AN EXPLANATION OF THE SOLAR TRANSITION REGION

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ABSTRACT

Prompted by high-resolution observations, I propose an explanation for the 40+ year old problem of structure and energy balance in the solar transition region. The ingredients are simply cross-field diffusion of neutral atoms from cool threads extending into the corona, and the subsequent excitation, radiation, and ionization of these atoms via electron impact. The processes occur whenever chromospheric plasma is adjacent to coronal plasma, and are efficient even when ion gyrofrequencies exceed collision frequencies. Cool threads—fibrils and spicules perhaps—grow slowly in thickness as a neutral, ionizing front expands across the magnetic field into coronal plasma. Radiative intensities estimated for H Lyα are within an order of magnitude of those observed, with no ad hoc parameters; only thermal and geometric considerations are needed. I speculate that the subsequent dynamics of the diffused material might also explain observed properties of trace elements.

Subject headings: Sun: atmosphere — Sun: chromosphere — Sun: corona — Sun: magnetic fields — Sun: transition region

1. INTRODUCTION

The upper transition region (TR), plasma with electron temperatures in the range \( 2 \times 10^5 \text{ K} \leq T_e \leq 10^6 \text{ K} \), is adequately described by field-aligned thermal conduction down from the corona. The lower TR (\( 10^4 \text{ K} < T_e < 2 \times 10^5 \text{ K} \)) is inadequately understood (Gabriel 1976; Jordan 1980). Models dominated by field-aligned heat conduction produce too little emission from the lower TR by orders of magnitude, a problem already evident in work by Athay (1966). Neither could such models radiate away the downward-directed conductive flux of \( F_{\text{cond}} \sim 10^4 \text{ ergs cm}^{-2} \text{ s}^{-1} \) (e.g., Jordan 1980; Athay 1981). Fontenla et al. (2002 and earlier papers in the series, hereafter FAL02) showed that energy balance can be achieved through field-aligned (1D) diffusion of neutral hydrogen and helium atoms. The neutral atoms diffuse into hot regions, radiate away much of the coronal energy, and can reproduce the H and He line intensities.

The problem might be considered by some as solved, in principle. But there exists the serious and nagging problem of the peculiar spatial relationship between the observed coronal, TR, and chromospheric (Feldman 1983). Feldman and colleagues have since analyzed many observations, concluding that the lower TR is thermally disconnected from the corona (e.g., Feldman et al. 2001 and references therein). Yet Fontenla et al. (1990) declared that “the above [i.e., their] scenario explains why (as noted by Feldman 1983) the structure of the transition region is not clearly related to the structures in the corona.” That the debate still rages is evidenced by advocates for “cool loop” models in which lower TR radiation originates from loops never reaching coronal temperatures and having negligible conduction (Patsourakos et al. 2007 and references therein, hereafter PGV07). Here I propose a different scenario, prompted by new data and analyses which show that neither cool loops nor field-aligned processes adequately describe the Lyα chromospheric network. I speculate that other TR lines might also be accounted for.

2. A NEW SCENARIO

Lyα network emission, at 0.3° resolution, appears mostly as threads of relatively uniform intensity, of 5–10 Mm length and 1 Mm diameter (PGV07). PGV07 argued that “the different appearance the TR has in the quiet Sun [i.e., network] is suggesting that the bulk of its emission comes from structures other than the footpoints of hot loops.” Convolved Lyα images from PGV07 appear to correspond to those seen in many other TR lines at lower resolution (e.g., Curdt et al. 2001). Judge & Centeno (2008) showed, using magnetic field measurements from Kitt Peak, that much of the network Lyα emission originates in long spicule-like structures lying along the lowest few Mm of magnetic field lines extending into the corona, but that plage emission may correspond to the thin footpoints as suspected by PGV07 and modeled by FAL02. Even in plages, on subarcsecond scales, field-aligned threads of cool plasma (fibrils, spicules), extend into the low corona forming nonplanar thermal interfaces between hot and cool plasma (Berger et al. 1999). Prompted by these data, I examine the diffusion of neutral particles into the corona, across magnetic fields (following a suggestion by Pietarila & Judge 2004).

Consider a straight cylinder of cool, partially ionized material embedded in a hot corona, of radius \( r_L \). Length \( L \gg r_L \) of the tube contains cool plasma in contact with the hot corona. The magnetic tube is of length \( L \gg r_L \), mostly containing coronal plasma. Tube parameters are given in Table 1. Note that the neutral density greatly exceeds other densities. The chosen geometry is typical of values found by PGV07, and thermal parameters are typical of the quiet Sun. The plasma is assumed to be in a low plasma-β regime.

