640 | -2 | 4 | 15.0 | 16.9 | 17.1 | 245 | 25 |
| 2019-07-05 09:39:36.5 | 590 | 2 | -6 | 8.0 | 11.2 | 4.2 | 112 | 4 |
| 2019-07-08 09:49:21.4 | 600 | 2 | -6 | 8.0 | 11.2 | 4.4 | 116 | 4 |
| 2019-07-11 17:19:23.4 | 128 | 1 | -2 | 8.0 | 37.4 | 3.2 | 85 | 4 |

Note.
$^a$ These are two of the data sets examined by Hansteen et al. (2014). $\mathcal{N}_{exp}$ is the number of slitjaw frames obtained, $X$ and $Y$ are coordinates of the center of the frames in arcseconds, exposure time (exp.) and cadence are in seconds, the mean intensity $\bar{I}$ is in erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$. SSN is the monthly sunspot number compiled by Space Weather Services.

### 3. Analysis of IRIS Data of the Quiet Sun Transition Region

Here we examine more IRIS data from the 1400 Å channel of the Slit Jaw Imager (SJI). We will conclude that indeed dynamic cool loops found by H2014 contribute to the quiet Sun’s emission in the resonance lines of Si IV, formed in the middle TR near 10$^4.8$ K. However, we will also find that the statistics of dynamical cool loops identified by H2014 indicate that these structures contribute far less that 50% to the emission from the quiet Sun. This stands in contrast to the claim by H2014:

IRIS observations prove that a large fraction of the solar TR emission is due to low-lying, relatively cool, loops having no thermal contact with the corona.

The equivalent area observed at disk center in the quiet Sun containing just 1 dynamic loop is then $\ell \cdot s \approx 700 \text{ Mm}^2$. The area of a single supergranule is roughly 700 Mm$^2$. We should expect to observe one of these bright loops per supergranule at any given time.

The total radiative flux from these features, assuming they are optically thin, is independent of viewing angle. Using the reported median intensity of UFS at the limb of $I = 40 \text{ DN s}^{-1}$ (H2014), we would compute a mean disk center intensity $\bar{I}$ distributed over area $\ell \cdot s$ of

$$\bar{I} \approx 0.003I.$$
Are these SJI intensities comparable to previous measurements of “average quiet Sun” intensities of TR lines at disk center? The “averages” are rather poorly defined because the rms spatial variations in Si IV lines are on the order of the mean values (Athay & Dere 1991). Nevertheless, the SUMER atlas of the quiet Sun has $I \approx 260 \text{ erg cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$ (Curdt et al. 2001). Brekke’s atlas of HRTS data has $I \approx 170$ (Brekke 1993). All these estimates are at least an order of magnitude larger than the summed contributions of the limb dynamic loop intensities, using the above parameters.

To check this analysis, we filtered the disk center IRIS data in time using a filter centered at 120 s, twice the lifetime of the dynamics loops. The cadences of the time series SJI frames analyzed here and by H2014 are between 3.8 and 18.9 s. Low-pass data were generated using a Gaussian filter to remove dynamic variations on timescales of 1 minute. The resulting low-pass time series was then subtracted from the initial data to produce a high-pass time series and the low- and high-bandpass data sets compared. Typical results for data obtained in 2013 are shown in Figure 2. The data obtained near sunspot maximum, show features at low frequencies with intensities up to $2 \times 10^4 \text{ erg cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$. The high frequency component has features only as bright as 800 erg cm$^{-2}$sr$^{-1}$s$^{-1}$. Figure 3 shows similar data obtained close to solar sunspot minimum (from 2013 September 13 near to sunspot maximum. The middle panel shows the intensity in all features where the dominant power is at frequencies below 8 mHz (a period of 120 s). The right power shows the absolute value of power at high frequencies (>8 mHz). The morphology is slightly different in the HMI image because of the difference in timing of the order of tens of minutes between the HMI and IRIS time series of observations. The area shown is about the same as one supergranule. This is an area considered as “quiet” even though it was obtained when the Sun was relatively active.

Figure 3. A figure identical to Figure 2 except that the data were acquired close to solar minimum conditions, it can be considered as “very quiet” Sun. “Cool loop” (dipolar) contributions are present near the top left of each panel, other areas of emission are more unipolar. Color scales are the same as for Figure 2. The lines help to reveal the precision of the alignment of the images.

