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LIMB EFFECT ALONG THE CENTRAL MERIDIAN OF SOLAR DISK

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Abstract. The well known Fe I 6302 Å spectral line has been measured by a special equatorial solar spectrograph designed at the Belgrade Astronomical Observatory. The first results showing the limb effect along the central meridian (for $0° < \theta < 52°$) were obtained. The proposed theories for the limb effect have been analysed. A suggestion was made for the interpretation of the obtained results in the vicinity of the solar equator.

Introduction

As descovered by Halm (1907), and confirmed by many other observers, almost all absorption lines in the spectrum of the solar limb are shifted to the red as compared with their wavelengths at the center of the solar disk. The phenomen was named „limb effect". Its magnitude varies for different wavelengths, but is usually a few milliangstroms or, if described by Doppler displacement, relative radial velocities of several hundered meter per second were obtained. This effect becomes much more interesting especially after surprising results of Howard and Harvey (1970) about variations of the equatorial rotational velocity of the sun.

Spectoscopic measurement of radial velocity at any point on the solar disk (V_0) consists of the folowing components along the sight — line:

$$V_o = V_{sr} + V_{er} + V_{eo} + V_{ls} + V_{le} \qquad (1)$$

where V_{sr} is the component of the velocity of solar rotation; V_{er} and V_{eo} are the components of the observer's velocity due to the rotation and the orbital motion of the earth, (both could be evaluated with a sufficient accuracy).

There are two components which remain uncertainly determined, namely, large scale motions on the solar surface (V_{ls}), and the limb effect (V_{le}). In such a way limb effect, although known for long, but not determined with a great precision, arose recently great interest among the solar physicist.

The limb effect V_{le}, expressed in km/s, is assumed to be a function of μ alone, given in the form

$$V_{le}(\mu = 1) \equiv 0; \quad \mu = [1 - (R/R_{\odot})^2]^{1/2} \tag{2}$$

the shape of which is unknown as well as its physical origin. That is why it has to be found empirically for every value of μ.

It was evident from measurements that the displacement of spectral lines at solar limb was greater than expected gravitational red — shift, predicted by Einstein's general relativity, which, for the case of the sun should be: $GM_{\odot}/c^2R_{\odot} = 2.12 \times 10^{-6}$ i.e. $V = 0.636$ km/s. The difference could not be due to measurements errors for a) gravitational shift has been checked in laboratory with error to less than 1%, and b) it should be constant, whereas, measured shift shows a heliocentric angle θ dependance, found by many autors. It is obvions that besides the gravitational shift ($GM_{\odot}/c^2R_{\odot}$) there exists another, always present, we shall call it residual shift (δR_{θ}) which changes the shape and the magnitude of the gravitational shift. Observations give the resultant shift which might be expressed as

$$\Delta_{\theta}\,(\text{km/s}) = GM_{\odot}/c^2R_{\odot} - \delta\, R_{\theta} \tag{3}$$

There are three theories or, better, hypotheses that proposed the explanation of the shape and origin of the function $\delta\, R_{\theta}$.

Schröter (1957) considerably modified St. John's the radial — current theory. According to Schröter's theory, what one actually observed is a blue — shift at the center of the disk caused by rising elements of solar plasma. There must be, of course, descending elements as well, but these are much cooler, so we are getting less light from them. Close to the limb these radial currents have small line of sight components and cause small blue shift ($\delta\, R_{\theta}$). As a result the red — shift Δ_{θ} is smallest in the center and the largest at the solar limb. According to Schröter the resultant shift is given by:

$$\Delta_{\theta}\,(\text{km/s}) = 0.636 - V\beta \cos\theta \tag{4}$$

where V (km/s) is vertical current velocity in the disk center β — quantity which depends mainly on the granulation contrast.

Another explanation for the limb effect was proposed by Hart (1974). According to his hypothesis, solar lines in the center of the disk are also shifted to blue. The blue-shift decreases towards the limb causing the observed increase of the resultant red-shift (Δ_{θ}). There is a basic difference in the proposed theories about the explanation of the origin of the central blue-shift. Hart has accepted Spitzer's (1950) suggestion that a blue-shift is a result of collisions between the absorbing atoms and the neutral hydrogen atoms. From the atomic theory Hart has computed the magnitude and the shape of the residual shift, not taking into account the classical impact theory but the repulsive forces due to the interaction at small distances, using the Lennard—Jones potential approximation. The blue-shift (β) is proportional to the density of hydrogen atoms, and therefore is greater at the center of the disk, wherefrom we get the spectral lines originated in the deepest layer:

$$\beta = 2\pi\,(3\pi/8)^{\frac{2}{5}}\, n_H\, V^{\frac{3}{5}}\,(C_6/\hbar)^{\frac{2}{5}}\, S(\alpha) \tag{5}$$

where:

β — is the blue-shift
n_H — the number density of hydrogen atoms
C_6 — coefficients depending on the state of the atom
V — the relative velocity of colliding atoms
$S(\alpha)$ — a function which has been computed numerically and tabulated by Hindmarsh et al. (1967).