2.1. Initial Diffusion, Relaxation, Radiation

Imagine an injection of dense neutral material into the tube footpoint by some chromospheric process. The tube surface acts as a semipermeable membrane. Neutral particles travel freely between collisions, but ions gyrate about magnetic field lines with gyroradii orders of magnitude smaller than mean mean.

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2 I do not adopt the higher temperatures of cool loops used by PGV07, because here the corona and dynamics supply all the energy for Lyα emission.
free paths (mfps; Table 2). Ions and electrons are essentially frozen to field lines, but neutrals can diffuse across field lines almost as efficiently as along them, and find themselves impacted by hot electrons and protons. Table 2 lists timescales for kinetic processes for a “cool” hydrogen atom embedded in a hot corona of $T = 10^6$ K, using data from Allen (1973), Hansteen et al. (1997, hereafter HLH97), and Gilbert et al. (2002). A hydrogen atom crossing the boundary encounters other diffusing hydrogen atoms and hot protons and electrons. Statistically, the first interaction is a collision with a coronal proton, involving the exchange of energy and ($\sim 50\%$ of the time) an electron (charge transfer, CT). Charge transfer yields an exchange of momentum (180° change in direction) but little exchange of energy (e.g., Osterbrock 1961). The kinetic energy exchanged is $\sim 2kT_p$, shared between them after two such collisions (I use subscript $h$ to denote hot and $c$ cool plasma). The CT cross section is roughly $6 \times 10^{-3} \text{ cm}^2$.

From kinetic theory, the flux density of neutral hydrogen atoms initially crossing the boundary into the corona is $\frac{2n_b v_b}{\pi} \sim 2 \times 10^{16} \text{ particles s}^{-1} \text{ cm}^{-2}$, where $v_b = (8kT_p / \pi m)^{1/2}$. The kinetic energy per “hot” proton is $\frac{1}{2} kT_p$, which is shared roughly equally after two CT collisions with a neutral, producing a population of $n_b \ll n_e$ “warm” neutrals with $T \sim T_p / 2$. After a few, say $m$, more collisions (time $m\tau_{CT}$ later), all the proton energies are the larger of $\frac{1}{2} kT_p / 2^m$ and $\frac{1}{2} kT_p$, and $m n_b$ of the $n_e$ neutrals have suffered a proton impact. (A time of $n_b / n_e = 100$ times $\tau_{CT} \approx 1 \text{ s}$ is required before all neutrals have been impacted.) The warm neutrals relax via collisions with the cool neutrals.

The initial electron evolution is largely determined by inelastic collisions with hydrogen: each hot electron typically has sufficient energy to excite and ionize 5 neutral hydrogen atoms, which takes $\sim 7 \tau_{te} \sim 0.6 \text{ s}$. (Electron-electron collision times are $\approx 0.08 \text{ s}$.) The electrons lose energy $\epsilon = 5 n_e (I + E) e$ per unit volume at the rate

$$\epsilon \approx \frac{5 n_e (I + E) e}{7 \tau_{te}} \approx 0.13 \text{ ergs cm}^{-3} \text{ s}^{-1},$$

where $\Delta$ is the sheath thickness at time $\tau (60 \tau_{CT})$, and $v^{\text{diff}}_e = \Delta / \tau$ is the diffusion speed. For a random walk, $\Delta \approx \frac{1}{7} (60 \tau_{CT}) v_e \approx 3.3 \times 10^4 \text{ cm}$, for warmed neutrals $\Delta_e \approx 1.8 \times 10^4 \text{ cm}$ ($v^{\text{diff}}_e = 0.57$ and $v^{\text{diff}}_e = 3.2 \text{ km s}^{-1}$ respectively; the factor $\frac{1}{7}$ accounts for the random direction of the “walk”). As a rough estimate, I take $v^{\text{diff}}_e \approx 3 \tau_{te} \approx 3 \times 10^4 \text{ cm s}^{-1}$.

Thus, $f$ is initially just a fixed fraction of the local coronal energy density multiplied by the diffusion speed. The specific intensity $I$ equals $f / \pi$ when the line is optically thick and all the radiation scatters away from the solar surface. (Photon mfps for Lo in the sheath are just $10^2 \text{ cm}$. This estimate of $f$ is a factor of 100–300 below measured values of $(1.8-5.6) \times 10^4 \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ in active network threads (PGV07) and 30 below average network intensities (Vernazza & Reeves 1978). But, as will be made clear below, this is an underestimate. Similar estimates of intensities for H Ly$\beta$ and the 584 Å line of He I, relative to Ly$\alpha$, are quite reasonable, recognizing that Ly$\beta$ is optically thick across the sheath.

