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# From chromosphere to corona through ground-based to space observatories(*)

P. Lemaire

*Institut d'Astrophysique Spatiale, Unité mixte CNRS-Université, Université de Paris XI bat.121, F-91405 Orsay Cedex, France*

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**Summary.** — The solar photosphere-chromosphere, as observed from ground-based observatories, is a very thick atmosphere where phenomena related to magnetic fields, differential rotation, waves, take place. The transition region between the thick atmosphere and the extended thin corona can be observed in the ultraviolet from space observatories such as SOHO and TRACE. In this paper we present some results which show the structuring of the transition region as a result from phenomena having their source in the lower atmosphere and we point out some connections with the corona. An overview of the main characteristics of the transition region obtained from space observations evidences the progress in our understanding of the onset of the solar wind and allows to put constraints on the coronal heating.

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## 1. – Introduction

When the high temperature of coronal ions was first determined [1] in a region with a very low density (deduced from the very tenuous atmosphere observed above the solar limb during the eclipses) the question of a region able to make the transition between the chromosphere and the corona arose. The Transition Region (TR) was really detected only when rockets and satellites could observe the solar ultraviolet radiation above the Earth atmosphere [2, 3]. The TR is not seen in the visible light during eclipses and is difficult to detect using microwave radiations.

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Solar atmospheric models (*e.g.* [4]) predict a very thin transition layer (a few kilometers) to span the temperature range between the upper chromosphere (about $2 \cdot 10^4$ K) and the corona ($1 \cdot 10^6$ K). This paper is limited to the chromosphere-TR observed during a minimum of solar activity, *i.e.* mainly characterized by network and cells with a few active regions. Previous reviews of some properties of the solar quiet TR have been presented by [5] and [6].

In the quiet Sun, the electron density drops from chromospheric level (a few $10^{10}$ cm$^{-3}$) to coronal values (about $10^8$ cm$^{-3}$) within a 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 longer detected as dark areas, and the sunspot area cannot be distinguished from the surrounding plage. There are still density and 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 (sect. **2**). In the following sections, an overview of the TR network allows to extract some characteristic parameters of the structure (geometry, density, temperature) and its 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 [7], who suggested that the chromospheric network might correspond to the boundaries of a system of convection cells [8]. The supergranulation cells (large-scale horizontal currents) was only established 50 years later locally [9] and over the entire Sun [10]. The correspondence between the Ca II brightening and the magnetic pattern was done during the same period [11,12] and a detailed analysis was performed later (*e.g.* [13]).

The size of the supergranular pattern, or the network enclosure, has been measured by [10] and [26] to be about 32 Mm. Series of recent measurements (cf. table I) confirms this value with some statistical uncertainties, which can be related to the way the data are analyzed, *e.g.*, autocorrelation functions [17]. Smaller values were obtained (23 Mm) by manual methods on Ca II data [27], 23 Mm by skeletonization of Ca II images [16,20] and autocorrelation of magnetograms [19], 12 Mm by wavelet analysis of Ca II [21], 16 Mm from cross-correlation analysis of magnetograms [15] or from a new finding algorithm [22]. The cell size increases with network enhancement [19], but it is anticorrelated with solar activity [27, 28]. The relative variation of the network area over a solar cycle can reach 24% [28, 29]. At the minimum of activity cycle, the network area covers 37% of the total solar surface [30].

The average lifetime of chromospheric network cells spans a large range of values, from 20–24 hours to 50 hours in quiet network [17, 18, 24] and greater than 70 hours in enhanced network [14].

The upflow from center and the slow drift [16, 19, 31] from the center to the edge of the supergranular cell pushes the magnetic Inter-Network (IN) elements to collide or to merge with the network [31]. The replenishement rate of the IN elements of 10.2 elements s$^{-1}$ with an average 2.5 hours lifetime [19] 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.* [32]).

TABLE I. – *Some characteristics of the chromospheric network and supergranular cell.*

| Cell | quiet | enhanced | active | Reference |
|---|---|---|---|---|
| Size | 30–32 Mm | | | [14-18] |
| | 23 Mm | 28 Mm | | [19, 20] |
| | 24 Mm | | | [21] |
| | 14–16 Mm | 12–14 Mm | 14 Mm | [22, 23] |
| | increases with magnetic activity | | | [19] |
| Lifetime | 20–24 h | 36 h | | [18] |
| | 24–34 h | 59–61 h | | [24] |
| | 25–50 h | | | [17] |
| | | $\geq$ 70 h | | [14] |
| | increases with cell size | | | [18] |
| cell dynamics (Inter-Network elements) | | | | |
| radial flow from cell center | | 0.25–0.50 km $s^{-1}$ | | [16, 19] |
| replenishment rate | | 10.2 elements $s^{-1}$ | | [19] |
| lifetime of IN elements | | 2.5 h | | [19, 25] |

## 3. – Quiet-Sun transition region

**3**˙1. *Overview.* – The transition region network is present over the whole solar surface and is visible through its connection with the chromospheric network to the top where it diffuses (or expands in a canopy-type structure?) near $10^6$ K.