4. Discussion

4.1. The Active Solar Transition Region

The conclusions of the analyses of Judge & Centeno (2008) and Ishikawa et al. (2021) appear unassailable. The active region plages consist of bright emission from unipolar magnetic structures threading from the chromosphere (or lower, perhaps) into the overlying corona, as inferred from Figure 1. Readers may be surprised in that the TR associated with active regions is itself active (dynamic), with much evidence for magnetic reconnection (e.g., Dere et al. 1989). However, it should be remembered that reconnection will occur in unipolar

Figure 2. The left panel shows an HMI magnetogram obtained several minutes before the frequency-filtered 1400 Å slitjaw images in the right panels were obtained at disk center on 2013 September 13 near to sunspot maximum. The middle panel shows the intensity in all features where the dominant power is at frequencies below 8 mHz (a period of 120 s). The right power shows the absolute value of power at high frequencies (>8 mHz). The morphology is slightly different in the HMI image because of the difference in timing of the order of tens of minutes between the HMI and IRIS time series of observations. The area shown is about the same as one supergranule. This is an area considered as “quiet” even though it was obtained when the Sun was relatively active.
magnetic fields, which define the overall structure. Within these unipolar fields, tangential discontinuities (Parker 1988, 1994) are expected that can readily lead to reconnection not of the strong unipolar but the transverse components. This conclusion will modify some conclusions in the extensive literature (e.g., Mariska 1992, and later work).

The consequences of the work of Ishikawa et al. (2021) are particularly interesting for applications to understand the origin of flares, CMEs, and other phenomena associated with the slow storage and sudden release of magnetic energy in the corona (Gold & Hoyle 1960). Measurements of magnetic fields in the lines of Mg II can be used to probe the magnetic structure and evolution as active regions evolve and release magnetic energy, plasma, radiation, and perhaps magnetic helicity into interplanetary space.

4.2. The “Quiet” Sun

The main results of our study of quiet regions at disk center are based upon Figures 2 (a close-up of data from 2013 September 13 with a sunspot number of 105) and 4 (a larger view including TR and coronal AIA data from Solar Dynamics Observatory; SDO). For comparison, and because the Sun center intensities measured by IRIS are a strong function of monthly sunspot number, Figure 3 shows similar data covering about four supergranule areas when the monthly sunspot number was four. In all cases but one, the brightest 1400 Å emission lies directly above the HMI magnetograms of one polarity. The exception is the bipolar region of Figure 3 close to (X, Y = −17, +20) where emission at both high and low frequencies are seen spanning the opposite polarity regions. In the more active disk center data (Figure 4), the lower two panels reveal coronal structures: the He II channel formed near 10^5 K shows structure clearly associated with the Fe IX/X 171 Å coronal brightness. This again suggests an energetic connection of a unipolar region to the overlying corona. The spatial relationships are far from 1:1 because the coronal emission is spread along magnetic fields by efficient electron heat conduction.

Figure 4. Various data obtained on 2013 December 1 close in time to the first IRIS image of a sequence obtained at disk center. The area shown is roughly that of three supergranules. Synoptic views reveal this to be a quiet region, although with a monthly SSN of 108, the 1400 SJ1 data are quite bright compared with solar minimum conditions (Table 1). The images are coaligned to within a second of arc. Some of the patches of negative polarity are marked with boxes for reference between images. The HMI magnetogram is saturated at ±40 Mx cm\(^{-2}\), the strongest flux concentrations range between −150 and +100 Mx cm\(^{-2}\).
But to what extend might there be direct evidence that the corona and the IRIS 1400 Å emission are energetically connected? The very different angular resolutions (0.32” for IRIS versus 1” for SDO) preclude identifying the small bright IRIS structures with the overlying atmosphere. However, the white boxes in Figure 4 highlight some of the stronger regions of opposite polarity. Two such boxes (X = -6, Y = 7 and X = 11, Y = 22) also include nearby positive polarity and so low-lying small loops might connect these regions. Indeed there is a small amount of Si IV 1400 Å emission present but this does not span from positive to negative polarity. In these data there is therefore little indication of cool loop emission. This is as we expected on the basis of statistics of limb data obtained during the same season derived above (perhaps just one dynamic cool loop per supergranular area).

