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ΑΣΤΡΟΝΟΜΙΑ. – **Doppler shifts in the Solar Transition Region**, by C. Gontikakis, H.C. Dara*, διὰ τοῦ Ἀκαδημαϊκοῦ κ. Γεωργίου Κοντόπουλου.

ABSTRACT

We consider the problem of the apparent redshifts of the UV lines in the transition region. We give a review of the basic observations during the last decades, especially the observations of the last few years from satellite observatories. Moreover, we revise the most popular theoretical explanations for the motions in the transition region. This review is a contribution to the understanding of the physical processes in this important layer of the solar atmosphere and it points out the open problems.

1. Introduction

One of the biggest enigmas in solar physics is the apparent redshifts of the ultraviolet emission lines in the transition region. This phenomenon was first observed in the early seventies with Skylab (1973) by Doschek *et al.* (1976) and shortly after with the Orbiting Solar Observatory (OSO 8 satellite by Bruner *et al.* 1976, Roussel-Dupré *et al.* 1976, Lites *et al.* (1976). In the last decades the phenomenon has been studied again with Sklylab data and data obtained from the missions that followed it. From Skylab data, Doschek *et al.* (1976), Feldman

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et al. (1982) concluded that the measured redshifts, which were less than the thermal width of the transition lines, do not necesserely imply that there is net downward mass flow. They suggested that there is a possibility of faint upward motions, unresolved because of low spatial resolution. Doschek *et al.* (1976), measured negligible Doppler shifts from limb observations and realized that the plasma motion was mainly radial. The correlation between Doppler shifts and intensities in the quiet sun network structures was investigated by Lites *et al.* (1976) and later by Gebbie *et al.* 1981 with Solar Maximum Mission (SMM) data. The previous studies concerned time averaged spectra and found steady flows (see also Roussel-Dupré and Shine 1982 with OSO 8 data). However, Bruner *et al.* (1976) detected implusive downward motions in the transition region over a sunspot. The SMM, the High Resolution Telescope and Spectrograph (HRTS) and the Laboratory for Atmospheric and Space Physics (LASP) EUV Coronal Spectrometer missions with their enhanced technical capabilities, higher angular, temporal and spectral resolution, improved our knowledge about the impulsive nature of plasma motion (Porter *et al.* 1984 with SMM, Cheng 1991 with HRTS), as well as the spatial varation of the measured Dopper shifts, both red and blue (Athay and Dere 1989, Brekke 1993, Kjeldseth-Moe *et al.* 1993 Brynildsen *et al.* 1996 with HRTS data). It is important to realise that the transition region redshift dominates after averaging over a statistically meaningfull part of the solar surface. The relation of this average redshift with the formation temperature of the corresponding emission lines has been studied by many observers. The difficulty in finding a reliable method for measuring absolute velocities is obvious in all these studies (Athay and Dere (1989), Brekke (1993), Achour *et al.* (1995) with HRTS, and Hassler *et al.* (1991) with LASP EUV data). The data from the Solar and Heliospheric Observatory (SOHO, Domingo *et al.* 1995) obtained with the Solar Ultraviolet Measurements of Emitted Radiation (SUMER, Wilhelm *et al.* 1995) and the Coronal Diagnostic Spectrometer (CDS, Harrison *et al.* 1995) have given us the possibility for new investigations on this subject. Redshifts in the transition region, apart from being a Solar characteristic, were also observed in the spectra of large age stars from the International Ultraviolet Explorer (Ayres *et al.* 1983) and recently from the Hubble Space Telescope (Wood *et al.* 1996, 1997). Therefore the problem is of general interest.

In section 2 we present the observations, including the more recent ones from the SOHO mission as well as the techniques used to get calibrated Doppler shifts. In section 3 we discuss the theoretical simulations proposed for the explanation of the redshift phenomenon.

2. Observations

The difficulty in studying the motion in the transition zone is the lack of absolute calibration in the instrumentation. The most widespread method for absolute calibration is the use of chromospheric lines as a reference. Chromospheric lines have a redshift corresponding to an absolute velocity of 1 km s^{-1} (Samain, 1991). This value can be considered negligible compared to the velocities of 5-10 km s^{-1} deduced from transition region lines (Doschek *et al.* 1976, Athay and Dere 1989, Brekke 1993, Brynildsen *et al.* 1995 Achour *et al.* 1995 and others). If there is a chromospheric reference line within the spectral range we use, we attribute its wavelenght to the pixel of the spectrograph corresponding to the peak intensity of the reference line. Thus, we get the relation between wavelength and pixels in Å /px and we determine the wavelenght of the peak intensity of the transition region line. The Doppler shift can be found by comparison with the wavelength of the line emitted at rest. The reliability of this method is based on the number of reference lines present in our spectral range and on the accuracy of the laboratory measurements. For the neutral atoms, which are the common emitters in the chromosphere, the measurements in the laboratory are reliable. However, the accuracy of measurements of multi-ionised atoms, as the ones in the transition region, is not reliable. Chromospheric lines are present in the 900-1600 Å spectral range, so the method cannot be applied to transition region lines with wavelength lower than 900 Å. As we will see this is the cause for many contradicting results.

