Structures in Transition Region Plasma of Active Regions

Philip G. Judge
High Altitude Observatory, NCAR\footnote{The National Center for Atmospheric Research is sponsored by the National Science Foundation},
P.O. Box 3000, Boulder CO 80307-3000, USA

Paal Brekke
Institute of Theoretical Astrophysics, University of Oslo,
P.O. Box 1029 Blindern, N-0315 Oslo 3, Norway

Abstract. We derive properties of the solar transition region from absolute intensities of emission lines observed with the HRTS instrument on its second rocket flight on 1978 February 13. We study lines of C II, C IV, N III\textsuperscript{2}, N IV\textsuperscript{2}, N V\textsuperscript{2}, O III\textsuperscript{2}, O IV\textsuperscript{2}, O V\textsuperscript{2}, Si III and Si IV, using density sensitive line ratios, opacity sensitive line ratios and emission measure analysis, based upon the best available atomic data.

Striking features of these data include the relative weakness of all the intersystem lines, and variations in the intensities of lines of Si relative to the other elements. Our major conclusions based upon standard assumptions are: (i) We extend earlier work which indicated extremely small volume filling factors for transition region plasma emitting the resonance lines ($\leq 0.001$), but with higher electron densities than previously found ($N_e \sim 10^{12}$ cm$^{-3}$). (ii) We identify a lower density component ($N_e \sim 10^{10}$ cm$^{-3}$) leading to the bulk of the emission in the intersystem lines. (iii) We demonstrate that changes in Si line intensities result both from changes in element abundances and in the shape of the emission measure distributions.

1. Introduction

Before comparisons between theory and observations can be sensibly made, which is the objective of this meeting, one must first understand what are the basic properties of the solar plasmas. The present contribution seeks answers to this question for the optically thin plasma with electron temperatures between $10^4$ and $10^6$ K – the “transition region” (henceforth TR). One might expect, after over 30 years of UV work, that a consensus has been reached and that we have a generally accepted picture of the basic properties of the TR. Alas, this is not true. As data of higher spatial and temporal resolution have become available, the only consensus seems to be one of increasing complexity. Physical models are available, but the validity of these models has been cast into doubt.
by the astonishing variety of phenomena revealed, to a large part, by various groups’ work using the HRTS instrument (see reviews by Mariska (1992), in the context of the quiet Sun, and by Cook and Brueckner (1991) in more active regions).

The present work is “new” because (i) it is based upon methods which minimize the number of assumptions needed to draw quantitative conclusions from the solar data; (ii) it is based upon the most complete set of emission lines available in the vacuum UV region (1200-1700Å); and (iii) it contains the best atomic data yet used to analyze solar spectra. Early work in the 1970s was incomplete because electron-ion cross sections for density-sensitive (intersystem) lines were unavailable or inaccurate (e.g., Kjeldseth-Moe and Nicolas 1977). Work in the 1980s also tended to be incomplete – as accurate atomic data were becoming available, typically authors analyzed fewer lines and were therefore forced to make assumptions concerning the emission measure distribution (e.g., Hayes and Shine 1987, Doschek, Dere and Lund 1991). A full discussion of this work is in preparation (Judge and Brekke 1994).

2. Observations

We study data obtained during the second HRTS flight on 1978 February 13. We chose the rocket material over the more extensive Spacelab 2 observations because of better pointing stability, better signal to noise levels, and the higher relative photometric precision of the rocket data (Brekke 1992).

The spectrograph slit was oriented radially from disk center through the active region McMath 15139, including a sunspot, and extended across the NW solar limb, also crossing active region McMath 15135. The spectrograms were recorded on UV sensitive photographic film, in four exposures spanning a total of 35 seconds. Microphotometry was carried out at the Institute of Theoretical Astrophysics in Oslo. The absolute intensity calibration was obtained by comparing relative intensity scans of a quiet solar region with absolute intensities from the Skylab S082B calibration rocket, CALROC (Kjeldseth-Moe et al. 1976). We estimate uncertainties in relative measured intensities to be ±30% (rms) (1450 \( \leq \lambda \leq 1730\text{Å} \)), ±40% (1270 \( \leq \lambda \leq 1450\text{Å} \)), and ±50% or more for wavelengths below 1270Å (Brekke et al. 1991). Quiet Sun absolute intensities obtained with HRTS (or CALROC) were compared with SUSIM flux data (VanHoosier et al. 1988) by Brekke (1992). The SUSIM fluxes are approximately a factor 1.5–2 higher than the convolved HRTS data, which may point to a systematic error in the HRTS calibration.