The quiet-Sun TR seems very thin and the limb brightening curves [33] indicate a thickness of a few arcseconds (a few Mm), but closed loops from lines formed in the TR temperature range above active regions may reach a few ten arcseconds (see [34]).

**3**˙2. *Geometry and contrast.* – Some properties of the transition region network have been deduced [35] from the results of the Harvard College Observatory (HCO/S055) EUV spectrometer/spectroheliometer on SKYLAB/ATM (see table II). 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 $2 \cdot 10^4$–$6 \cdot 10^5$ K temperature range [35, 36, 38], in agreement with the [40] model. The ratio between cell and total area as a function of temperature is either constant [35] or has a small variation [38, 41], while the network emission contributes from 60% to 70% to the total emission [35-37].

Although subject to discussion, there is some observational evidence for hot TR loops within the supergranular network [42].

The measurement of the network parameters in a coronal hole is difficult. Although no average coronal hole seems to have been detected in the mid TR by HCO/S055, some SUMER/SOHO measurements show a signature in the average quiet Sun to coronal hole intensity ratio (1.5 at $10^5$ K [39]) as opposed to some chromospheric observations [43].

**3**˙3. *Temperature, density and abundance.* – Although the TR is defined in the $2 \cdot 10^4$ K to $10^6$ K temperature interval, over a polar coronal hole the maximum temperature is

TABLE II. – *Quiet-Sun geometry and contrast.*

| | $10^4$ K | $10^5$ K | $10^6$ K | Reference |
|---|---|---|---|---|
| area cell/total | 54%, 54% | 54%, 50% | 54%, 60% | [35, 36] |
| network emission | 60%, $\geq$ 60% | 70%, 70%, 60% | 50%, 70%, 45% | [35-37] |
| network full width at half-maximum (arcsec) | 10,12,15 | 10,10,15 | 10,15,20 | [35, 36, 38] |
| cell intensity ratio between quiet Sun and coronal hole | 1 | 1,1.5 | 1 | [35, 39] |

reached near $8 \cdot 10^5$ K [44], 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. The first results published by [45] show that the density in a quiet cell is higher than the density in the network by a factor between 1.4 and 1.9 at $1.6 \cdot 10^5$ K and nearly 1 above $3 \cdot 10^5$ K. Elemental abundance variations have been detected from the SKYLAB/ATM data (*e.g.* [46-49] and from the NRL High Resolution Telescope/Spectrograph (HRTS) data [50]. The comparison between quiet Sun and equatorial coronal hole networks shows a decrease of density by about 1.6 in the coronal hole [45].

The abundance determination done by the same authors seems to indicate a depletion of low FIP (First Ionization Potential [51]) ions in the quiet Sun and in the coronal hole network, with an enrichment of the high FIP ions in the cells (table III). 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. The greatest care must be taken in the interpretation of the measured line intensities.

**3**˙4. *Dynamics*. – Dynamical properties are inherent to 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 I 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. D o p p l e r  s h i f t s. Systematic flows in the TR were discovered by the NRL (Naval Research Laboratory) S082-B experiment on SKYLAB/ATM [52] and confirmed by OSO8 observations [53].

There is a large dispersion of data obtained by [54-57] and [58] at the same temperature. The determination of the shift is already the result of some averaging over dispersed solar values and requires an absolute reference. Up-to $6 \cdot 10^5$ K there is a systematic redshift (reaching 8–10 km $s^{-1}$ near $3 \cdot 10^5$ K) which may be misleading because the real Sun produces a distribution of shifts (blue and red) for each intensity (*e.g.*, the analysis of [59] 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 [60, 61] to confirm the blueshift observed above $6 \cdot 10^5$.

