SOLAR CORONA AS OBSERVED DURING FOUR TOTAL SOLAR ECLIPSES BY EXPEDITIONS OF THE ASTRONOMICAL INSTITUTE OF THE SLOVAK ACADEMY OF SCIENCES

J. Sýkora
Astronomical Institute of the Slovak Academy of Sciences,
059 60 Tatranská Lomnica, Czechoslovakia

ABSTRACT. A condensed summary of the solar corona study, performed within KAPG cooperation during four total solar eclipses, is given. Namely: a) polarizations in the emission lines and in the white light corona are discussed in connection with the structure of the coronal magnetic fields; b) some physical characteristics of the coronal loops have been found and their relation to the background magnetic field is underlined; c) responses of the disk solar activity in the variety of the coronal structures are studied; d) absolute photometry of the white light corona was a standard point of our solar eclipse program - intensities and electron densities are analysed for discrete coronal structures and in dependence from the position angle, and further, integral brightness and flattening are described as a function of the phase of the solar cycle; e) influence of solar activity on geophysical disturbances is demonstrated for one special case.

СОЛНЕЧНАЯ КОРОНА ПО НАБЛЮДЕНИЯМ ЧЕТЫРЕХ СОЛНЕЧНЫХ ЗАТМЕНИЙ ЭКСПЕДИЦИЯМИ АСТРОНОМИЧЕСКОГО ИНСТИТУТА СЛОВАЦКОЙ АН: Дается концентрированный обзор исследования солнечной короны, проведенного в рамках многостороннего сотрудничества КАПГ во время четырех солнечных затмений. Именно, a) поляризация в эмиссионых линиях и в белом свете короны обсуждается в связы со структурой коронального магнитного поля; b) были найдены некоторые физические характеристики корональных петель и подчеркивается их отношение к фоновому магнотному полю; c) изучаются отклики активности на солнечном диске в разнородности корональных структур; d) абсолютная фотометрия белой короны являлась стандартным пунктом программы наших затменных наблюдений - интенсивности и электронные плотности анализуются для дискретных корональных структур и в зависимости от позиционного угла, и кроме того интегральная яркость и сплющение короны описиваются как функции фазы солнечного цикла; e) влияние солнечной активности на геофизические возмущения демонстрируются для одного специального случая.

SLNEČNÁ KORÓNA AKO BOLA POZOROVANÁ ŠTYRMI EXPEDÍCIAMI ASTRONOMICKÉHO ÚSTAVU SAV ZA ÚPLNÝMI ZATMENIAMI SLNKA: V práci je podaný stručný prehľad najdôležitejších výsledkov štúdia slnečnej koróny, prevedeného v rámci mnohostrannej spolupráce akadémií vied socialistických krajín. Menovite: a) je diskutovaná polarizácia v emisných čiarach a v spojitom spektre koróny a ich súvislosť s magnetickým poľom v koróne; b) boli odvodené niektoré fyzikálne charakteristiky koronálnych oblúkov, pričom je podčiarknutá ich genetická súvislosť s hranicami polarít magnetického poľa; c) sú študované vplyvy aktivity na disku Slnka na rozmanitosť koronálnych štruktúr; d) absolutná fotometria bielej koróny bola štandardným bodom programu našich zatmeňových expedícií - intenzity a elektrónové hustoty boli stanovené pre diskrétne koronálne štruktúry a v závislosti od pozičného uhlu, okrem toho je popísaný priebeh integrálnej jasnosti a sploštenia koróny s časom a najmä v zmysle ich závislosti na fáze slnečného cyklu; e) vplyv slnečnej aktivity na niektoré geofyzikálne parametre je demonštrovaný pre jeden konkrétny prípad (31.7.1981).

1. INTRODUCTION

Astronomical Institute of the Slovak Academy of Sciences is from 1965 engaged in optical observations of the solar corona by means of the out-eclipse coronagraph (Lexa, 1965). Namely, the strongest emission lines of corona are observed regularly. A good number of interesting results were obtained on large-scale and long-termed distribution of the emission corona alone, on its connections with the same distribution of the photospheric magnetic fields, a star-like coronal index was involved, the total brightness, coronal rotation and coronal asymmetry were analysed in some details during solar cycles and coronal morphology was outlined for many of individual active regions.

