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STRUCTURE AND ROLE OF THE TRANSITION REGION

P. Lemaire
Institut d'Astrophysique Spatiale, Unité mixte Université-CNRS,
Bat.121, Université de Paris XI, 91405 Orsay Cedex (France)

ABSTRACT

The transition region is a very thin region between the high density (Ne $\geq 10^{10}$ cm^{-3}) and relatively low temperature (Te $\leq 2.10^4$ K) chromosphere and the corona (Ne $\leq 10^8$ cm^{-3}, and Te $\geq 10^6$ K). Within this small region complex phenomena driving the energy processes (heating and solar wind) are in action. The strong temperature and density gradients induce the conduction from the corona towards the chromosphere which acts against the energy transfer to the corona. The transition region is very unstable and is dynamically maintained by a lot of time variable phenomena at all scales driven by the dynamics of the magnetic loops deeply rooted in the chromosphere (and below) and shaken by the convection and the differential rotation.

An attempt of a summary of our knowledge of the transition region structure is done in looking at the different types of structures: quiet Sun cell and network, coronal hole cell and network, active regions. There is some relation between the properties and the characteristics of the structures and the local phenomena that will be recalled. Some opened questions on the role of the transition region as an amplificator or/and as a filter between the chromosphere and the corona are reviewed.

Key words: Sun; transition region; network; euv spectrum.

1. INTRODUCTION

Since the the first determination of the high temperature in the corona (Edlén 1942) combined with the low density (deduced from the very tenuous atmosphere above the solar limb) the need of a region able to make the transition between the chromosphere and the corona was required. The Transition Region (TR) was really detected only when rockets and satellites where able to observe the solar ultraviolet radiation above the Earth atmosphere (Rense 1953, Johnson et al. 1958). The TR is not seen in visible during eclipses and is difficult to detect in using microwave radiations.

Solar atmospheric models (e.g. Vernazza et al. 1981) predict a very thin transition layer (few kilometers) to span the temperature range between the upper chromosphere (about 2 10^4 K) and the corona (1 10^6 K). In this presentation we will limit ourself to the Sun seen in the TR during activity minimum, i.e mainly characterized by network and cells with few hints on active regions.A previous review of some properties of the solar quiet TR has been presented by Anderson-Huang 1998.

In quiet Sun, the electronic density drops from chromospheric level (few $10^{10} cm^{-3}$) to coronal value (about $10^8 cm^{-3}$) within few tens (hundreds or thousands?) kilometers. That implies a strong negative density gradient, while there is a strong positive temperature gradient.

In active regions sunspots are no more detected as dark area, but the sunspot area can not be distinghished from the surrounding plage. There is still a density and a temperature gradients but varying from location to location in the highly structured plage.

The TR network cannot be understood without the knowledge of some properties of the chromospheric network and its relation to the photospheric magnetic field. After this presentation, an overview of the TR network will provide the frame to extract some characteristic parameters of the structure (geometry, density, temperature) and of the dynamics (Doppler velocities and flows, non-thermal velocities, and events).

2. RELATION TO THE CHROMOSPHERIC NETWORK

The chromospheric pattern or network was first reported by Deslandres 1899, who suggested that the chromospheric network might correspond to the boundaries of a system of convection cells (Deslandres 1910). The supergranulation cells (large-scale horizontal currents) was only established 50 years later locally (Hart 1956) and over the entire Sun (Leighton et al. 1962). The correspondence between the Ca II brightening and the magnetic pattern was done during the same period (Leighton 1959, Babcock 1963) and a detailed analysis was later performed (e.g. Martin 1988).