The spatial resolution was \( \approx 1.8 \) arcsec across the dispersion direction. However, to get reliable measurements of the weak intersystem lines, we integrated over areas between 5 and 20 arcseconds across the dispersion direction to derive intensities.

3. Methods and Results

We adopt “empirical” methods in which assumptions are made concerning processes influencing spectral line formation and then properties of the emitting

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structures are inferred from a comparison between observed and computed spectral lines. Techniques for determining physical properties of transition region plasmas using emission line intensities have been employed for several decades (e.g., Jordan and Wilson 1971, Jordan and Brown 1981). These methods have the advantage of being simple. The price to pay for simplicity is the neglect of potentially important physical processes in the calculation of the atomic number densities. Two critical assumptions made almost universally include (i) the neglect of time-dependent terms in the atomic rate equations, and (ii) the adoption of single-temperature Maxwellian distribution functions for all particles. Such effects may be important in the solar transition region (e.g., Hansteen 1993, Shoup 1983), but they can only be inferred a posteriori from inconsistencies in the emission measure analysis.

3.1. Emission measures

We write the emission measure $E_{mi}^j(T_e)$, which represents the amount of the plasma needed to produce the observed intensity $I_{ji}$ erg cm$^{-2}$s$^{-1}$sterad$^{-1}$ for the line transition between levels $j$ and $i$ at a given temperature $T_e$, as

$$E_{mi}^j(T_e) = \int_{\Delta z} N_e^2 dz = \frac{I_{ji}}{\frac{\hbar \nu_{ji}}{4\pi} N_j A_{ji} N_e^2}.$$  

$N_j$ is the number density of the upper level, $A_{ji}$ is the Einstein A-coefficient of the line and $N_e$ is the electron density. The ratio $N_j A_{ji}/N_e^2$ is computed from solutions to the rate equations, with an assumed abundance, and with $N_H = 0.8 N_e$. For permitted lines, $N_j A_{ji}/N_e^2$ depends strongly on $T_e$ but only weakly on $N_e$. For inter system lines which are collisionally de-excited (i.e., when $N_e C_{ji} > A_{ji}$, where $C_{ji}$ cm$^{-3}$ s$^{-1}$ is the collisional de-excitation rate), $N_j A_{ji}/N_e^2 \propto f(T_e)/N_e$. In this case, $E_{mi}^j(T_e)$ is proportional to $N_e$ for $N_e \gg A_{ji}/C_{ji}$.

Solutions to the multi-level rate equations were obtained for atomic models of C, N, O and Si, including ionization stages II through VI for all elements. Details will be presented by Judge and Brekke (1994). The largest sources of uncertainty in these equations comes from the treatment of ionization balance. We used the rate coefficients of Shull and VanSteenberg (1982), including charge transfer with hydrogen for ions of Si (rates from Arnaud and Rothenflug 1985). We adopted photospheric abundances from Grevesse and Anders (1991).

“Coronal” abundances were also examined: we set abundances of C,N,O to photospheric values and that of Si to 3 times the photospheric value (Meyer 1993).

Emission measure curves for representative regions are plotted in the Fig. 1. Two $E_{mi}^j(T_e)$ curves are shown for the inter system lines (labeled with “p”): one computed in the “low density limit”, the other computed for $N_e = 10^{11}$ cm$^{-3}$. For higher densities, $E_{mi}^j(T_e) \propto N_e$ in the inter system lines. The most striking features of the figure are:

(i) A smooth emission measure distribution can be constructed from the $E_{mi}^j$ curves for the resonance lines (solid lines), provided abundance changes between active and quiet regions are considered (see (ii)).

(ii) There is strong empirical evidence that “photospheric” and “coronal” abundances are present in transition region plasmas: The ratios of both Si III
and Si IV lines with lines of C, N and O clearly are determined both by the abundances (compare the quiet and active regions) and the emission measure distributions (compare the spot with the other regions).

(iii) $E^2_{\nu}$ curves for the resonance lines all lie substantially above the emission measures for the intersystem lines. Only when $N_e \gtrsim 10^{12}$ cm$^{-3}$ do the C IV N V and O IV emission measures come into agreement.