All the mentioned results are out of the scope of the present review paper. Indeed, here we would like to describe different activity of our institute in the study of the solar corona, and namely, its investigation during total solar eclipses. It is clear that the solar eclipses give, in nature, another observational possibilites and in some sense they make possible to treat some scientific tasks better than it can be done outside of eclipses. The main reason to speak on this matter in this meeting follows from the fact that the mentioned eclipse research of the solar corona was included in the last two five-years programs of KAPG Working group 2.4 (1975-1980) and KAPG Project No.4 (1981-1985). That is why this paper can be understood as some report on the accomplished work.

Altogether, we have realized four expeditions to observe the total solar eclipses in Republique du Niger (1973), India (1980), USSR (1981) and Indonesia (1983). The scientific cooperation of "IZMIRAN" (Moscow) was very much acknowledged in the first three expeditions - it resulted in several common publications. Somewhat smaller collaboration was also with "GAIS" group (Moscow). The scientific program of the expeditions and methods of observations were most fully described by Rušin and Sýkora (1981).

2. RESULTS

a) Polarization in the emission lines and in the white light corona.

Growing attention have been devoted in the last two decades to the study of polarization in coronal emission lines, because it is still one of the best sources of information about the structure and strength of the magnetic fields in the solar corona. Observations of polarization were carried out during spacefligts and during total solar eclipses, as well. Earlier experimental results are too contradictory to hold the problem solved. The degrees of polarization in green line (Fe XIV 530.3 nm) have been found from rather high values - 55 % by Mogilevskij et al. (1960) to no polarization found by Beckers and Wagner (1971). In the theoretical papers of Charvin (1965), Hyder (1965) and House (1972) it was proved that polarization must exist in the green line Fe XIV 530.3 nm (as well as in other coronal lines for which the resonance fluorescence is considerable), provided, of course, that the depolarization factors are not substantial. The decisive role of the magnetic field for the degree of polarization and orientation of the plane of polarization (considering the classical Hanle effect) were discussed in a number of the papers mentioned above. The magnetic field in the corona (local and global) changes the nature of the resonance dispersion considerably, so that the study of the structure of the coronal magnetic field by means of polarization observations, particularly in the green coronal line, seems to be prospective.

Unfortunately, a fairly concentrated effort to put more light to the problem of the green line polarization was not very successful in the latest years (Solar Maximum Mission; Fisher's, Hiei's and ours eclipse experiments in 1981 - USSR and 1983 - Indonesia, influenced by not sufficiently good weather). Our quantitative results relating to 1973 eclipse - Niger and qualitative analyses of 1980eclipse - India show that the polarization in line Fe XIV 530.3 nm does exist (Sýkora et al., 1977). The observed values of the degree of polarization (from 4-8 % to 45-54 % at individual points of the corona) as well as the characteristic distribution of the plane of polarization prove that there in fact is no controversy between the forecasts of the theory of the polarization in the presence of the resonance fluorescence of Fe XIV ions in a magnetically active medium and our observational data (Figure 1).

In order to prove the existence of the association between the observed distributions of the polarization data P_g and φ_g, and the magnetic field structure of the corona, we have analysed Figures 2 and 1. Figure 2 shows a schematic outline of the coronal structure of June 30, 1973, adopted from Khecuriani (1975), into which we plotted the φ_g-values. Into the same figure we have plotted the isolines of the photospheric magnetic field ($H_{\parallel}$) on the disk for the eclipse day according to Mt.Wilson observations. One should firstly notice the distinct difference between the coronal structures a the E and W limbs. At the W limb there is a system of regular helmets and streams. At the E limb there are semi-closed, complicated stream structures which form a nearly smooth overal stream over the whole mid-latitude zone. This, on the whole asymmetrical (E and W) distribution of the structures, associated with photo-