The size of the supergranular pattern, or the network enclosure, has been measured by Leighton et al. 1962 and Simon & Leighton 1964 to be about 32 Mm. Series of recent measurements (cf Table 1) confirms this value with some statistical uncertainties, which can be related to the way the data are analyzed,

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e.g. autocorrelation functions (Srikanth et al. 1999). Smaller values were obtained (23 Mm) by manual methods on Ca II data (Singh & Bappu 1981,), 23 Mm by skeletonization of Ca II images (Berrilli et al. 1998) and autocorrelation of magnetograms (Wang et al. 1996), 12 Mm by wavelet analysis of Ca II (Berrilli et al. 1999), 16 Mm from crosscorrelation analysis of magnetograms (Komm et al. 1995) or from a new finding algorithm (Hagenaar et al. 1997). The cell size increases with network enhancement (Wang et al. 1996), but it is anticorrelated with solar activity (Singh & Bappu 1981, Kariyappa & Sivaraman 1994). The relative variation of the network area over a solar cycle can reach 24% (Kariyappa & Sivaraman 1994, Caccin et al. 1998). At the minimum of activity cycle, the network area covers 37% of the total solar surface (Steinegger et al. 1998).

The average lifetime of chromospheric network cells span a large range of values, from 20-24 hours to 50 hours in quiet network (Singh et al. 1994, Raju et al. 1998, Srikanth et al. 1999) and greater than 70 hours in enhanced network (Wang et al. 1991).

The upflow from center and the slow drift (Wang et al. 1996, Schrijver et al. 1996, Berrilli et al. 1998) from the center to the edge of the supergranular cell push the magnetic Inter-Network (IN) elements to collide or to merge with the network (Schrijver et al. 1996). The replenishement rate of the IN elements of 10.2 elements s^{-1} with an average 2.5 hours lifetime (Wang et al. 1996) indicates the disappearance of a lot of IN elements before reaching the network.

The chromospheric network, seen in visible chromospheric lines, is also mapped into the 1-2 cm microwave band (e.g. Bastian et al. 1996).

Table 1. Some characteristics of the chromospheric network and supergranular cell.

cell	quiet	enhanced	active	reference
size	30-32 Mm			1,3,5
	23 Mm	28 Mm		4,6
	24 Mm			7
	14-16 Mm	12-14 Mm		2,8
			14 Mm	9
	increases with magnetic activity			6
lifetime	20-24 hr	36 hr		3
	24-34 hr	59-61 hr		10
	25-50 hr			5
		$\geq$ 70 hr		1
	lifetime increases with cell size			3
cell dynamics (Inter-Network elements)				
radial flow from cell center		0.25-0.50 km s^{-1}		6,4
replenishment rate		10.2 elements s^{-1}		6
lifetime of IN elements		2.5 hr		6,11

(1) Wang et al. 1991; (2) Komm et al. 1995
(3) Singh et al. 1994; (4) Berrilli et al. 1998
(5) Srikanth et al. 1999; (6) Wang et al. 1996
(7) Berrilli et al. 1999; (8) Hagenaar et al. 1997
(9) Foing et al. 1986; (10) Raju et al. 1998
(11) Zhang et al. 1998

3. QUIET SUN TRANSITION REGION

3.1. Overview

The Transition Region network is present all around the Sun and visible from the bottom through its connection to the chromospheric network to the top when it diffuses (or expands in a canopy type structure?) near 10^6 K.

Examples of quiet and active network seen at the bottom and at the mid-range of the TR are given in Figure 1. The quiet Sun TR seems very thin and the limb brightening curves (Wilhelm et al. 1998) indicates a thickness of few arcseconds (few Mm), but closed loops from lines formed in the TR temperature range above active regions may reach few ten arcseconds (see Brekke et al. 1997a).

3.2. Geometry and contrast

Some properties of the Transition Region network have been deduced (Reeves 1976) from the results of the Harvard College Observatory (HCO/S055) EUV spectrometer/spectroheliometer on SKYLAB/ATM (see Table 2). The TR network is seen from the upper chromosphere to the limit of the TR where it begins to diffuse over the cell areas. The width of the network wall does not seem to change in the 2 10^4 - 6 10^5 K temperature range (Reeves 1976, Gallagher et al. 1998, Patsourakos et al. 1999), in agreement with the Gabriel 1976 model. The ratio between cell and total area in function of temperature is either constant (Reeves 1976) or has a small variation (Patsourakos et al. 1999, Worden et al. 1999), while the network emission contributes from 60% to 70% to the total emission (Reeves 1976, Gallagher et al. 1998).