### TABLE 1

| Quantity | Inside (Cool) | Outside (Hot) |
|----------|--------------|---------------|
| Radius $(r_c)$ (cm) | $5 \times 10^7$ | ... |
| Length $(l_c)$ (cm) | $5 \times 10^4$ | $\geq 10 l_c$ |
| $T$ (K) | $10^7$ | $10^6$ |
| $n_p$ $(\text{cm}^{-3})$ | $8 \times 10^{20}$ | $\approx 10^8$ |
| $n_e$ $(\text{cm}^{-3})$ | $n_e/40$ | $4 \times 10^9$ |
| $p$ $(\text{dyn cm}^{-2})$ | 0.11 | 0.11 |
| Magnetic field strength $B$ (G) | 10 | 10 |
| $B^2/8\pi$ $(\text{dyn cm}^{-2})$ | 3.8 | 3.8 |

### TABLE 2

| Plasma Conditions |
|--------------------|
| Quantity | Value | Scaling | Notes |
|----------|-------|---------|-------|
| Initial corona: |
| $T_e (K)$ | 10$^6$ | |
| $n_e$ $(\text{cm}^{-3})$ | $8.0 \times 10^8$ | |
| $n_p$ $(\text{cm}^{-3})$ | $4.0 \times 10^7$ | |
| $p$ $(\text{cm}^{-3})$ | $1.1 \times 10^4$ | |
| $B$ (G) | 10 | |
| $\beta$ | $2.8 \times 10^{-2}$ | |
| $\omega_p$ $(\text{s}^{-1})$ | $9.6 \times 10^9$ | |
| $r_{\text{H}}$ (km) | $1.5 \times 10^{-3}$ | |
| $\tau_{\text{H}}$ (s) | $1.6 n_e^{-1/2}$ | |
| $\omega_p\tau_{\text{H}}$ | $1.5 \times 10^3$ | |
| $\tau_{\text{H}}$ (s) | $5.0 \times 10^{-2} n_e^{-1/2}$ | |
| Chromospheric tube: |
| $T_e (K)$ | $8.0 \times 10^4$ | | |
| $\nu$ $(\text{km s}^{-1})$ | 13 | | $T_{1/2}$ |
| $n_e$ $(\text{cm}^{-3})$ | $10^4$ | | |
| $\tau_{\text{H}}$ (s) | $1.4 \times 10^{-2} n_e^{-1/2}$ | | |
| Hot protons impacting hydrogen atoms: |
| $\tau_{\text{H}}$ (CT) (s) | $1.0 \times 10^{-2} n_e^{-1/2}$ | | 1 |
| H atom mfp (km) | $6.5 \times 10^{-2} n_e^{-1/2}$ | | |
| Cool hydrogen atoms impacting protons: |
| $\tau_{\text{H}}$ (CT) (s) | $8.0 \times 10^{-3} n_e^{-1/2}$ | | |
| Proton mfp (km) | $5.8 \times 10^{-3} n_e^{-1/2}$ | | |
| $\omega_p\tau_{\text{H}}$ | 7.7 | | |
| Hot electrons impacting H atoms: |
| $\tau_{\text{H}}$ (s) | $9.5 \times 10^{-2} n_e^{-1/2}$ | | 2 |
| $\tau_{\text{H}}$ (s) | $8.2 \times 10^{-2} n_e^{-1/2}$ | | 3 |
| $\tau_{\text{H}}$ (s) | $4.0 \times 10^{-1} n_e^{-1/2}$ | | 4 |

Notes.—(1) CT = charge transfer. (2) Excitation of $n = 2$ level. (3) Ionization. (4) Radiative recombination.

$\tau_{\text{H}}$ refers to the time taken for a particle of type $b$ to be impacted by a sea of particles of type $a$, except where noted.
2.2. A Multifluid Calculation

To examine the evolution at later times, multifluid equations for conservation of mass, momentum, and energy were solved as functions of time and distance across the field lines following Schunk (1977) and HLH97. Just electrons, protons, and neutral hydrogen atoms were treated. Cartesian geometry is used because the diffusion region is much thinner than the tube. I assume that electrons are strongly tied to protons, so that their densities and fluid velocities are equal \( n_e = n_p, \ u_e = u_p; \) net charge and electrical currents are neglected. The conservation equations used for mass, momentum, and energy density for the fluid of species \( s \) are

\[
\frac{\partial n_s}{\partial t} + \frac{\partial}{\partial x} (n_s u_s + d_s^x) = \frac{\partial n_s}{\partial t},
\]

\[
m_s \frac{\partial n_s u_s}{\partial t} + \frac{\partial}{\partial x} (m_s n_s u_s^2 + p_s + d_s^u) + F = \frac{\delta M_s}{\delta t},
\]

\[
\frac{\partial E}{\partial t} + \frac{\partial}{\partial x} [u(E_s + p_s) + d_s^e] = \frac{\delta E}{\delta t} + Q - L.
\]

