АСТРОФИЗИКА

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SPECTRAL SIGNATURES OF SOLAR STRUCTURES

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A review on physical properties of various regions of the solar atmosphere is given for both quiet and active sun. More typical morphological and spectral features for each region are presented. Possible genetic relations between solar structures are indicated.

1. *Introduction.* The findings of research in the Solar atmosphere may help interpret the stellar spectra, at least for stars of spectral classes F and G.

Stellar atmospheres can be studied by scanning the surface of the star, using either the companion (in the case of double stars) or the stellar rotation as for Doppler-Zeeman Imaging methode (Semel,1995). For the long lived structures, stellar rotation introduces a modulation of the spectral features, in which case structures are considered to constant in time. In the present paper we shall propose a spectral method, in which the variation of spectral lines is studied generally in relation to the rotation of the star. We shall review specific spectral characteristics of certain solar structures, which can help in identifying the structures in the stellar atmosphere.

Traditionally, the Sun's atmosphere is divided into three layers - the photosphere, the chromosphere and the corona - and radially, into the Quiet and Active Sun. The two main phenomena which structure the solar atmosphere are the convection and the magnetic field, which guide the energy flow and/or the material flow, with higher efficiency in chromosphere and in corona. The existence and the variation of the Active Sun is due to the magnetic field. On the other hand, convection is the cause of the appearance of Photospheric Granulation, of Supergranulation, and probably of the Giant Cells (Unipolar Magnetic Regions).

In the following sections we shall mention - for a limited number of solar structures - a short morphological description, their origin (how they may be generated), their general properties, and their spectral characteristics. These may help in detecting these structures in the stellar atmosphere. We shall limit the present paper to the discussion of the visible spectrum.

In stellar atmospheres the structures may have different geometrical dimensions and small variations in physical characteristics with respect to the Sun. The differences observed between the stellar atmosphere and Solar quiet atmosphere, can be interpreted as differences in the physical conditions.

2. *Quiet sun.* The main characteristic of the quiet Sun is its homogeneity with regards to the spatial resolution expected from the rotation effect. An average model of the quiet atmosphere is given by the VAL-C model (Vernazza et al., 1981) in Fig. 1, which is always taken as reference for the quiet Sun atmosphere.

2.1. Photospheric Granulation. Morphology: Photospheric granules are the smallest convective elements of solar quiet atmosphere. They are irregular polygons. Granules are bright, surrounded by darker intergranules.

Origin: The granules are formed in the last 300 km of the convective zone, where convective instability occures because of hydrogen atom recombinations.

Physical Properties: The average granular diameter is 1000 km, and the distance between granules is around 2000 km. The upward velocity is ~0.5 km/s and the temperature jump relative to the intergranular material of 700 K. The granule - intergranule contrast is about 15%.

Spectral detection: The integrated solar spectrum, covering granules and intergranules, is revealed in a C-shaped distortion of spectral lines. The line width also shows variations with time, relative to the Solar Activity cycle (Livingston,1994).

2.2 Spicules. Morphology: Spicules are the fine structures of the solar chromosphere. At the limb they appear as inclined cylinders penetrating the corona. In fact, they are chromospheric plasma trapped in magnetic flux tubes and ejected into the corona.

Origin: Spicules form at the boundary of supergranules. Several models propose upward mechanism for the plasma. The most likely models are those based on the pinching of magnetic field.

Physical Properties: The geometrical dimensions are: height ~11000 km, diameter ~800 km; tilt of 30° with in respect to the local vertical. The upward velocity is 40 km/s; the temperature is about 10^4 K and the density 10^{11} cm^{-3} at 6000 km. There are roughly $7 \cdot 10^6$ spicules on the solar surface, i.e. covering 1% of the solar surface. Spicules continually feed the corona with plasma, which is partially lost through solar wind.