Another method of calibrating is to consider null motion at the limb, since the flow is perpendicular to the solar surface and, statistically, the horizontal motions towards and away from the observer are canceled (Doschek *et al.* 1976, Hassler *et al.* 1991). Therefore, the redshift amplitude depends on the angle θ between the line of sight and the normal to the solar surface. We insist on the statistical nature of the cancelation of motions, since many observers occasionally mention non zero redshift at the limb (e.g. Brekke 1993). The LASP instrument, which flew on a sounding rocket mission (Hassler *et al.* 1991), used for calibration a platinum spectrum from an on-board hollow cathode, which was very accurate. It was the only measurement of transition region Doppler shifts which used on board absolute calibration.

There are two additional causes which make the task of absolute wavelenght measurements even more difficult: The low signal to noise ratio in the emission of the hot, upper transition region of the quiet sun (e.g. Teriaca *et al.* 1999a could not measure the Doppler shift of the FeXII 1242.0 Å line in the quiet sun), and the presence of line blends. A well known blend, mentioned by Brekke (1993), is the wing of the Hydrogen Ly α 1216 Å with the O V 1218 Å line, which results to zero redshift in the O V line. This misled some observers (Dosckek *et al.* 1976) to the conviction of zero redshift for emission temperatures larger than 100 000 K.

There has been an effort to correlate the redshifts to parameters like temperature, magnetic field and line intensity, so that theoreticians could use some constrains for their models. The redshifts seemed to increase with temperature in the region between 2×10^4 and 10^5 K, with a maximum for the logarithm of the temperature (log T) varying from 5.1 K (Achour *et al.* 1995) to 5.27 K (Peter & Judge 1999), depending on the author.

However, for formation temperatures higher than $\log T = 5.2$ this relation has not been clarified yet. Doschek *et al.* (1976) claimed that the redshift in this region is decreasing abruptly, due to the Ly α blend we mentionned earlier. Later on, measurements of HRTS and, recently, with SUMER, which observes lines of ions with formation temperatures up to 10^6 K in the quiet sun, showed that, for the mentioned temperature range, there is still a measurable redshift, but smaller than the one corresponding to 10^5 K (Achour *et al.* 1995, Brekke *et al.* 1997, Chae *et al.* 1998). This year, the scenery has changed for the upper part of the transition region. The spectrum emitted for $\log T > 5.7$ was measured to be blueshifted (Hassler *et al.* 1999, Peter & Judge 1999, Teriaca *et al.* 1999a, Teriaca *et al.* 1999b)! The new results are different becase they are based on the change of the estimation of the rest wavelength of a Ne VIII line emitted at Log $T \simeq 5.7$. The recent value is 770.428 Å (Dammasch *et al.* 1999) while the previous one was 770.409 Å (Bockasten *et al.* 1963, Kelly 1987). Let us note that Sandlin *et al.* (1977) had observed blueshifts in the coronal line of Fe XII 1349 Å, result which is in agreement with the recent ones and which had fallen into oblivon until recently. In section 3, we will discuss some theoretical models which find blueshifts in some line profiles.

In Table 1 we present the measurements of Chae *et al.* (1998) and the most recent observation of Teriaca *et al.* (1999a) and Peter & Judge (1999). log T is the logarithmic temperature where the ion abundance is maximal (Arnaud & Rothenflug 1985). We should remark here, that while the redshift measurements of the low temperature region do not change significantly, for formation temperatures of the order of 10^6 K, we can see the change in the sign of the Doppler shift.

Table 1. Temperature versus average Doppler shift (km s^{-1}) in a quiet solar region*

Ion	log T (K)	(km s^{-1})	(Km s^{-1})
		Chae *et al.* (1998)	(1999) Results
C I	3.90	1.5	0.0 ± 1.5 TBD
O I	4.00	1.8	-0.1 (1.3) ± 1.4 TBD
Fe II	4.15	1.8	0.0 ± 1.6 TBD
Si II	4.20	2.6	1.8 ± 1.5 TBD
C II	4.35	4.2	5.3 ± 1.9 TBD
Si III	4.70	5.3	...
Si IV	4.85	7.8	7.4 (10.6) ± 1.4 TBD
C IV	5.00	9.6	4.9 (10.7) ± 1.2 TBD
O IV	5.20	11.0	8.0 ± 1.2 TBD
N V	5.25	11.3	9.8 ± 1.6 TBD
S V	5.25	...	12.8 ± 1.2 TBD
S VI	5.28	11.6	8.8 ± 1.5 PJ
O V	5.35	10.6	7.0 ± 1.5 TBD
O VI	5.42	8.7	8.7 (12.7) ± 1.9 TBD
Ne VIII	5.80	5.3	-1.9 ± 2.0 TBD
Mg X	6.05	3.8 (5.9)	-4.5 ± 1.3 PJ

The magnetic field relation to the Doppler shifts was also studied by Brynildsen *et al.* (1996). They compared magnetograms and cospatial transition region images. They found a correlation between the C IV line redshifts and the magnetic field, with timescale of 50-100h, at the supergranulation boundaries. However, they did not find any correlation of line shifts with the weak intranetwork field, which has shorter time scales. Klimchuck (1987) found that the redshifts in active regions occur in regions where the field is strong (B>100 G) and that blueshifts are found in weak magnetic field regions.