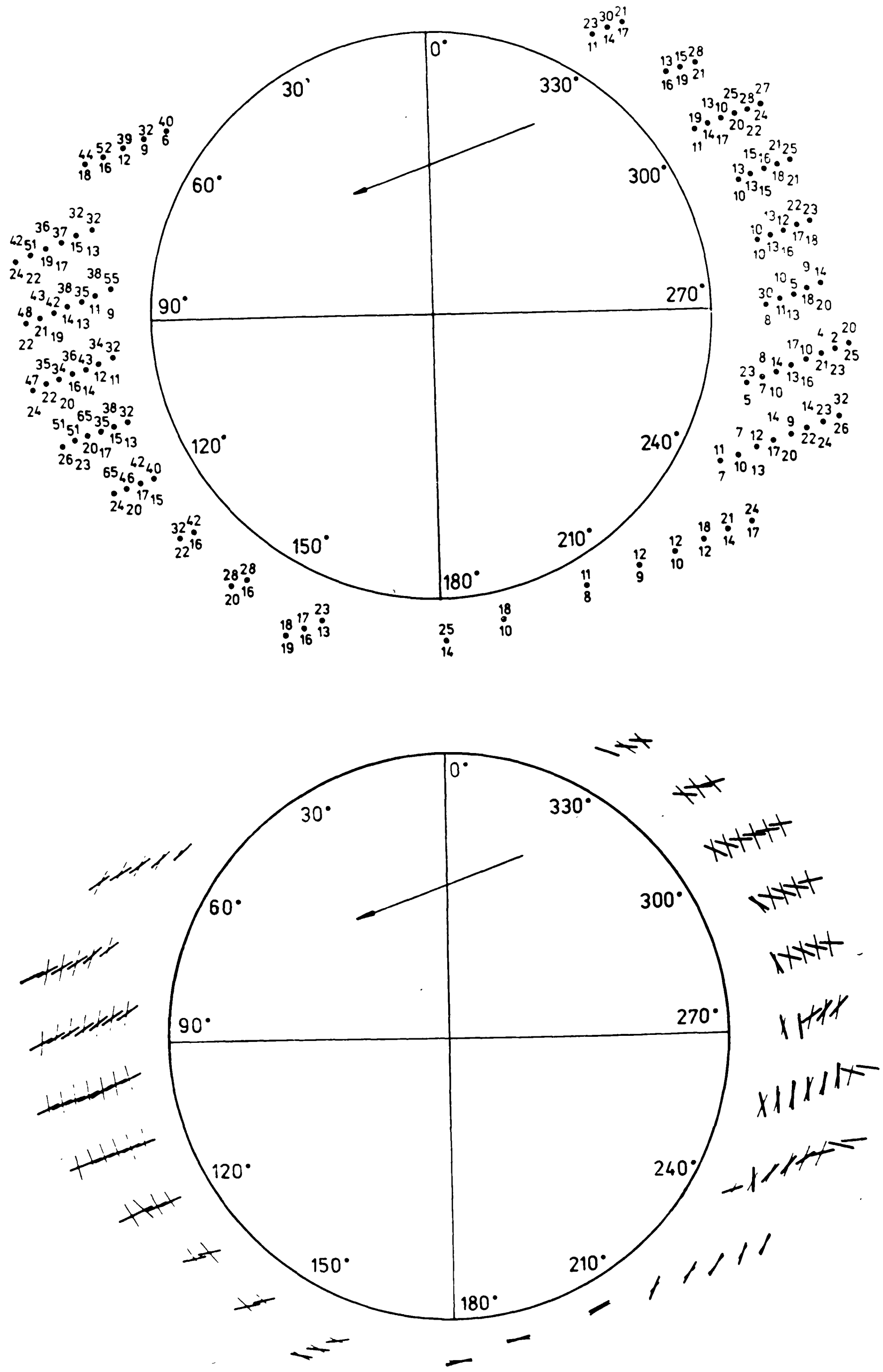

Fig. 1: Upper diagram shows the distribution of the observed degrees of polarization (in %) in the green (upper numbers) and white (lower numbers) corona. Lower diagram shows the distribution of the observed directions of polarization in the green (bold lines) and white (thin lines) corona. The directions correspond to the electric waves vector.