No conservation equation is used for the heat flux since here it is treated as \( d_s^e \) using the mfp approximation. Above, \( F \) is a body force term (gravity, Lorentz force for example), \( E_s = \frac{4}{3} n_s k T_s + \frac{2}{3} m_s n_s u_s^2; \ p_s = n_s k T_s, \) and the \( \delta \) terms are nonlinear collisional terms. \( Q \) and \( L \) are the energy gains and losses respectively, where I adopt \( Q = 1.67 \times 10^{-2} n_n n_p e^{-4/3} \) ergs \( \text{cm}^{-3} \text{s}^{-1} \) to maintain a chromosphere against losses \( L \) (HLH97), and \( L \) includes latent heat and Ly\( \alpha \) radiative losses computed explicitly from the collisional terms.

The diffusion terms \( d_s \) (not included by HLH97, except for the heat flux) require care especially for the dynamics of the proton fluid. For individual protons and electrons, the momentum equations are dominated by the Lorentz force. Their cross-field motion on timescales short compared with collision times is circular with frequency \( \omega_e = e B / m_e. \) On longer timescales the summed (fluid parcel) momenta can change only after a collision. The net effect of the Lorentz force is thus to limit the cross-field displacement of charged particles to a single gyroradius \( r_g = v / \omega_e \) in collision time \( \tau \) instead of the collisional mean free path \( \lambda_c = v / \tau. \) Thus, a simple recipe for calculating cross-field transport via the fluid equations is to set both \( F \) and \( \partial p_s / \partial x \) terms to zero in the proton momentum equation, and modify the \( d_s^u \) terms to account for the reduced displacements. Field-free diffusion is described by equations (4.41), (4.46), and (4.52) of Gombosi (1994):

\[
d_s^e = - \frac{1}{3} \lambda_* \frac{\partial}{\partial x} (n_s u_s), \quad d_s^M = - \frac{1}{3} \lambda_* \frac{\partial}{\partial x} (m_s n_s u_s),
\]

\[
d_s^E = - \frac{\pi}{12} \lambda_* \frac{\partial}{\partial x} (n_s m_s u_s^2).
\]

For charged particles, \( \lambda_* \) must be replaced by \( \lambda_* = \lambda_c / (1 + \omega e \tau), \) following the above argument; see Braginskii [1965], eqs. [4.37], [4.40]. Note that, written in terms of \( T_s, \) \( d_s^E \) yields the widely used “Spitzer” thermal conductivity parallel to the field, and the ion-dominated conductivity perpendicular to the field. The net effect for \( \omega_e \tau > 1 \) is that only the neutral fluid diffuses efficiently across the field; the charged fluid evolves mostly via the collisional coupling to the neutrals (via \( \delta M / \delta t \)), and to a lesser degree to the small \( d_s \) terms.

The variables \( (n_s, u_s, E_s) \) for electrons, protons, and neutral H atoms, functions of \( (t; x) \), were initialized according to Table 1. Only 7 variables were solved since it is assumed that \( n_e = n_p \) and \( u_e = u_p; \) net charge and electrical currents are neglected. The equations were integrated in time using MacCormack’s method to include the collisional terms (Griffiths & Higham 1999). For the first three points near \( x = 0 \), the variables were held fixed to their initial values, maintaining the same chromospheric conditions there. Figure 1 shows conditions several seconds after the beginning of the diffusion process. Pressure gradients drive neutrals into the corona against friction forces; thus the diffusion speed, measured by tracking the steep temperature rise, is \( \approx 0.8 \text{ km s}^{-1} \), far below the thermal speed. The computed flux density of Ly\( \alpha \) \( \approx 5 \times 10^{6} \) ergs cm\(^{-2}\) s\(^{-1}\), and is roughly constant in time. It is some 10 times higher than the simple kinetic result above, because of the nonlinear dynamics: (1) the densities become higher in the corona, (2) flow energy is converted to heat, and (3) the Ly\( \alpha \) losses/latent heat ratio is higher (the photons are created at electron temperatures lower than the initial coronal temperature). \( I \) is computed to be just a factor of 10–30 below observed active network thread intensities, and 3 below average network intensities.