Spectral detection: The upward motion of the plasma and the optically thick Ca II K (3934Å) and H (3968Å) lines produce a higher intensity of the K2v or H2v

Table 1

INTENSITY RATIOS IN THE SOLAR SPECTRUM

Spectral line	Intensity ratio	Disk center	Irradiance
Ca II K	I(K2v)/I(K2r)	1.11	1.12
Ca II K	I(K2v)/I(K3)	1.62	1.72
Ca II H	I(H2v)/I(H2r)	1.10	1.07
Ca II H	I(H2v)/I(H3)	1.68	1.73
HI	$I_0(H\alpha)/I_0(H\beta)$	0.91	1.15
HI	$I_0(H\alpha)/I_0(H\gamma)$	1.03	1.01
HI	$I_0(H\alpha)/I_0(H\delta)$	1.12	0.77

components with respect to the K2r (H2r) or to K3 (H3) (see Table I). Another spectral signature of spicules is the emission of He I lines (5875 Å and 10830 Å).

2.3 Supergranulation. Morphology: Supergranulation is a convective feature of the photosphere, clearly showing the material flow from the center to the boundary. Between two adjacent supregranules we find the faculae (flocculis), which are the basis of the spicules. The distribution of flocculis on the surface gives the appearaence of a net, called chromospheric network.

Origin: Supergranulation is due to a convective instability in the convective zone, produced by the recombination of He I atoms.

Physical Properties: The diameter of a supergranule is around 30 000 km, and the lifetime is about one day.

Spectral detection: No direct detections possible, but the presence of spicules is a proof of the existence of the supergranules.

2.4 Quiet Corona. Morphology: The corona is the outerlayer of the solar quiet atmosphere. It is formed by a great number of arch shaped magnetic field tubes. Coronal Holes are regions of open magnetic field. Generally they are located on the solar magnetic pole.

Origin: The corona exists because the coronal arches are heated, but no generally accepted model exists for the heating mechanism; the Alfven Waves seem to be a good candidate (Ofman, 1994; 1995).

Physical Properties: The specific characteristics of the corona are its high temperature (10^6 K) and its low plasma density of about 10^8 cm^{-3} at the base and 10^5

cm^{-3} at four Solar radii. In Coronal Holes the temperature is ~1.6 10^6 K and the density one-third of the quiet corona. A strong temperature gradient (~10^{-2} °/cm) characterizes the transition region between chromosphere and corona.

Spectral detection: The intensity of the white-light corona is about 10^{-6} times that of the photosphere. The continuum spectrum is linear polarized. The spectral lines are due to forbidden transition, as FeXIV 5305Å, Fe X 6374Å. The chromosphere-corona transition provides a rich EUV solar spectrum.

2.5. Prominences. Morphology: The prominence, or filaments when seen on the disk, are the cool components of the corona. They have the appearance of a fine curtain suspended by the magnetic field over the photospere B''=0 line. They are well observed in H I Hα and Ca II K lines, 6563 Å and 3934 Å respectively. In visible solar spectrum the filament is in absorption mode while the prominence at the limb, is in emission.

Origin: The formation of the prominences by condensation of the coronal plasma under the effect of the magnetic field is not generally accepted.

Physical Properties: Prominences are about 50 000 km high, and ~5000 km thick.They may range from 10^4 to 10^5 km in length. The temperature is 6 000^0-10 000^0 K and the density of 10^{10} to 10^{11} cm^{-3}. The magnetic field is 5-25 G. Prominence may undergo ejection processes, in which case velocities of a few 10^2 km/s may be observed. This is followed by a Coronal Mass Ejection.

Spectral detection: The spectrum of a prominence is very similar to that of the chromosphere. The filament is in absorption in Hα, and invisible in Hγ. So the ratio of these two lines may be an indicator of filaments. The prominence has emission lines in K, Hα and He I 10830Å.

2.6. Global Magnetic Field. The Global Magnetic Field of the Sun is that of the quiet Sun, concentrated on supergranules boundaries. The magnetic field has the effect of a background field even if they are no Active Regions (see Kitt Peak National Observatory magnetic field dayly observations)

The Sun's magnetic flux varies with the Solar Activity. At the minimum, the flux is 8 G. It reaches to 20-25 G during the Sunspot maximum, due to the high number of active regions (Lean,1994).

3. *Active Sun.* Since the spatial distribution of active region being random, in certain limits, the solar rotation may introduce some modulation in spectral lines.