(iv) The data for Capella show that the electron densities are substantially lower in this more active, lower gravity star, since the $E^2_{\nu}$ curves for resonance lines and intersystem lines are in closer agreement. This serves as a "reality check" on point (iii).

![Figure 1. Emission measures for regions on the Sun and Capella, an active giant star (Linsky et al. 1993). Resonance lines are shown as solid lines, intersystem lines are dashed.](image)

3.2. Electron densities

Ratios of lines within the O IV] $2s^22p^2\,^2P^o \rightarrow 2s2p^2\,^4P$ multiplet are excellent diagnostics of electron density (Judge and Brekke 1994 and references therein). The measured line ratios yield $N_e \sim 10^{10.3\pm0.3}$ cm$^{-3}$, for most of the regions measured. This is in stark contrast to the values closer to $10^{12}$ cm$^{-3}$ inferred from a comparison between the resonance and intersystem line emission measures.

This can only be reconciled (keeping in mind our assumptions concerning the calculations of $N_j$) if the resonance lines are formed in regions where $N_e \gtrsim 10^{12}$ cm$^{-3}$, and if the intersystem lines are formed in regions where $N_e \sim 10^{10.3\pm0.3}$ cm$^{-3}$ (cf. Doschek 1984) This appears to be true both for quiet and active regions. (This may be a result of the large $[5-20 \times 1$ arcsecond$^2]$
areas which have been summed over in the HRTS data – some level of enhanced activity might be expected in such large areas, especially nearer the limb.)

3.3. Column densities

Ratios of lines of Li-like and Na-like ions are sensitive to the optical depths in the emitting structures. The data indicate that the line center optical depths of NV λ1238.8 are \( \gtrsim \) unity, but that those of Si IV λ1393.8 and C IV λ1548 are \( \lesssim \) unity, in the regions for which most of the resonance lines photons originated. From this we infer that the column density \( \int N_e dz \approx 6 \times 10^{18} \text{ cm}^{-2} \), near \( T_e = 2 \times 10^6 \text{ K} \), adopting the non-thermal line widths of Athay (1988).

3.4. Putting these together

We can now attempt to derive additional properties of the emitting structures. We start by acknowledging the existence of (at least) two separate types of structure, based upon the available density diagnostics, which are unresolved in the HRTS data: "resonance line" and "intersystem line" structures. The table lists the derived properties of these structures, determined for plasma at temperatures near \( 10^5 \text{ K} \).

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<thead>
<tr>
<th>Table 1. Physical Properties of Typical Transition Region Structures</th>
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<td>Parameter</td>
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<td>( \log_{10} \int_{\Delta z} N_e^2 dz )</td>
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<td>( \log_{10} \int_{\Delta z} N_e^2 dz )</td>
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<td>( \log_{10} \int_{\Delta z} dz )</td>
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<td>Filling Factor ( f )</td>
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<td>( \log_{10} \Delta x ) (See text)</td>
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\( \int_{\Delta z} dz \) was determined from \( \int_{\Delta z} N_e^2 dz \approx < N_e > \), and the filling factors \( f \) have been derived from the ratio of \( \int_{\Delta z} N_e^2 dz \) to \( < N_e >^2 \int_{\Delta z} dz \). If there are \( \sigma \) "resonance line" structures per unit area, then the characteristic horizontal scale \( \Delta x \) of each structure is \( \Delta x \sim \sqrt{f/\sigma} \). A lower limit on \( \sigma \) may be obtained by assuming that there is at least one such structure inside our integrated observing slit areas \( A \) which are typically \( 5 \times 10^{16} \text{ cm}^2 \) (\( \approx 1 \times 10 \text{ arcseconds}^2 \) area), yielding \( \Delta x \) given above. Clearly, (i) gas at very different pressures exists within the areas observed with the HRTS spectrograph, (ii) the transition region is extremely inhomogeneous, (iii) we have not resolved the smallest length scales of the fundamental structures in the transition region, (iv) the structures are deeper than they are wide (\( \Delta z > \Delta x \)).
4. Discussion

*How “robust” are our results?* The results have been derived empirically from absolute emission line intensities, certain line ratios, and from atomic calculations in which time-dependent terms and non-Maxwellian electron velocity distributions have been neglected. Aside from our basic assumptions, errors in the ionization balance present the greatest source of uncertainty – we have analyzed at least two ionization stages of each element in order to minimize these problems. Further work is needed on ionization balance in high density regions (Summers 1974). The data for Capella, showing higher intersystem/resonance line ratios, indicate that uncertainties in the other atomic parameters cannot explain the relative weakness of the solar intersystem lines.