A calculation with twice the coronal density, more appropriate for active network, yields smaller diffusion speeds and Ly\( \alpha \) fluxes which are just 1.7 times higher. EUV/X-ray coronal intensities scale with (density)\(^2\), and so would be a factor of 4 brighter. This nonlinear relationship is an important property of the calculations.

3. DISCUSSION, SPECULATIONS

Based on observations of spicules and other fine, threadlike structures on the solar disk, it is clear that nonplanar thermal interfaces exist at the base of the corona, and that the morphology of the TR emission from such interfaces cannot be explained by field-aligned particle transport at the base of coronal loops, in contrast to the claims by Fontenla et al. (1990). The picture proposed here uses unspecified mechanisms in the chromosphere to maintain a reservoir of cool mostly neutral plasma directly adjacent to hot coronal plasma. The cylindrical geometry, inspired by observations, presents a large surface...
area (per unit volume) of contact between cool and hot plasma. The chromosphere supplies mass via neutral diffusion across the surface to a thermal boundary layer, and the corona supplies energy to the neutral particles. The originally neutral particles drain energy from the corona by latent heat of ionization and by inelastic collisions leading to strong Lyα emission. The diffusing layer propagates outward, emitting radiation like the boundary of a wild fire, into the corona until either the supply of neutral mass or coronal energy dries up. The present proposal is related to models invoking cross-field heat conduction (Rabin & Moore 1984; Athay 1990). This effect is included here (via \( d^2 \)), but it is far less efficient at moving heat to cool plasma than diffusion is at moving neutral atoms to the coronal heat.

The calculations presented here fall short of accounting for the large radiative flux of Lyα, by factors of \( \approx 10 \). However, the calculations miss important additional sources of energy in the corona: thermal and gravitational potential energy. The cool threads extend only a few \( \mathrm{Mm} \) into the corona, and form just the lower parts of a much larger coronal structure. The diffused cool material is thus subject to parallel transport (heat conduction, diffusion) which will transfer heat from the overlying coronal plasma to the diffused material. Spicules formed by ejection from the chromosphere will have their entire length exposed to this energy flux, because the lowest parts of the spicules diffuse first into the corona; the diffusion fronts are not exactly parallel to field lines. Coronal plasma along connected field lines contains \( L^2 n k T \) ergs \( \mathrm{cm}^{-2} \) of thermal energy, where \( L \) is the pressure scale height (\( \approx 50 \, \mathrm{Mm} \)) or loop length. Since \( L \gg L_s \), the energy available for Lyα radiation would be \( L \| \geq 10 \) times larger than computed above, more if the tubes expand with height. I speculate that cross-field diffusion and subsequent parallel conduction might bring theoretical and observed intensity values into agreement.

The time needed to conduct this energy must lie between the electron sound speed \( c_e \) as \( L/c_e \sim 13 \, \mathrm{s} \), and \( \sim 10^3 \, \mathrm{s} \), an upper limit obtained from the thermal energy divided by the conductive flux for a uniform temperature gradient. Gravitational potential energy might contribute to the heating and dynamics of the sheath as the diffused material cools the corona and adds mass, such that vertical pressure balance no longer is expected. It may be that larger redshifts would be expected where magnetic fields are more vertical, i.e., directly over the magnetic network. This expectation is not in disagreement with results found by McIntosh et al. (2007). However, little more can be said without solving the 2D multifluid conservation equations including parallel heat conduction and cross-field diffusion, beyond the scope of this Letter. Such calculations will also show if the emission lines of trace species (ions of carbon, oxygen, etc., in the TR) can be explained.

Cool threads are observed in different coronal environments (PGV07); their intensities appear to vary relatively little compared with the embedding coronal intensities. This fact is part of Feldman’s (1983) claim that TR emission is energetically disconnected from the corona. The calculations presented here indeed produce a nonlinear relationship between Lyα and coronal brightness. The Lyα intensities scale with the local coronal energy density and with the diffusion speed. But the EUV and X-ray radiation emitted by the corona itself vary with (density)\(^2\) and peaked functions of temperature along lines of sight different from the direction of field lines into the sheath. The scenario might therefore explain most of the observed puzzling facets noted by Feldman and colleagues, yet still maintain a strong energetic link between the corona and TR, and thereby resolve a long-standing debate (see the different perspectives of Feldman et al. [2001] and Wikstøl et al. [1998], for example).

To see if the scenario survives scrutiny, more observations of chromospheric fine structure and its relation with the corona and TR would be as important as numerical modeling work.

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