A constraint probability analysis of th HRTS data, in the C IV line, showed that the redshift is more probable for higher intensities and line widths, whereas the blueshift is less probable (Brynilsden *et al.* 1995, 1996). A similar analysis has

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* NOTE: TBD means measured from Teriaca *et.al.* 1999a and PJ from Peter & Judge (1999). Chae *et al.* 1998 estimate that their error bars are lower than 1 km s^{-1} whereas for the other authors the error bar is noted. The value in parenthesis for the Mg X line in the third collumn is the measure obtained neglecting the blends. In the collumn, some ions have two Doppler shift values (the one in parenthesis) measured from different spectral lines. We present them when they show discrepancies larger than the error bars.

been carried out with the CDS and SUMER data in higher temperature lines (Brynildsen *et al.* 1997 and Brynilsdsen *et al.* 1998b) and has confirmed the relation between redshifts and intensity for other spectral lines (He I 584.33 Å, O V 629.76 Å, O IV 554.5 Å and Mg IX 386.6 Å from CDS and Si IV 1393.7 Å, C IV 1548.2 Å, N V 1238.8 Å, O V 629.76, O VI 1031.9 Å and Ne VIII 770 Å from SUMER). This study had been carried out for the quiet sun, as well as for active regions. In the quiet sun this relation comes from the fact that the redshift is stronger in the bright network. However, the variance of the distribution of redshift is large and the intensity-redshift correlation is evident only if we consider a large amount of datapoints.

The calculated Doppler shifts vary with the kind of solar structure. Achour *et al.* 1995 compared the redshifts above active regions with the ones of the quiet sun. They found that there is a more important redshift above the active regions which becomes maximal for lines with formation temperatures of 10^5 K. However, Brynildsen *et al.* 1998a, measured the average value of the Doppler shifts above a sunspot region and found it less important than the one

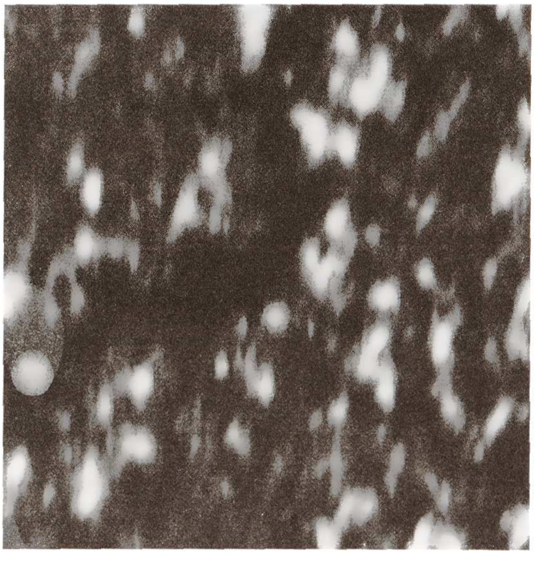

Fig. 1. Image of the quiet sun in the O V 630 Å line of the transition region, observed with the CDS/NIS. We can clearly see the bright features which outline the network cells, inside which are located the dark ones. The dark structure in the center of the images is a filament.

presented by Achour *et al.* 1995 and Brekke *et al.* 1997 for the quiet sun. For coronal lines, the redshifts were the same above the active and the quiet sun regions. For the quiet sun structures, the analysis of observations with SUMER had shown that the redshift in the network bright lanes is more pronounced than in the dark features in the center of the supergranule (Judge *et al.* 1997). Gontikakis *et al.* (1999), with a different method and data from CDS (Figure 1), confirmed this result calculating, moreover, the values of velocities of the bright network features relative to the dark ones in the low transition region lines.

Measurements of Doppler shifts have also been carried out in coronal holes. Rottman *et al.* (1982) studied an equatorial coronal hole, using spectrograms in the O V 629.73 Å and Mg X 624.94 Å lines. They found that the material was blueshifted relative to the quiet sun and concluded that the mass flux was consistent with the proton flux at 1 AU. Hassler *et al.* (1999) studied the network velocities in a coronal hole using SUMER observations in the Ne VIII (770.428 Å) line. They found that the observed outflow was stronger in the network boundaries, especially at the intersection of the network cells. Their result is in disagreement with previous work of Dupree *et al.* (1996) who found, using the He I 10830 Å line, that the outflow in the coronal holes was predominantly at the center of the supergranular cells. However, it should be mentioned that the association of the wing asymmetries of the He I 10830 Å line, whose formation is very complicated (Andretta and Jones 1997), with outflows is difficult.

3. Theoretical efforts

There has been a lot of effort for a theoretical explanation of the observed redshifts in the transition region. If these redshifts corresponded to net downflows, they would empty the coronal structures in half an hour, which, of course, is out of question. Therefore the different theoretical approaches admit that the total mass flow across the transition region should be zero, neglecting the upward flow corresponding to the solar wind. We present some of the most outstanding models which show that, even with a zero total flow, the observation of the redshift may dominate.