3.1. Sunspots. Morphology: Sunspots are dark limited areas of the photosphere. A sunspot consists of a dark "umbra" and a "penumbra", less dark. They are produced by strong magnetic fields. They exhibit a bipolar structure, nearly parallel to the equator. The magnetic polarity of the preceding spot and that of the following spot are

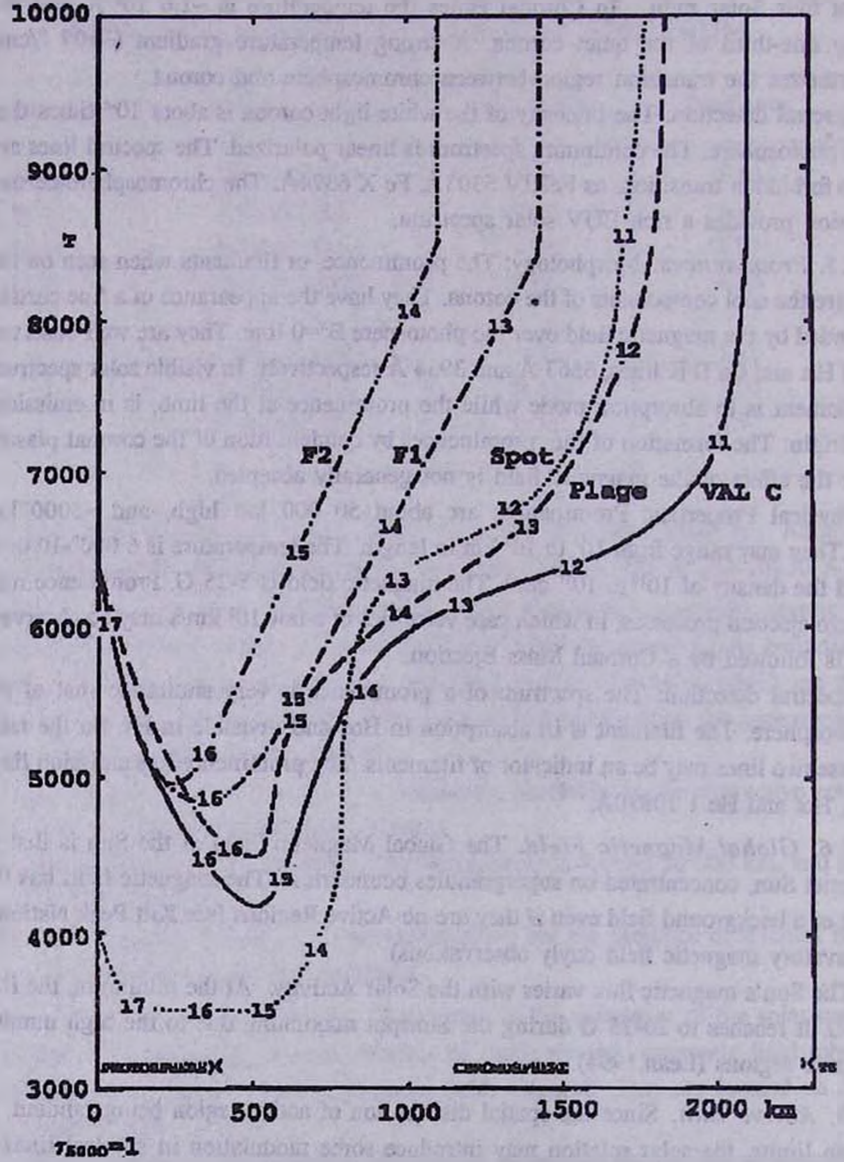

Fig. 1. Comparison of five models of solar armosphere structures: the Quiet Atmosphere (Val-C), the Facular Plage (Plage), the Sunspot (Spot), and Flares (F1 and F2). The numbers indicate the total number of hydrogen atoms.

opposite, and are of reverse polarity in either hemispheres. Sunspots accumulate in "Sunspot Groups".

Origin: *Sunspots are form* when magnetic field tubes are close up by the photospheric velocity field. The magnetic field concentration prevents the energy flux reaching the solar surface. Consequently, the photosphere is locally cool with respect to the environment.

Physical Properties: The spots are almost circular, and can extend to dimensions of one-twelfth the solar diameter. The magnetic field can reach 2 000-3 000 G, and sometimes even 5000 G. The effective temperature and the gas pressure are 0.7 and 0.4 times that of the quiet photosphere, respectively(the Fig. 1 gives the sunspot model of Avrett et al,1981). The average life-time of a sunspot is a few days to a week, but can also be as long as 3 months. The larger the umbra,the stronger the magnetic field and the cooler the temperature is (Bray and Loughhead, 1964).