The third hypothesis about the possible origin of the limb effect was given by Pecker and Vigier (1973). They have exposed the idea according to which the residual shift (δR_θ) was originated by a non-linear photon-photon interaction, not considered in the frame of quantum electrodynamics, and implied the existence of a non-zero rest mass of the photon ($m = 10^{-48}$ gr). This hypothesis, in itself a very interesting new idea, is lacking elements for the complete determination of the function δR_θ. For the time being two of the mentioned ideas: Radial current and Collisional hypothesis, complete with equal probabilities for the explanation of the limb effect (V_{le}) in different wavelengths. Observations could be the only arbiter in the dilemma which of the two suggested theories is the correct one. With that aim we undertook our observations.

Observations

Observations in the absorption line Fe I 6302 Å were done by the newly constructed equatorial spectrograph of the Belgrade Astronomical Observatory (Kubičela 1975).

It was programmed to observe sight-line velocities at 9 selected points along the central meridian of the solar disk. The zero velocity reference has been obtained from the sky spectra at $0.2\,R_\odot$ (figure 1). The sky spectra have been used assuming that the scattered sky radiation contains the same amount of positive and negative sight-line rotational velocity components, and that the contributions of photospheric small and medium scale velocities are averaged to some extent. The time resolution of the two successive observations (one per day) has been selected according to the low space resolution of our programme. The approximate deflection of the central meridional line, due to the daily solar rotation, is shown in Figure 1, as well as the applied space resolution.

In order to diminsh the r. m. s. errors of the sight-line velocities, several spectrograms were obtained at each of the observed points. The series of observations was carried out from October 1974 till February 1975. The results of these measurements for each of the selected points are presented in the Table I. The sight-line velocities are referred to the velocity of the solar disk center.

Table I

Observed Sight-line Velocities

Date	The observed point										
1974/75	A	B	C	D	S	V	X	Y	Z	Sky	Δ
	m/s	m/s	m/s	m/s	m/s	m/s	m/s	m/s	m/s	m/s	m/s
Oct. 19.	+ 61	+ 8	— 5	+ 12	0	+ 32	+ 56	+ 63	+110	+ 81	+ 11
Jan. 11.	+108	+ 37	— 17	— 80	0	+ 4	— 17	+ 48	+ 64	+102	+ 32
Jan. 15.	+ 47	— 4	— 20	— 29	0	+ 11	— 35	+ 57	+ 86	+ 62	— 8
Jan. 16.	+ 60	+ 44	— 4	— 22	0	0	+ 11	+ 43	+ 77	+123	+ 53
Jan. 17.	— 42	+ 6	+ 13	+ 76	0	+ 18	+ 17	+ 24	+ 94	+ 83	+ 13
Jan. 18.	+ 53	+ 23	+ 18	+ 5	0	+ 14	+ 60	+ 53	+104	+ 83	+ 13
Jan. 19.	+ 16	— 44	— 11	— 5	0	+ 6	— 14	+ 27	+110	+ 58	— 12
Jan. 25.	— 19	— 18	— 42	+ 18	0	+ 11	— 28	+ 30	+ 42	+ 65	— 5
Jan. 27.	+ 52	+115	— 28	— 06	0	— 18	— 9	+ 31	+ 67	+ 33	— 37
Jan. 30.	— 73	— 14	— 27	— 3	0	—135	— 30	— 7	+ 45	+ 49	— 21
Febr. 1.	+ 62	+ 15	— 20	— 2	0	+ 3	+ 1	+ 35	+ 34	+ 65	— 5
Febr. 9.	+ 31	+ 27	0	+ 1	0	+ 26	+ 6	+ 30	+ 60	+ 78	+ 8
Febr. 10.	+ 9	— 14	+ 4	— 30	0	+ 28	— 7	+ 30	+ 60	+ 81	+ 11
Febr. 11.	+ 53	+ 1	— 21	0	0	+ 7	— 4	+ 28	+ 62	+ 67	— 3
Febr. 18.	— 17	— 43	— 48	— 33	0	— 47	— 58	— 12	+ 31	+ 42	— 28
Febr. 19.	+ 39	— 9	— 26	— 9	0	+ 1	— 18	+ 36	+ 65	+ 54	— 16
Mean:	+ 28	+ 8	— 15	— 7	0	— 2	— 4	+ 32	+ 69	+ 70	

Discussion

Measuring relative values of sight-line velocities (V_o) along the central meridian and assuming the random character of large scale velocities in a sufficiently long time interval, by taking the mean velocity values of two observations at the same heliocentric angle, one can interprete the obtained velocities as the limb effect only. In that case the right hand side of expression (1) is reduced to one term

$$V_o = V_{le} \tag{6}$$

V_{le} is equivalent to Δ_θ given by relation (3). The results of our measurements, given in Table I, are presented in Figure 2 a and 2b as solid lines. For the comparison the limb effect measurements done by Howard and Harvey (1970) are shown with the dotted line as well as is Plaskett's (1973) extrapolated limb effect function (7) with the dashed line, which reads:

$$V_{le} = -1{,}36\,(\mu - 1) + 0{,}735\,(\mu^2 - 1) \tag{7}$$

It is obvious from Figure 2a that the positive part of the obtained curve representing the limb effect has the expected trend. As neither of the limb effect theories offers a non monotonous function for Δ_θ, the problem appears in the explanation of negative values of the curve (Figure 2). Besides, in Figure 2b where unaveraged velocity values for Northern and Southern parts of the central meridian are presented, an obvious N—S asymetry is noticeable. The origin of this asymetry is not clear yet.