The common procedure followed is the solution of the hydrodynamic equations, considering a frozen-in approximation for the plasma embedded in a coronal loop. The deviation from the state of ionization equilibrium plays also an important role in the study of plasma flows in a steep temperature gradient, like the one of the transition region. The best way to compare the models with the observations is to calculate the line profile of the resonance spectral lines. In the tenuous transition region and coronal plasma, resonance lines are excited with electron collisions and emit light by spontaneous radiative decay. This is called the coronal approximation and, as the plasma is considered optically thin for these lines, the line intensity as a function of frequency is described by the equation:

$$I_\nu = \frac{h\nu_{12}}{4\pi} \int \phi_\nu(u)\, n_e\, n_{ij}\, C_{12}(T_e)\, ds \qquad (1)$$

This equation calculates the average light emitted from a spectral line by integrating the emissivity of the plasma along the line of sight ds. hv_{12} is the energy of the transition from the level 1 to 2. In the integral, Φv is the emission profile described by a gaussian function of the frequency with thermal broadening, n_e is the electron density and n_{ij} is the density of the emitting atom i with a degree of ionisation j. The function C_{12} (T_e) of the electron temperature T_e is the collisional excitation coefficient from level 1 to 2.

One of the first proposed models was based on the idea of loops with unidirectional (siphon) flows. The feet of these loops are anchored in the bright edges of the supergranules. The estimated distance between their footpoints is of the order of 11 arcsec (Mariska 1988). The embedded plasma, which is at 10^4-10^5 K temperatures, has a low filling factor, due to the small width of the transition region. Therefore the loops are unresolved in the transition region lines, and one can observe only the average effect of a number of loops. A heat source at the foot of the upward motion is responsible for the flow. Due to this local heating the loop has high (coronal) temperatures at the foot with the upflow and lower temperatures at the foot with the downflow (Mariska and Boris 1983, Mariska 1988). Thus, the upflowing plasma in one of the feet is at coronal and high transition region temperatures, while the downflowing plasma is cool material at low transition region temperatures. The result is that a redshift is observed at the low transition region temperatures and a blueshift for temperatures $T > 10^5$ K. The plasma flow is of the order of 10 km s^{-1} and crosses the ~100 km thickness transition region, as it moves up, in times shorter than the ionization and recombination characteristic times of ions which give the observed spectral lines. As the temperature increases by two orders of magnitude in the transition region, the ionization equilibrium will be perturbed. Spadaro *et al.* (1991) included this effect in their asymetric loop computations and found significant departures from equilibrium for ions like C III, O III and C IV. They mentioned that C IV shows overabundances in the upflowing foot, leading to an average blueshift of the C IV lines. The fact that this model gives blueshifts, for lines at C IV (1548 Å), and O IV (1218 Å), disagrees with the present observations. Another problem of this model is to explain the existence of a localized heat function that produces the steady flow along the loop. Moreover, this conception concerns steady flows, whereas observations, with good temporal resolution, show a dependence of the transition region phenomena on time, with time scales less than one minute. This was the reason why models including impulsive events were developed for the explanation of the redshift phenomenon. However, the discussion of steady flow solutions has not been settled yet. Chae *et al.* (1997) presented recently a simulation of the low transition region with flows of ~7 km s^{-1}. They computed the partial hydrogen ionisation concidering optically thick effects (Ly α). They found that the transition region is brighter for models with upflows than for models with downflows.

One of the models with an impulsive mechanism is based on spicules. Spicules are chromospheric material accelerated up to the corona and only one percent of this material is believed to contribute to the solar wind. The rest should return to the chromosphere. Pneuman and Kopp (1978), as well as Athay and Holzer (1982) suggested that redshifted lines originate in the spicular material, heated to transition region temperatures, which falls back to the chromosphere. Cheng (1992a, 1992b) proposed a numerical simulation for the acceleration of the spicular material by a single quasi-impulsive acoustic wave. The wave pulse evolves to a shock followed by an oscillating wake. The interaction of the shock fronts with the material imposes a periodic vertical motion upwards, simulating a spicule, which desappears gradually in time. Cheng calculated the average gas velocity at the temperature of formation of the C IV ion (10^5 K), which is one of the most observed lines. The oscillation of the gas in Cheng's model includes short time upflows, due to the plasma acceleration caused by the acoustic pulses. Then, long duration downflows of high velocity follow, due to the falling, because of gravity and radiative cooling, material. Therefore, the temporal average of the velocity is in the direction towards the solar surface (redshifted), even if there is no total mass flow in this direction.

Hansteen and Wikstøl (1994) have reproduced, with their numerical simulation, a spicule rebound shock model, similar to Cheng's. They computed the gas velocities and the Doppler shifts of the transition region spectral lines. The mean profiles, averaged over time, presented by Hansteen and Wikstøl are weighted by the density of material according to equation (1). They realized that the upflows, due to the passage of the acoustic pulse, correspond to dense material producing bright profiles. On the contrary, the downflows, even if they have a longer duration, concern low density flows with faint emission. The mean profile calculated over time is blueshifted. So, even if the mean gas shows a downflow, the line profiles are blueshifted. This conclusion is in desagreement with the observations, therefore this spicule model cannot explain redshifts.