Although subject to discussion, there is some observational evidence for hot TR loops within the supergranular network (Dowdy 1993).

The measurement of the network parameters in coronal hole is difficult. Although the average coronal hole does not seem to have been detected in the mid TR by HCO/S055, some SUMER/SOHO measurements show a signature in the quiet Sun to coronal hole averaged intensity ratio (1.5 at 10^5 K, Lemaire et al. 1999) as opposed to some chromospheric observations (Bocchialini & Vial 1996).

3.3. Temperature, density and abundance

Although the TR is defined from the 2 10^4 K to 10^6 K, over coronal hole at the solar limb the maximum temperature is reached near 8 10^5 K (David et al. 1998), while the temperature is higher than 10^6 K at quiet solar limb.

The characterization of the density and abundance in the TR is very difficult. First results published by Del Zanna & Bromage 1999 show that the density in quiet cell is higher than the density in network by a factor between 1.4 and 1.9 at 1.6 10^5 K and nearly 1 above 3 10^5 K. Elemental abundance variations have been detected with the SKYLAB/ATM data (e.g. Noci et al. 1988, Feldman & Widing 1993, Sheeley 1996, Spadaro et al. 1996a) and from HRTS

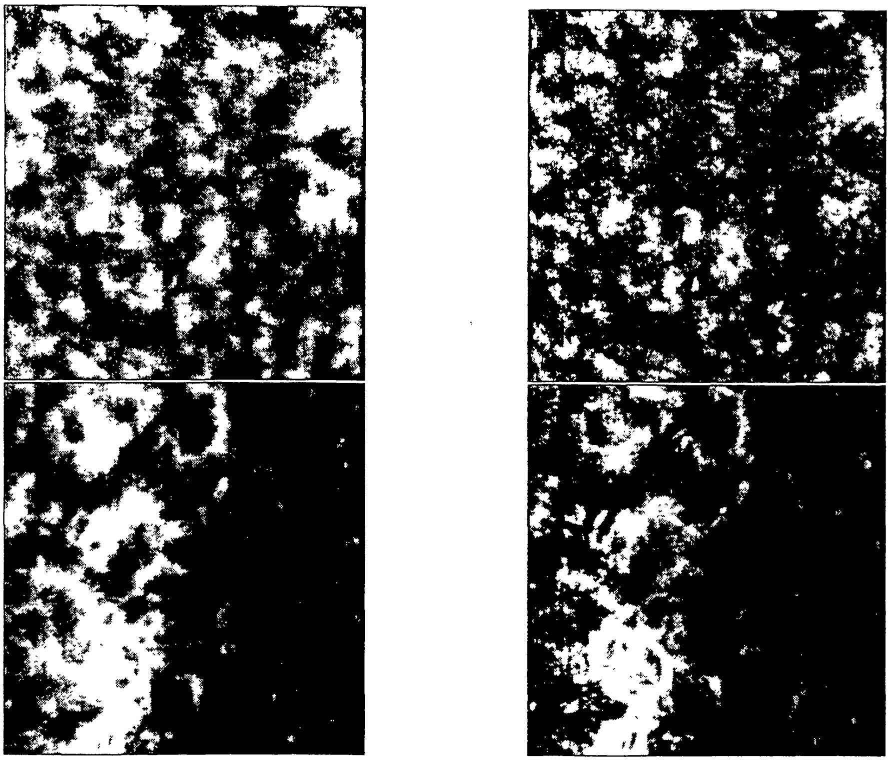

Figure 1. Transition Region network as seen from SUMER in lines of H I Lϵ (2 10^4 K, left) and S VI (2 10^5 K, right) in a quiet region (top) and in an active region (bottom); area 290 × 290 arcsec^2.