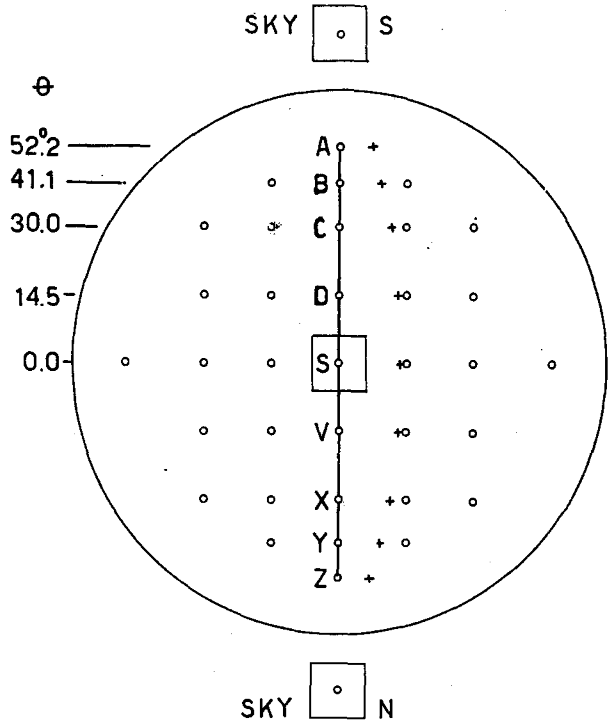

Fig. 1. — The programme of observations along the central meridian, space and time resolutions and reference sky points for the zero velocity.

As far as limb effect results are concerned, we are left under the impression that an explanation could be the existence of some kind of unknown stationary photospheric motion, which we did not eliminate by averaging the sight-line velocities. If sight-line component of that unresolved motion is denoted by V_{um}, then the measured quantity is a „combined" limb effect:

$$\Delta_{\theta} = GM_{\odot}/C^2R_{\odot} - \delta R_{\theta} + V_{um} \tag{8}$$

We wish to point out here that the shape of Plaskett's function (7) is similar to our curve (Figure 2). However he did not give any comment on his function for $\theta < 30°$.

We would suggest a more specific explanation for the combined limb effect. Namely, we suppose that a stationary down-ward motion in the vicinity of the equator produced the observed red shift (maximum in Figure 2b). The velocity of this motion is probably about 20 m/s.

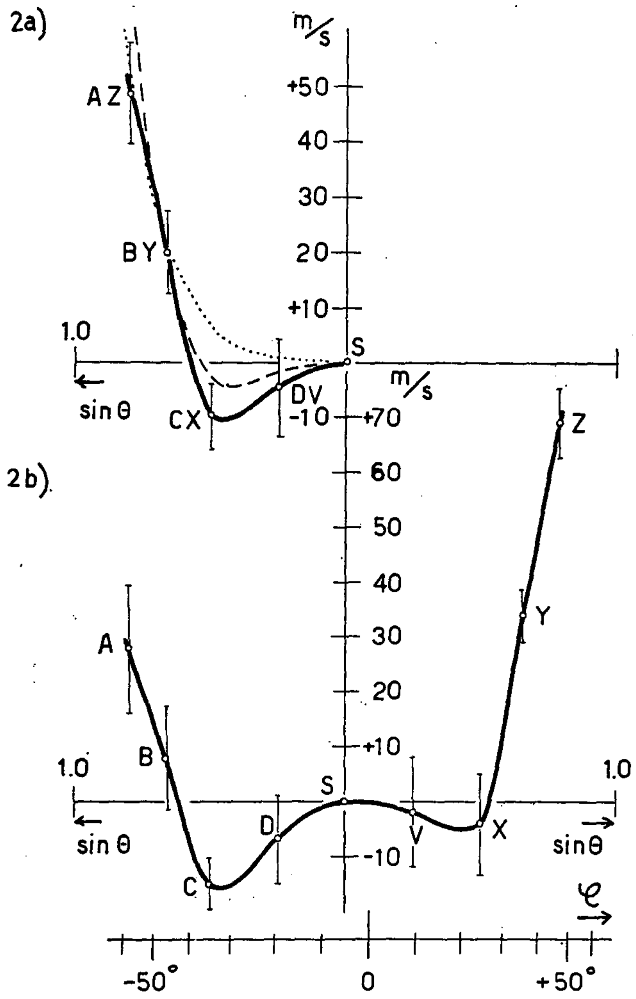

Fig. 2. — Measured limb effect averaged for Northern and Southern parts of the central meridian (2a) and unveraged (2b).

We expect the nature of the observed phenomena to become clearer from further observations.

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