Another theoretical mechanism is based on nanoflares, a candidate also for the solution of the coronal heating problem (Parker 1988, 1991). Nanoflares are supposed to occur in coronal loops and are the cause of dissipation of small amount of energy, of the order of 10^{23}-10^{25} erg, due to magnetic reconnection in subarcsecond angular scales, below the resolution limit of today's instrumentation. A considerable number of these events can explain the X-ray emission observed in coronal loops. Hansteen and Maltby (1992) and Hansteen (1993), modelled the triggering of acoustic waves by nanoflares at the crest of the coronal loops. They studied the interaction of these pulses with the transition region plasma and computed the line profiles of the C IV 1548 Å, O IV 789 Å, O VI 1037 Å and Ne VIII 770 Å spectral lines. As the acoustic pulse crosses the transition region, the compression of plasma produces velocities towards the solar surface, while the relaxation corresponds to outward motions (Eriksen and Maltby 1967, Hansteen 1991, Hansteen and Wikstøl 1994). This results in a redshift of the transition region spectral lines. The propagation of pulses through the transition region, the reflection of part of them back to the corona, as well as the change of the level of the transition region due to heating and cooling by the nanoflares, are the factors that influence the line profiles. The mean Doppler shift that Hansteen (1993) deduced, corresponds to velocities of ~1 km s^{-1} towards the solar surface. The same model, including magnetosonic waves travelling with Alfvén velocities (Hansteen *et al.* 1996, Wikstøl *et al.* 1997) gives redshifts closer to the observed ones, and blueshifts for the Mg IX 368 Å line.

Roumeliotis (1991) modelled the low transition region as being formed by cool loops with maximum temperature lower than 3×10^5 K, located in the network features. This picture of the low transition region as consisted of small cool loops rather than open magnetic field funnels, (which is the standard way to describe the transition region, Gabriel 1976), is presented in Dowdy *et al.* (1986). In those small loops, the thermal conduction must be negligible, due to the fact that the magnetic field lines close before they reach the hot corona. The dominating thermal mechanism presented in this work is the Joule dissipation of electric currents, produced by the shearing of the magnetic field wherever the loops interact with each other. The author found that above a critical value of the current, the radiative losses cannot balance the Joule heating. This leads the loop to a hot state. He modelised the transition from the cool to the hot state, using one dimensional hydrodynamic computations and deduced that the gas expands due to the energy deposition by Joule heating at the top of the loop. This produces a symmetric mass flow from the top to the legs of the order of ~ 10 km s^{-1}. However, when there is a transition from the hot to the cool state the upward flows are slower. According to this picture, an observer would see the average effect of hot and cold loops and would detect redshifts, due to the transition, from cool to hot loops, whereas he would not perceive the opposite transition from hot to cool loops, due to the low line shifts it produces. Brynildsen *et al.* 1996 critisized this model, wondering how it is possible that the described electric currents do not evolve to tangential discontinuities implying reconnection of the magnetic fields.

Reale *et al.* (1996, 1997) developed a mechanism where 2-D isobaric perturbations in the low transition region cause redshifts in the computed spectral lines. These perturbations, estimated to be of the order of sub-arcsecond, have high density and low temperature and propagate downwards. Briefly, the top of the perturbation is heated by the hot upper part of the transition region, while the low transition region below, is cooled because of the blocking of the thermal conduction from the cool perturbed material. The perturbation is displaced downwards. The computation includes different model parameters corresponding to active regions, as well as to the quiet sun. As these structures are unresolved we ignore their spatial distribution over the solar surface, as well as their temporal spectrum. A question to be clarified is how these thermal instabilities are produced by the low transition zone.

4. Discussion

The redshifts in the low transition region spectral lines seem to be present in all the observed solar structures, with the exception of the coronal holes. However, the models proposed for its explanation are concerned only with some particular solar features. Spicules are structures observed at the chromospheric network boundaries and are absent in active regions. Nanoflares are expected to be present in coronal bright loops which are mainly found in active regions, but also in coronal bright 'points' at the quiet solar network boundaries (Habbal 1991). The models with steady flow loops are also located in the network bright patches of the quiet sun. The region which seems not to be considered in these models in the dark internetwork (Rutten 1999) region. However, redshifts are also observed there, even though they are less intense.

The proposed models have many difficulties. First, they cannot be directly compared with observations. With the exception of spicules, which are a well studied solar phenomenon, the nanoflares, the thermal instabilities and the loops with steady siphon flows are supposed to be smaller than the limits of today's spatial resolution. This has as a consequence that observations may give the mean effect of a large number of events, whose spatial and temporal distribution we ignore. Despite this, we can examine how well the models explain some essential observations. To start with, the variation of the average redshift with the line formation temperature can be explained in different ways depending on the theoretical approach. This must be in conjunction with the new (1999) observational results.

The models of siphon flows in assymetrically heated small loops, compute that the upward motion in one footpoint takes place at coronal temperatures. This shows that the coronal lines with formation temperatures greater than 10^5 K as the one of O V 1218 Å, should be blueshifted. Recent results measure blueshifts for plasma hotter than $10^{5.7}$ K, so this model is still in disagreement with observations. However, one should be cautious with the observations since they are derived from averages along the SUMER slit which scans all the region and not just the bright network patches.

The fact that the redshift is decreasing when we observe lines with formation temperatures higher than 10^5 K, is explained by Hansteen (1993) as a result of the circular geometry of the loops. The direction of propagation of the acoustic pulses at the crest of the loop forms an important angle with the line of sight, while near the feet, in the transition region, this angle is nearly zero. This means that the projection of the plasma motion along the line of sight, at the crest of the loop, which has coronal temperatures, is weaker and therefore the measured redshifts smaller. The passage from redshits to blueshifts can also be predicted by a new version of this model (Hansteen *et al.* 1996) which includes the effect of MHD waves. The computed Mg IX (368 Å) line is found blueshifted by 15 km s^{-1} which is still too high in respect with the recent observations (see Table 1).