Table 2. Quiet Sun geometry and contrast.

	10^4 K	10^5 K	10^6 K	reference
area cell/total	54%	54%	54%	1
	54%	50%	60%	2
network emission	60%	70%	50%	1
	≥60%	70%	70%	2
network full width at halfmaximum (arcsec)				
	10	10	10	1
	12	10	15	3
	15	15	20	2
cell intensity ratio between quiet Sun and coronal hole				
	1	1	1	1
		1.5		4

(1) Reeves 1976; (2) Gallagher et al. 1998
(3) Patsourakos et al. 1999; (4) Lemaire et al. 1999

data (Doschek et al. 1991). The comparison between network in quiet Sun and in an equatorial coronal hole gives a decrease of density by about 1.6 in the coronal hole (Del Zanna & Bromage 1999).

The abundance determination done by the same authors seems to indicate a depletion of the low FIP (First Ionization Potential) in the quiet Sun and in the coronal hole network, with an enrichment of the high FIP in the cells (Table 3). These results need to be confirmed by other measurements.

It should be noticed that in a dynamic atmosphere elements may have different behaviors and may not be entirely ionized (Table 4) and the interpretation of the measured line intensities must be carefully weighted.

Table 3. Quiet sun temperature, density and abundance.

temperature	quiet Sun	coronal hole	reference
top of TR	10^6 K	8 10^5 K	1,2
density ratio	temperature	cell/network	reference
quiet & coronal hole	1.6 10^5 K	1.4-1.9	1
	≥ 3 10^5 K	0.8-1.2	1
quiet/CH network	1.6 10^5 K	1.6	1
	6.3 10^5 K	1.6	1
abundance ratio	low FIP	high FIP	
quiet cell	1	2	1
network	0.7	2	1
CH cell	0.5	1.5-3	1
network	0.3	1-2	1

(1) Del Zanna & Bromage 1999; (2) David et al. 1998

Table 4. Ionization Potentials and Standard Ionization Times at the solar surface (Geiss 1998).

Element	IP(eV)	SIT(s)	Element	IP(eV)	SIT(s)
He	24.6	260	C	11.2	20
Ne	21.5	81	S	10.3	11.6
O	13.6	81	Fe	7.9	2*
H	13.6	70	Na	5.1	1.5
N	14.5	68	Si	8.1	0.64
Ar	15.7	50	Mg	7.6	0.3*
Kr	14.0	20.3	Al	6.0	0.02

**estimate*

3.4. Dynamics

The dynamical properties is inherent in the TR. The instability of the chromospheric base (supergranular flow pattern over the photospheric granulation, local emergence and drift of magnetic elements, differential rotation,...) propagates throughout the TR. As seen from Table 1 the network pattern is in continuous interaction with moving magnetic elements and is approximately replenished in one day. Systematic Doppler shifts, line broadenings, and dynamic events are presented in this section.

3.4.1. Doppler shifts

Systematic flows in the TR were discovered by the NRL (Naval Research Laboratory) S082-B experiment on SKYLAB/ATM (Doschek et al. 1976) and confirmed by OSO8 observations (Lites et al. 1976). There is a large dispersion of data obtained (see Figure 2) by Brekke 1994, Achour et al. 1995, Hassler et al. 1991, Brekke et al. 1997 and Chae et al. 1998c at the same temperature. The determination of the shift is already the result of some averaging over dispersed solar values and from the estimation of the absolute reference. The systematic redshift given by this plot may be misleading because the real Sun produces a distribution of shifts (blue and red) for each intensity (e.g. the analysis of Brynildsen et al. 1998) and the high intensity profiles with strong redshifts can bias the averaged shifts. More accurate absolute laboratory wavelengths are also required for some lines of highly ionized elements (Dammasch et al. 1999).