The evidence of upflows in a few areas nearby the quiet-Sun network and the predominance of upflows in coronal hole are an important clues for the understanding of the

TABLE III. – *Quiet-Sun temperature, density and abundance.*

| Temperature | Quiet Sun | Coronal hole | Reference |
|---|---|---|---|
| top of TR | $10^6$ K | $8 \cdot 10^5$ K | [44, 45] |
| density ratio | temperature | cell/network | reference |
| quiet and coronal hole | $1.6 \cdot 10^5$ K | 1.4–1.9 | [45] |
| | $\geq 3 \cdot 10^5$ K | 0.8–1.2 | [45] |
| quiet/CH network | $1.6 \cdot 10^5$ K | 1.6 | [45] |
| | $6.3 \cdot 10^5$ K | 1.6 | [45] |
| abundance ratio | low FIP | high FIP | reference |
| quiet cell | 1 | 2 | [45] |
| quiet network | 0.7 | 2 | [45] |
| CH cell | 0.5 | 1.5–3 | [45] |
| CH network | 0.3 | 1–2 | [45] |

fast and slow solar wind origins [62-64]. In active regions high velocity flows ($\pm 50$ km $s^{-1}$ range) have been observed along loops in O V ($2.4 \cdot 10^5$ K) line [34].

**3**˙4.2. Non-thermal velocities. The line broadening in the TR was first measured by [65] using line profiles obtained across the solar limb by the NRL/S082-B experiment. After removing the instrumental contribution to the line width, the Doppler width is a function of the kinetic temperature of moving ions [66], sometimes assimilated to the addition of the electron temperature, and a non-thermal contribution (with the hypothesis of a Maxwellian velocity distribution).

Data [61, 80-82] taken on the solar disk with HRTS and SUMER show a maximum of the non-thermal velocities (25–30 km $s^{-1}$) near $3 \cdot 10^5$ K. The large dispersion of the 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 [39, 64] show an increase of the line broadenings with line intensity (from cell to network) and a width larger in a coronal hole than in the quiet Sun. A weak center-to-limb variation in the TR line width was detected by [83].

**3**˙4.3. Dynamical events. Turbulent events and jets in the TR have first been observed with HRTS during rocket flights [84]. It was the first time that a UV instrument combined high angular, spectral and temporal resolution over a large spatial scale. The rocket results were confirmed by the SPACELAB2 observations [85]. 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 lifetimes and sizes. Further studies [73, 86, 75, 87] have located the appearance of explosive events at the edge of the network, while the network bright points are seen above network neutral lines [88]. SUMER observations [76] show that the events appear in bursts.

In table IV we have tried to show in parallel some chromospheric and TR events with similar lifetimes [89, 90]. Some similarities between spicules [67, 68] and blinkers (detected by CDS/SOHO [78]) also exist which can be interpreted as unresolved explosive events appearing in bursts [79]. The rotation of macrospicules has been reported by [74].

Table IV. – *Some comparison between chromospheric and transition region dynamical events.*

| | Chromosphere | Transition region | Reference |
|---|---|---|---|
| ——— | *spicule* | *spicule* | ——— |
| location | cell border | bipolar | [67, 68] |
| size | 0.7-2.5 Mm | 18 Mm | [67] |
| lifetime | 12–16 min | similar | [67] |
| velocity | 20–40 km $s^{-1}$ | | [67] |
| ——— | *Hα spike/polar surge* | *macrospicule* | ——— |
| location | polar hole | polar hole | [69-72] |
| size | 7–15 Mm | 3-45 Mm | [71] |
| lifetime | 5–30 min | 3–45 min | [73] |
| velocity | 25 km $s^{-1}$ | 30–130 km $s^{-1}$ (tornado) | [74] |
| ——— | *Hα dark jet* | *explosive event* | ——— |
| location | cell border | edge of network | [75-77] |
| size | 1.4–2.1 Mm | 0.7–2.1 Mm | [75, 77] |
| lifetime | 60–120 s | 30–120 s | [75, 77] |
| repetition | - | burst | [75, 76] |
| velocity | 20–40 km $s^{-1}$ | 50–200 km $s^{-1}$ | [75-77] |
| ——— | | *blinker* | ——— |
| location | | bipolar reconnection | [78] |
| size | | 18 Mm | [78] |
| lifetime | | 30–40 min | [78] |
| repetition | | 2000 s | [78] |
| | | unresolved explosive events? | [79] |

## 4. – Conclusion

The quiet-Sun Transition Region, frontier between the dense and cold chromosphere and the thin and very hot corona, is the location of very contrasted structures and phenomena. It is a place where the radiative contribution to heating ends and where the acceleration of the solar wind begins. More detailed studies are needed to understand the processes acting in this thin atmospheric layer.

* * *

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