Chae *et al.* (1998) suppose that the downflow along a vertically oriented flux tube is weakened in its coronal part, due to the increase of the cross section of the flux tube with height. They calculated the steady flow along a flux tube with variable cross section and their results are in agreement with the variation of redshift with formation temperature (see Table 1) of the spectral lines observed.

The various mechanisms take place inside flux tubes, like loops or spicules, which means that the magnetic field seems to be a necessary condition. The only exception is the model of Reale *et al.* who use isotropic thermal conduction, which implies plasma motions without the influence of a magnetic field. The fact that many observers find a correlation between high intensity magnetic fields and strong Doppler shifts, in the quiet sun as well as in active regions, reinforces the idea of including the magnetic field in the theoretical simulations.

The relation between observed intensities and Doppler shift is an observational result that is commented in theoretical works (Hansteen 1993, Reale *et al.* 1996, 1997). However, the comparison with observations is not possible because the modelled structures are too small to be detected individually, as mentioned above.

As a final remark, let us note that the theoretical studies give a geometry of the magnetic field in which the transition region plasma is embedded in a coronal loop or in a funnel anchored in the network, and extends upwards to the low corona. In this picture, considered as the 'standart model', the energy balance includes two terms: The thermal conduction from the corona along the magnetic field lines, which heats the plasma, and the radiation losses which cool it. However, this model fails to reproduce the radiated energy in the temperature range of 10^4-10^5 K. This energy is higher than the emitted by a thermal conduction heated plasma. This means that the low transition region is not in thermal contact with the corona. To overcome this difficulty the low transition region could be described by low altitude, cool loops, where the thermal conduction is unefficient (e.g. Antiochos & Noci 1986). These authors propose other mechanisms for the heating of the loops besides thermal conduction. Roumeliotis' (1991) model is the only one which follows this alternative view for the transition region structure.

A lot of work has been carried out since the pionner work of Doschek *et al.* (1976) regarding observations and theoretical computations of the redshifts in the transition region. However, the mechanism responsible for this phenomenon is still unknown. As with the coronal heating mechanism, which is certainly connected with the redshifts of the transition spectral lines, the answer must by searched in the observation of small features still unresolved by the current generation of instruments. For both problems higher resolution observations will significantly contribute to their solution.

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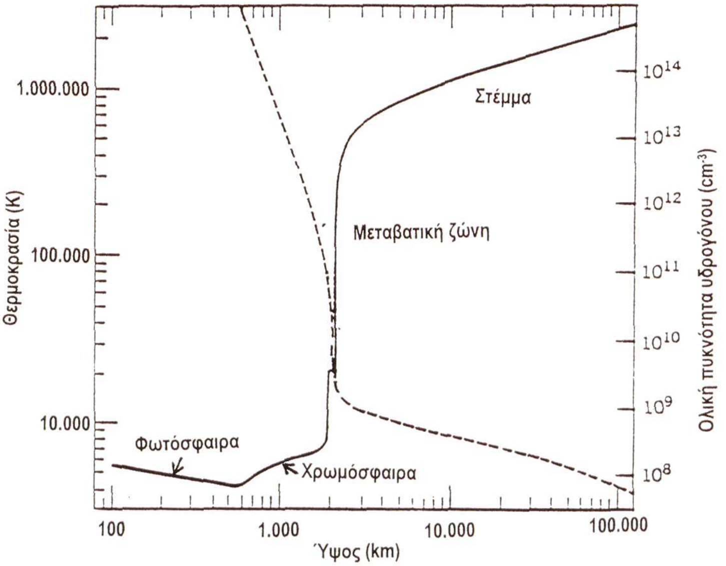
ΠΕΡΙΛΗΨΗ

Μετατοπίσεις Doppler στὴ μεταβατικὴ ζώνη τοῦ Ἡλίου

Ἡ παρούσα ἐπισκόπηση πραγματεύεται τὸ πρόβλημα τῆς παρατηρούμενης μετατόπισης πρὸς τὸ ἐρυθρὸ τῶν φασματικῶν γραμμῶν τῆς Μεταβατικῆς ζώνης, ἡ ὁποία ἐκπέμπει στὸ ὑπεριῶδες. Παρουσιάζονται οἱ παρατηρήσεις τῶν τελευταίων δεκαετιῶν, ἰδιαίτερα δὲ τῶν παρατηρήσεων ποὺ ἔχουν γίνει τὰ τελευταῖα ἔτη ἀπὸ ὄργανα σὲ δορυφόρους. Ἐπιπλέον, ἀναπτύσσονται οἱ ἐπικρατέστερες θεωρητικὲς ἑρμηνεῖες γιὰ τὶς κινήσεις ποὺ παρατηροῦνται στὴ Μεταβατικὴ ζώνη. Ἡ ἐπισκόπηση αὐτὴ συμβάλλει στὴν κατανόηση τῶν φυσικῶν διαδικασιῶν ποὺ λαμβάνουν χώρα στὸ σημαντικὸ αὐτὸ στρῶμα τῆς ἡλιακῆς ἀτμόσφαιρας, ἐνῶ παράλληλα ἐπισημαίνει τὰ ἀνοικτὰ ἀκόμη θέματα.