Spectral detection: *As atmosphere of a sunspot* is cooler than that of the photosphere, the line spectrum is rich in molecular bands, and the continuum spectrum is close to that of stars of class dK0. The most characteristic molecular bands are (Sotirovski, 1971):

-C2 (0,0 band head 5165Å) absent in sunspot, present in the photosphere.

-CN (0,0 band head 3883Å) unchanged in sunspots and in the photosphere.

-MgH(0,0 band head 5212Å) more intense in sunspots than in the photosphere.

-TiO(0,0 band head 5166Å) strong in sunspots, and practically absent in the photosphere.

3.2. Facular Plage. Morphology: The facular plage, or Plage, is a structure of the high photosphere and chromosphere. It is hotter and brighter than the environment. It is composed of a great number of "Chromosphric grains". The plage surrounds the Sunspot group and appears before and disappears after it.

Origin: The medium intensity magnetic field transports the energy toward the surface and heats the facular plage.

Physical Properties: The magnetic field intensity is around 50 to 200 G, and the magnetic flux is 5-8 10^{8} Mx. The magnetic structure is generally bipolar, but may also be multipolar. The diameter of the grains is less than 1000 km, and the temperature greater than 900 K (see Fig. 1 Plage model of Lemaire, 1981). Plage range in area from 5 to 20 times that of Sunspot Groups.

Spectral detection: The facular plages are quite visible in Ca II K and H lines and the brightast regions are visible in Hα. A good index for plage is the radio emission in 10.7 cm. Plages can also be identified by the ratio of hydrogen lines (Hiei et al., 1981).

3.3. Coronal Condensation. Morphology: Facular plages in the Active Region are continuous in altitude, with magnetic arches forming a "dome"- shaped structure, the "Coronal Condensation". The plage is in fact the cool end of the hot coronal arches.

Origin: The formation of Coronal condensation is related to that of the AR.

Physical Properties: The temperature is somewhat higher $T=3\cdot10^6$ K, and the electron density is aboud 10^{10} cm^{-3}. Coronal condensation can reach heights of 1/10 $R_\odot$.

Spectral detection: The corona of an Active Region shows a characteristic emission, the forbidden lines (Fe XIV 5303 Å, Ca XV 5694 Å), detected only at the solar limb. On the disk the active regions are "visible" in EUV spectrum, in soft X-rays or in microwaves.

3.4. The Active Region. Morphology: An Active Region (AR) is a configuration consisting of a Sunspot Group, surrounded by a facular plage, and often a filament separating plages of opposite magnetic polarities. Coronal arches, flares and associated phenomena are also components of the Active Region. From the magnetic point of view, an AR may be bipolar or complex (Semel et al., 1991).

Origin: Active Regions are formed by the emergence of magnetic fields close to Pivot Points (Mouradian et al.1987), which are small regions in rigid rotation.

Physical Properties: An Active Region can extend in longitudes of over 20-30°, nearly parallel to the equator. It is located in latitude bands of 10 to 30°, in either hemisphere. During the solar cycle ARs migrate from high latitudes (~35-40°), toward the equator. Often a number of Active Regions are grouped in a limited area, the "Complex of Activity" (Gaizuskas et al., 1983). At the birth of an Active Region, the first composant which appears is the compact and brilliant facular plage, then the Sunspot Group, and in the last phase the Filament. The decreasing phase starts with the disappearance of the Sunspots, then of the Facular Plage, and at the end that of the Filament.

Spectral detection: An Active Region is detected as the sum of its components.

3.5. Flares. Morphology: The Flare is a sudden energy release in the chromosphere and corona, lasting anywhere from a few minutes to one or two hours. The whole solar spectrum is concerned, from elementary particles, γ or X-rays to long radio wave-lengths. The Flare starts by a short "impulsive" phase of a few seconds, and continues with the "gradual" phase. They are generally located inside an Active Region or between two close ARs.

Origin: The source of energy release is the Active Region's corona. The magnetic field accelerates and guides the particles, which tumble down into the chromosphere or upper the photosphere. The magnetic complexity of the Active Region facilitates the release of big flares.