*What have we learned that we didn’t already know?* Some authors have determined small filling factors ($f \sim 10^{-2}$) for the transition region plasma (e.g., see Doschek 1987, Dere et al. 1987). However, these have been less complete than in our study, and additional assumptions and/or data were required. Dere et al. (1987) had to assume pressure balance between the O IV- and C IV-emitting plasmas, a result we do not confirm (see also Hayes and Shine 1987), and Doschek’s discussion relies upon a length scale $\Delta Z$ derived from limb observations. We regard analysis of limb data as potentially dangerous owing to problems concerning optical depths which have never been quantitatively addressed. Our results help to remove uncertainties concerning the abundance variations in the transition region plasma which are inherent in earlier studies (e.g. Doschek, Dere and Lund 1991).

*Is our analysis consistent with other work?* Amongst others, Doschek (1987) has reviewed important results from limb data from SKYLAB in which the inferred scale height of transition region emission is $\sim 10^5$km and not $\sim 60$km as inferred here, and in which values of $N_e$ are typically $10^{11}$ and not $10^{12}$ cm$^{-3}$. However, again there is a potential problem with radiative transfer in resonance lines. Our analysis is not necessarily inconsistent with limb data if resonance line photons are scattered out of the line of sight close to the limb. Radiative transfer calculations in structured models are needed.

*What are the implications for models of the transition region?* Since the structures have characteristic scales which have never been resolved, any semi-empirical model or physical model not taking into account these small scale structures must be lacking in physically important information. For instance, how can one define rates for deposition of energy if the characteristic scale lengths of the atmospheric structure are not known? Of the available models, that of Roumeliotis (1991) seems the most likely candidate to survive the empirical constraints derived here, since the model depends on specification of gradients in the magnetic field, and this can be set to values determined by analysis of observations.

*Where do we go from here?* Spectrophotometric data of higher precision should become available from instruments on SOHO. This will surely open our eyes further to the mysteries of the solar transition region.
References

Group Discussion

Suematsu: You derived the very high electron number density of $10^{12} \text{cm}^{-5}$. Such high density plasma should radiatively cool down quickly and be unstable, unless large continuous heat supply exists.

Judge: Yes! but given that we don’t yet know the heating mechanisms in the transition region, I don’t believe that presents any problem. In fact, the kind of analysis I have presented define what those heating rates must be!

Fisher: The difference in density between the regions that emit in resonance lines as opposed to the intersystem lines is disturbing; surely the same plasma emits in both lines. Are you confident of the density diagnostic of the intersystem lines? Even if you are confident that you understood the atomic physics, the difference in emission measure distributions between the two types of lines is disturbing. If one attributes the difference to a distribution of densities within an observational element, how robustly can you determine the “filling factor” of the dense regions, as opposed to the more tenuous regions?

Judge: I am sorry that this was not made clearer in my talk. It is really very simple and it concerns the last point concerning the distribution of densities within the observed elements. The emission measures derived from the line intensities of the resonance lines, e.g. C IV are $\geq$ an order of magnitude larger than the intersystem lines, e.g. O IV] when the latter are computed in the “low density limit”. As you point out, plasma emitting C IV photons also emits the O IV] photons, and the only way these can be reconciled is if the density is increased so that the O IV] emission measures are raised to the C IV emission measure level. In the absence of other information, the observed line intensities of all lines would then be described by a single plasma component at a single density (or perhaps pressure). However, the relative intensities of the O IV] lines are not consistent with plasma emitting O IV] photons at those densities. Clearly there are multi-density plasma within the observing slit. The simplest extension beyond a one-component plasma is a two-component plasma. Thus the distribution of densities within the observational elements has essentially been assigned to two delta functions. The actual distributions must, of course, be more complex. The robustness of the filling factors I derive can only be assessed by looking at more general distribution functions which can be made consistent with the observed line intensities. This will be worthwhile when the very high precision spectro-photometric data become available, for example from the UV instruments on SOHO.