Ὁ Ἀκαδημαϊκὸς κ. **Γ. Κοντόπουλος**, παρουσιάζων τὴν ἀνακοίνωση, εἶπε τὰ ἑξῆς:

Ἕνα ἀπὸ τὰ ἄλυτα προϐλήματα τῆς φυσικῆς τοῦ Ἡλίου εἶναι ἡ ὑψηλὴ θερμοκρασία ποὺ ἀναπτύσσεται στὸ ἀνώτερο τμῆμα τῆς ἀτμόσφαιράς του, τὸ στέμμα. Ἐνῶ ἡ ἐπιφάνειά του, στὸ ἐπίπεδο τῆς φωτόσφαιρας, ϐρίσκεται σὲ θερμοκρασία 6.000 Kelvin, στὴ χρωμόσφαιρα ἡ θερμοκρασία ἀνεϐαίνει στὰ 20.000 Kelvin, ἐνῶ μερικὲς ἑκατοντάδες χιλιόμετρα πιὸ ψηλὰ φτάνει τὸ 1.000.000 Kelvin.



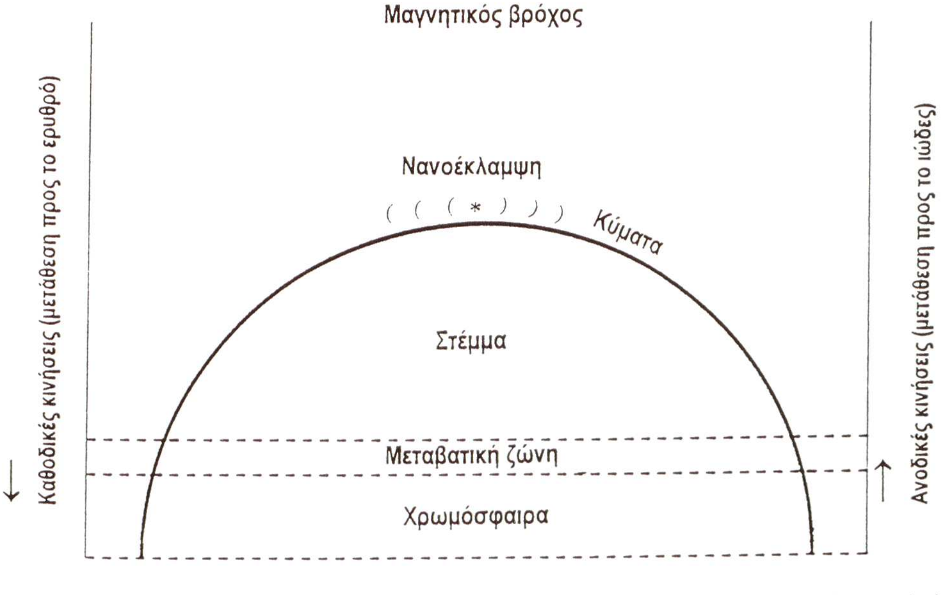
Σχῆμα 1. Διάγραμμα μεταϐολῆς τῆς θερμοκρασίας (συνεχὴς γραμμὴ) καὶ τῆς πυκνότητας (διακεκομμένη γραμμὴ) μὲ τὸ ὕψος σύμφωνα μὲ ἕνα θεωρητικὸ μοντέλο γιὰ τὸν ἤρεμο ἥλιο.

Ὁ μηχανισμὸς ποὺ εὐθύνεται γι' αὐτὴν τὴ ραγδαία αὔξηση τῆς θερμοκρασίας εἶναι ἄγνωστος καὶ πρέπει νὰ ἐνεργοποιεῖται στὴ μεταϐατικὴ ζώνη, τὸ λεπτὸ στρῶμα τῆς ἡλιακῆς ἀτμόσφαιρας μεταξὺ χρωμόσφαιρας καὶ στέμματος, τὸ ὁποῖο ἔχει εὖρος μόνο μερικῶν ἑκατοντάδων χιλιομέτρων. Στὴν παροῦσα ἐργασία γίνεται μιὰ ἀνασκόπηση τῆς μέχρι τώρα μελέτης τῆς μεταϐατικῆς ζώνης.

Ἡ μεταϐατικὴ ζώνη ἀκτινοϐολεῖ κυρίως στὴν ὑπεριώδη περιοχὴ τοῦ φάσματος. Γιὰ τὸ λόγο αὐτὸ συστηματικὴ παρατήρησή της ἔχει γίνει τὰ τελευταῖα ἔτη ἀπὸ δορυφόρους. Χαρακτηριστικὸ τῆς περιοχῆς αὐτῆς εἶναι οἱ παρατηρούμενες συστηματικὲς μετατοπίσεις πρὸς τὸ ἐρυθρό, οἱ ὁποῖες ἀντιστοιχοῦν σὲ καθοδικὲς ταχύτητες, δηλ. πρὸς τὴν ἐπιφάνεια τοῦ Ἡλίου, περίπου δέκα χιλιομέτρων τὸ δευτερόλεπτο. Ἡ συμπεριφορὰ αὐτὴ εἶναι ἀδύνατο νὰ ἐξηγηθεῖ ὡς συνολικὴ κίνηση τοῦ ὑλικοῦ πρὸς τὸν ἥλιο, διότι θὰ προκαλοῦσε τὴν ἐκκένωση τοῦ στέμματος σὲ διάρκεια μισῆς ὥρας.