The measurement of upflows in few area nearby the quiet Sun network and the predominance of upflows in coronal hole is an important clue for the understanding of the fast and slow solar wind origins (Warren et al. 1997, Hassler et al. 1999, Stucki et al. 1999). In active regions high velocity flows (± 50 km s^{-1} range) have been observed along loops in O V ($2.4\ 10^5$ K) line (Brekke et al. 1997a).

3.4.2. Non-thermal velocities

The line broadening in the TR was first measured by Kjeldseth-Moe et al. 1977 using line profiles obtained across the solar limb by the NRL/S082-B experiment.

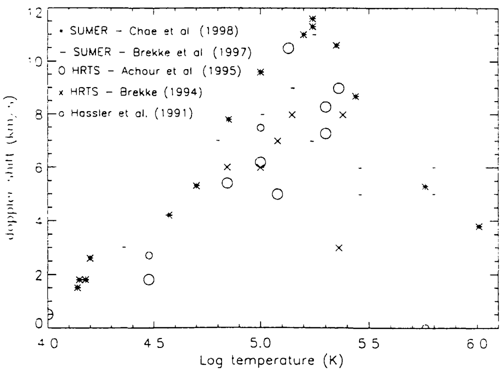

Figure 2. Doppler shift of lines issued from several ionized species as a function of the maximum ionization temperature. The data obtained above $10^{5.7}$ K may need to be shifted to lower values (Dammasch et al. 1999).

After removing the instrumental contribution to the line width, the thermal and non-thermal contributions to the Doppler width is given by equation 1

$$\Delta\lambda_D = 2\lambda/c[ln2(2kT_i/M + V^2)]^{1/2} \qquad (1)$$

- T_i is the kinetic temperature of moving ions ($T_i \cong T_e$ may be questionable if there is local abundance variation, Woods and Holzer 1991. T_e is used as the maximum ionization temperature while it is a temperature distribution which is modified by the flow velocity seen on Figure 2).
- V is the most probable velocity derived from a maxwellian velocity distribution (is the velocity distribution really maxwellian?).

Some results from data taken by Dere & Mason 1993, Erdélyi et al. 1997 and Chae et al. 1998 on the solar disk with HRTS and SUMER are shown in Figure 3. The large dispersion of measurements can be partly due to data analysis (e.g the retrieval of the instrumental contribution), to the averaging process and to the Sun itself. Some data obtained by SUMER (Lemaire et al. 1999, Stucki et al. 1999) show an increase of the line broadenings with line intensity (from cell to network) and a broader width in coronal hole than in quiet Sun.

3.4.3. Dynamical events

Turbulent events and jets in the TR have first been observed with the NRL High Resolution Telescope/Spectrograph (HRTS) during rocket flights (Brueckener & Bartoe 1983). It was the first time that a UV instrument combines high angular, spectral and temporal resolution over a large spatial scale. The rocket results were confirmed by the SPACELAB 2 observations (Brueckener et al. 1986). The statistics obtained during this flight permits to establish that all events (blue jets, red shifted events and explosive or turbulent events) have similar characteristic lifetime and size. Further studies (Dere et al. 1989a, Dere et al. 1989b, Dere et al. 1991, Porter & Dere 1991) have located the appearance of the explosive events at the edge of the network, while the

Table 5. Some comparison between chromospheric and transition region dynamical events.

	chromosphere	transition region
	spicule	blinker
location	supergranular cell border	bipolar reconnection?
size	0.7-2.5 Mm	18 Mm
lifetime	12-16 min	$\geq$5 min
repetition	?	?
velocity	20-40 km s^{-1}	?
	Hα jet - compact dark Hα-0.5Å	explosive event
location	border of supergranular cell?	edge of network (cancellation?)
size	1.4-2.1 Mm	0.7-2.1 Mm
lifetime	60-120 sec	30-120 sec
repetition	?	burst
velocity	20-40 km s^{-1}	50-200 km s^{-1}
References:	Beckers 1972; Dere et al. 1991; Harrison 1997; Innes et al. 1997 Wang et al. 1998, Chae et al. 1998b; Suematsu et al. 1995	