Our results for quiet regions appear to be self-consistent, with the possible exception of the N polar sequence of frames acquired on 2013 October 2, with mean intensities equal to those of the scan on 2013 December 9 at lower latitudes. Perhaps these bright loops are related to the roots of extended polar plumes, which are magnetically multipolar, relatively dense, and themselves bright.

Here we find that the magnetic and IRIS data indicate that quiet Sun TR emission is dominated by plasma connected to the corona, which, under typical coronal conditions, must lie near 2000 km above the photosphere. Spicular emission in TR lines will appear dominant at the limb because they are long and via Equation (1) they are many times more abundant and therefore on average appear brighter than at disk center. This then raises the question, why then is the proposed bright TR plasma connected to the corona not seen everywhere at the solar limb, for example, in the data from Figure 1 of H2014?

We recall that absorbers at 1400 Å are formed near heights of 0.8 Mm, where τ = 1 vertically at disk center (opacity from neutral Si; Vernazza et al. 1981). At the limb, we can find a lower limit to the projected height at which the τ = 1 surface will arise assuming the atmosphere to be exponentially stratified. The density scale height ℎ_ despre is in the mid chromosphere of Vernazza et al. (1981) is about 150 km. Then, the limb path length tangential to the limb is ℓ ∝ \sqrt{2R_☉ ℎ_ despre}, which is about 15 Mm, 100 times ℎ_ despre (Equation (1)). The τ = 1 surface will be found at a projected height above the disk center height of 800 km, when

\[
ℓ \cdot \exp(-z/ℎ_ despre) = 1, \quad \text{so that}
\]
\[
z = 1400 \text{ km.} \quad (4)
\]

However, in these 1D models this height is limited not only by the height dependence of the density, but also by temperature since the coronal temperature rises to 1 million K near heights of 2000 km at disk center. Thus z is perhaps at most 1200 km in these models, and so any limb emission at heights ≤800 + 1200 = 2000 km will be attenuated. Given the presence of dynamic extensions higher than the hydrostatic scale heights (clearly shown in Figure 1 of Judge 2015 based upon data from the Bifrost code of Gudiksen et al. 2011), this is perhaps a lower limit. So this is a minimal estimate of the attenuation of 1400 Å radiation at the limb. Brighter TR emission lies below the 2000 km height (see the scaling laws for coronal pressure of McWhirter et al. 1975; Rosner et al. 1978 and the sequence of models A-F of Vernazza et al. 1981, for example). Not only this, but the presence of spicules and other cool material and the dynamic nature of the chromosphere in simulations means that the bulk of the bright TR emission at the footpoints of the corona will be mostly absent in the images analyzed by H2014.

There is qualitative agreement of the visibility of loops observed with IRIS and those in the numerical modeling work of H2014. However, the initial mixed polarity state used in these calculations maximizes the number of low-lying loops. Therefore these modeling efforts cannot be used to refute our conclusions.

Finally, CLASP2 data analyzed by Ishikawa et al. (2021) include regions of network (points d and e marked in their Figures 1 and 3, and in this paper as small black circles in Figure 1). The Zeeman signals seen in the Mg II h and k line cores at these two locations are compatible with zero LOS magnetic field. The authors showed that these points are of opposite polarity in the photosphere with LOS average flux densities of ≈220 Mx cm⁻². Outside of the cores, the Mg II lines yielded 160 and 80 Mx cm⁻² LOS flux densities in the lower and middle chromosphere, respectively. Ishikawa et al. (2021) speculate that the nondetection may arise because associated loops may lie beneath the formation height of the line cores, because the magnetic flux densities lie below the Zeeman detection limit of ≈10 Mx cm⁻², or because the fields are perpendicular to the LOS. Here we can rule out the last possibility because local verticals at these points are inclined at ≈43° to the LOS, and any locally horizontal connecting loop structure between them would have to have as strong Zeeman component along the LOS as a vertical component. Until higher quality data and/or inversion scheme can be acquired, the precise meaning of these network observations for the conclusions of the present paper will remain unclear.

In conclusion, the bulk of TR emission from quiet and active regions on the Sun does not arise from UFS, but from a magnetically guided thermal interface between the corona and the chromosphere. This interface is probably highly corrugated, geometrically (see Figure 1, also, e.g., Athay 1990; Ji et al. 1996; Judge 2008).

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