Ἡ μεταβατικὴ ζώνη, ὅπως καὶ ἡ χρωμόσφαιρα, καλύπτεται ἀπὸ λαμπρὲς δομὲς ποὺ σχηματίζουν δίκτυο. Ὅπως φαίνεται στὴν εἰκόνα 1 τῆς παρουσιαζόμενης ἐργασίας (σελ. 70), οἱ λαμπροὶ σχηματισμοὶ τοῦ δικτύου περικλείουν περιοχὲς μικρότερης ἔντασης. Πρόσφατες παρατηρήσεις, μεταξὺ τῶν ὁποίων καὶ μιὰ μὲ συμμετοχὴ τῶν κ. Γοντικάκη καὶ κας Δάρα, διαπιστώνουν πιὸ ἔντονες μετατοπίσεις πρὸς τὸ ἐρυθρὸ τῶν λαμπρῶν σὲ σχέση μὲ τοὺς σκοτεινοὺς σχηματισμούς.

Οἱ θεωρητικὲς ἐργασίες βασίζονται στὴν παραδοχὴ ὅτι ἡ συνολικὴ ροὴ στὴ μεταβατικὴ ζώνη εἶναι μηδέν. Ἡ γεωμετρία τοῦ μαγνητικοῦ πεδίου ποὺ εἶναι ἀποδεκτὴ γιὰ τὴν μεταβατικὴ ζώνη, ἀντιστοιχεῖ σὲ συγκέντρωση τῶν μαγνητικῶν γραμμῶν στὶς λαμπρὲς περιοχὲς τοῦ δικτύου. Οἱ δυναμικὲς γραμμὲς τοῦ μαγνητικοῦ πεδίου ἀποκλίνουν μὲ τὸ ὕψος. Στὸ στέμμα ὁρισμένες μαγνητικὲς γραμμὲς συνδέονται μεταξύ τους, σχηματίζοντας μαγνητικοὺς βρόχους.



Σχῆμα 2. Ἡ γεωμετρία ἑνὸς δισδιάστατου βρόχου. «Μέτωπα κύματος» διαδίδονται ἀπὸ τὴν κορυφή, ὅπου δημιουργοῦνται οἱ νανοεκλάμψεις, πρὸς τὴν ἐπιφάνεια τοῦ Ἡλίου. Οἱ θέσεις τῆς χρωμόσφαιρας, μεταβατικῆς ζώνης καὶ τοῦ στέμματος δὲν σχεδιάζονται ὑπὸ κλίμακα.

Μία ἀπὸ τὶς πιὸ ἐλπιδοφόρες θεωρητικὲς ἑρμηνεῖες τοῦ φαινομένου τῶν μετατοπίσεων πρὸς τὸ ἐρυθρὸ ἀναφέρεται σὲ μαγνητοακουστικὰ κύματα τὰ ὁποῖα δημιουργοῦνται ἀπὸ μικρὲς ἐκλάμψεις (νανοεκλάμψεις) στὶς κορυφὲς τῶν βρόχων, καὶ διαδίδονται πρὸς τὴ μεταβατικὴ ζώνη. Πρόκειται γιὰ κύματα συμπίεσης (ὅπως τὰ ἠχητικὰ) ποὺ διαδίδονται παράλληλα πρὸς τὸ μαγνητικὸ πεδίο, μὲ τὴν ταχύτητα Alfvèn τοῦ πλάσματος. Καθὼς τὸ πλάσμα συμπιέζεται, κινεῖται πρὸς τὰ κάτω, ἐνῶ ἡ ἀνοδικὴ κίνηση συμπίπτει μὲ τὴν ἀραίωσή του. Τὸ πυκνότερο πλάσμα εἶναι λαμπρότερο καὶ ἔχει μεγαλύτερη συνεισφορὰ στὸ σχηματισμὸ τῆς φασματικῆς γραμμῆς. Ἔτσι, κατὰ μέσο ὅρο, ἡ μετατόπιση Doppler εἶναι πρὸς τὸ ἐρυθρό, ἂν καὶ ἡ συνολικὴ ροὴ εἶναι μηδέν.

Αὐτὴ ἡ θεωρία, καθὼς καὶ ἄλλες θεωρητικὲς ἑρμηνεῖες, βασίζονται σὲ ὑποθετικὲς ἡλιακὲς δομὲς ποὺ δὲν ἔχουν ἀκόμη παρατηρηθεῖ (ὅπως οἱ νανοεκλάμψεις). Ἑπομένως πρέπει νὰ γίνουν συστηματικὲς παρατηρήσεις μὲ τὴ μέγιστη δυνατὴ διακριτικὴ ἱκανότητα. Στὴν κατεύθυνση αὐτὴ συμβάλλουν οἱ πρόσφατες συστηματικὲς παρατηρήσεις ἀπὸ δορυφόρους, στὶς ὁποῖες συμμετέχουν ὁ κ. Γοντικάκης καὶ ἡ κα Δάρα.