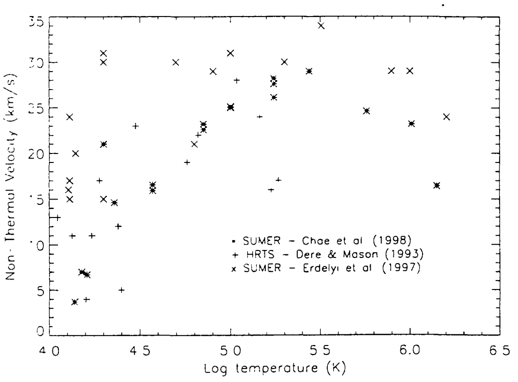

Figure 3. Non-thermal velocities of lines issued from several ionized species as a function of the maximum ionization temperature.

network bright points are seen above network neutral lines (Falconer et al. 1998). SUMER observations (Innes et al. 1997) show that the events appear in bursts.

In Table 5 we have tried to show in parallel some chromospheric events and TR events with similar lifetime (Chae et al. 1998a, Chae et al. 1998b). It also exists some similarities between spicules (Beckers 1972, Suematsu et al. 1995) and blinkers (Harrison 1997). The rotation of macrospicules has been reported by Pike & Mason 1998.

4. ROLE OF THE TRANSITION REGION

The understanding of the role of the TR is related to our ability to interpret the data, to organize the results in such a way that a model can reproduce them. A successful approach has being the use of the line ratio technique to obtain density and temperature, and the Differential Emission Measure (DEM) to characterize the local plasma.

4.1. Line ratio and differential emission measure

Our knowledge of the density and temperature in the TR comes from optically thin line ratios. The obseved line ratios are compared to computations implying atomic physics parameters. Besides the errors related to the atomic physics accuracy the computation is made with some hypotheses on the solar atmosphere integrated along the line of sight. From the detailed analysis given in Lang et al. 1990 we extract few points:

- the emissivity ratio is sensitive to changes in electron temperature (allowed transitions excited from the same level) if the difference of energy between the two transitions is equivalent to kT_e. Along the line of sight there can be regions with temperatures where the ion still has a significant abundance but different from the temperature of maximum ionization (T_m). In a flow or in rapid events T_m is changing (Joselyn et al. 1979) and may corrupt the ratio.
- it is supposed that the plasma pressure is constant over the temperature region where the lines are excited. Within a moving plasma, crossed by waves (?) that may not be always realized.
- the DEM is proportional to the square of the electron density and to the reciprocal of the thermal gradient so that gives more weight to regions of small gradient.

A critical analysis of some fundamental limitations of emission-line spectra as diagnostics of plasma temperature and density structure has been pursued by Judge et al. 1997b (see also Judge et al. 1995 for a critical assessment of DEM). It should be noticed that results of Griffiths et al. 1999 showing that there is no major variation in the shape of the lower TR emission measure distribution with either the intensity or the size of the area studied clearly open a crucial question: either the TR behaves the same way independently of the magnetic structure, or the DEM smooths too much the the observations to provide an unambiguous reference.

The improved angular and time resolutions obtained on SOHO put some limits on the realism of the hypotheses behind the diagnostics, and a re-assesment of their validity may be soon needed when higher resolutions will be reached.

4.2. Models

Transition region modellisation is a continuous task in a entirely inhomogeneous and dynamic atmosphere. Plane parallel models with only radiative losses required a very thin TR (Vernazza et al. 1981) which seems contradicted by the observations. The 2-D (e.g.Gabriel 1976) or 3-D (Elzner & Elwert 1980) models tried to take into account of the TR broad structure and included heat conduction from the corona, but failed in the representation of the lower temperature of the TR. A sketch of the TR structure has been done by Dowdy et al. 1987 which introduce a mixture of loops with different sizes, the smallest one building the network wall (few arcseconds), taking into account the very small loops seen across the network in H I Lα (Bonnet et al. 1980).