Physical Properties: The energy released by Flare can range up to 10^{28} to 10^{32} erg, and is often accompanied by a "Coronal Mass Ejection" (CME). A flare is formed by a number of "Flaring Arches" (Mouradian et al, 1983; Martine & Svestka, 1988). The plasma temperature rages from 10^4 to 10^7 K.

Spectral detection: The principal spectral lines (H_α, H_β, H_γ, H, K, 10830, among others) are in emission, their profiles are wide and the wings spread (Svestka, 1976). The flares producing accelerated particles induce X-rays and/or γ-rays. In very energetic flares, continuum spectrum emission, appears i.e. the "White Light Flares" (WLF). The spectra of WLF can be of two types (Machado et al., 1980): F1 and F2 (Fig. 1).

-Type I WLFs are the flares for which all the emission maxima are simultaneous. The Balmer jump may be from 0.1 to several times of the continuum. The Balmer lines are intense and broad, whereas the metallic lines are normally wide, as they are for non-WLF. A "blue excess" of the continuum may be detected for this type of flare. Type I flares belong to the F2 model (Fang & Ding, 1994).

-Type II WLFs are due to the H^- emission of the upper photosphere. The maxima of the various spectral features are not simultaneous. The Balmer jump is normal. Fang and Ding class the type II WLF as model F1 flares.

3.6. Coronal Mass Ejection. Morphology: Coronal mass ejection is a very faint long-scale structure, visible over the solar limb.

Origin: The corona plasma is pushed toward the outer corona triggered by a flare or a prominence disruption.

Physical Properties: CME generally covers up to 60° around the solar limb. The speed of ejection is of the order of 100 to 1200 km/s. Often coronal mass ejection is associated to type II or IV radio bursts. Some CME extend to 4.5 $R_\odot$.

Spectral detection: Coronal mass ejection is observed in white light at the Solar limb.

3.7. Solar Wind. Morphology: Solar Wind is a continuum flux of elementary particles toward the interplanetary space. It is a convective process in a divergent monopolar magnetic field.

Origin: Solar Wind emanates from Coronal Holes, principally those of North and South poles.

Physical Properties: The expansion velocity of the plasma is about 15 km/s. The two polar Coronal Holes will come together at a distance of 1 to 2 $R_\odot$ and will form a "Neutral Current Sheet", located around the equatorial plane. At 1 AU the velocity is 400 km/s, the density ~5 cm^{-3} and the T_{prot}~10^4 and T_{elect}~10^5 K. The magnetic field is $5 \cdot 10^{-5}$ G. The solar wind is divided into four alternative magnetic sectors: two high speed and two low speed.

Spectral detection: In the case of the Sun the detection is made in situ, by satellite.

3.8. Activity Cycle. Morphology: The Activity Cycle is an almost periodic variation of structures of the active Sun (Sunspot, Facular Plages, Flare, and so on). The number and importance of these structures vary roughly in phase.

Origin: All the structures participating in the activity cycle are of magnetic origin, so the evolution of the cycle is strongly related to that of the dynamo.

Physical Properties: An Activity Cycle occures between two minima. The increasing phase is more rapid than the descreasing, representing 1/4 and 3/4, respectively, of the total cycle duration. In the Solar case, the cycle is about 11 years for Sunspot numbers, but 22 years for the magnetic field cycle. Note also the longlasting cycle of 80-120 years. In the past, the Solar cycle has weakened, as in the 17th century,over a period of about 70 years. The magnetic flux grows from minimum to maximum by a factor of 2.5 to 3.

Spectral detection: The most sensitive spectral feature is the Ca II K line, due to the variation in the number of Facular Plages. Some other spectral lines also show intensity and width variations in phase with the Solar Activity (Livingston, 1994).

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СПЕКТРАЛЬНЫЕ ОСОБЕННОСТИ СОЛНЕЧНЫХ СТРУКТУР

З. МУРАДЯН

Дан обзор физических свойств различных областей солнечной атмосферы как для спокойного, так и для активного солнца. Для каждой области приведены наиболее характерные морфологические и спектральные оцобенности. Указаны возможные генетические связи между солнечными структурами.

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