Some recent sketches of the TR (Rutten 1998, Judge & Peter 1998) introduce the contribution of accoustic waves (with chocs) in the low TR which can be reflected on the top of TR by the canopy type magnetic field configuration.

In the low TR the DEM decreases, reaches a minimum near 10^5 K, increases and reaches a maximum near 10^6 K and then again decreases. Up to-day no model has been able to reproduce the observed DEM from the chromosphere to corona, although, in a static case, Mok & Van Hoven 1993, Fiedler & Cally 1990 and Ji et al. 1996 give a good representation in taking into account either the cross-field (ion) heat flux or a turbulent thermal conductivity, or curve isothermal surfaces with an adhoc heating function respectively.

Generally it is is supposed that the temperature gradient is aligned with the field, which implies a variation of temperature along the magnetic loops (cool footpoints and hot tops), but there is some evidence that the temperature gradient has a cross-field component (Athay & Dere 1991) which means a mixture of hot and cool magnetic loops.

The unresolved fine structure (UFS) TR is maintained by a population of bursts and follows a constant density law much more than a constant pressure law (Feldman & Laming 1993). The following argument from the same authors that the non-thermal mass motions are approximately independent of temperature , when the lines assumed to be emitted from plasmas with temperature about twice those where the lines are formed in ionization equilibrium, may be valid up-to 3 10^5 K but fails in the upper TR. The UFS model (proposed by Feldman 1983, Feldman 1987) was made to explain the small filling factor, the inability to resolve the temperature structure and the persistent redshifted UV emission lines near the solar limb. Under this assumption some computations are able to reproduce the line width, but they give blueshifted lines instead of redshifted lines (Spadaro et al. 1996b).

Other authors prefer to insist into the dynamic TR. From simultaneous observations of lines formed in the middle of the TR and from the corona O'Shea et al. 1998 support the constant pressure assumption against the constant electron density in the TR as proposed by Feldman & Laming 1993. In a time-varying thermal TR the UFS interpretation is not unique (Wikstøl et al. 1998). Results from Griffiths et al. 1999 seem to support this view.

The assumption of magnetic field funnels inside the network to provide the kick-off of the solar wind (Marsch & Tu 1997) increases the complexity of the TR modelling.

5. CONCLUSION

The complexity of the quiet Sun Transition Region and the difficulty to extract the main parameters provide an area of stimulating discussions. Few point can be noted:

- the TR structure is constrained by the presence of the photospheric/chromospheric magnetic field.
- the negative density gradient combined with the positive temperature gradient is the result or the cause of the strong radiatives losses in the low TR and the dominant thermal conduction from the hot corona?
- we need accurate measurements on line positions, line widths and line intensities with time resolution to estimate the role of dynamics in the different spatial structures (cell and network in quiet Sun and in CH. in AR...).
- 'line intensities by themselves are poor and perhaps misleading tracers of the magnetic structure' (Judge et al. 1997a).
- there is 'non uniqueness of inferring physical plasma properties from observations' (Wikstøl et al. 1998).
- is the TR only one continuous structure or two sets of separated structures ($T_e \leq 2 - 3 \times 10^5$ and $T_e \geq \times 10^5$) (Wikstøl et al. 1998, Feldman 1998). - is there a TR?

The data collected (or to be collected) by the SOHO instruments, will help to precise and to clarify some questions, but some critical problems (e.g. the continuity or not of the TR structure) will probably not be definitively solved. Future experiments with improved resolutions will be required (e.g. about 0.1 arcsecond, 1 km s^-1, 1 second angular, doppler velocity an temporal resolution respectively over several arcsec field) to provoke a jump in our understanding of the processes which create and maintain the TR.

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