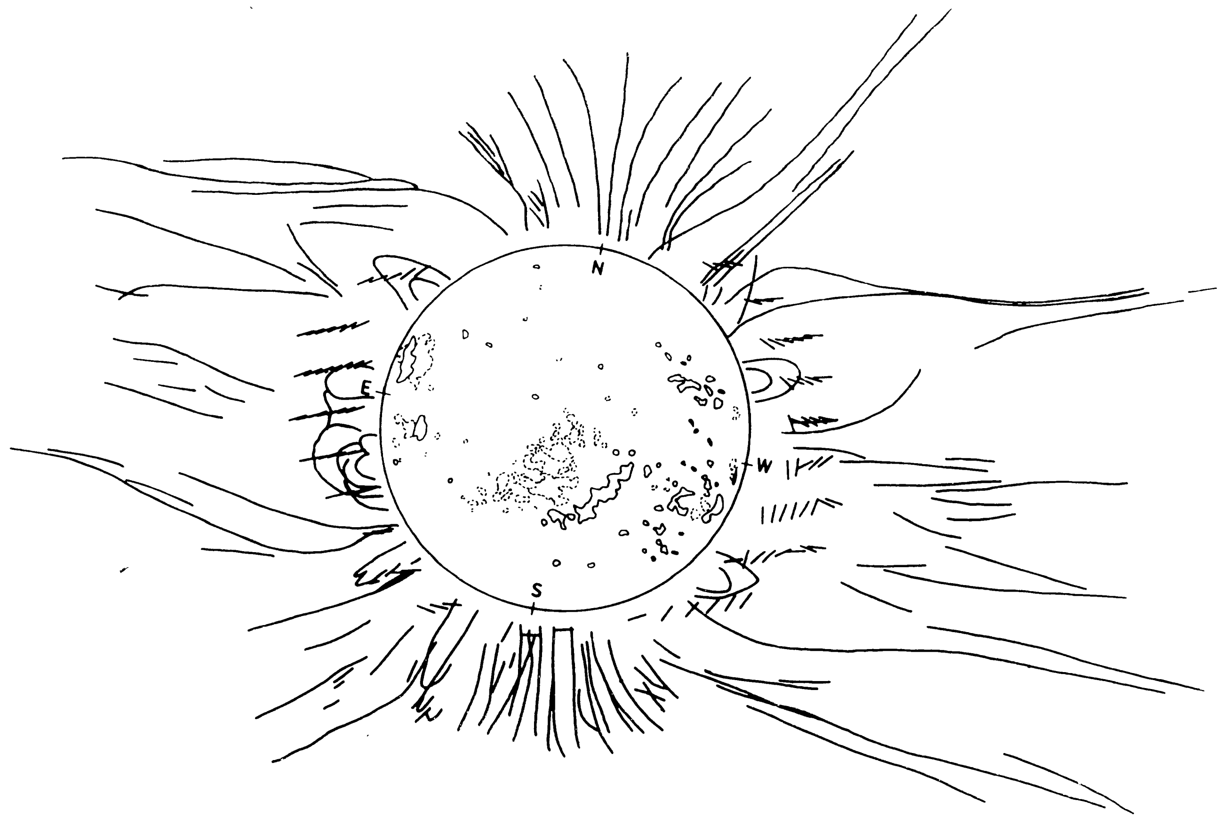

Fig. 2: Outline of the structure of the white corona for June 30, 1973 (Khecuriani, 1975). Isolines of the photospheric magnetic field after S.G.D. have been plotted on the solar disk. The lines indicate the directions of the polarization we have observed.

spheric fields and chromospheric phenomena, is also reflected in our pattern of the P_g - and φ_g - data distribution (Figure 1). At the E limb the values of the polarization are higher on the average than they are at the W limb, and the orientation of the polarization planes is closer to the radial direction in the mid-latitude zone, although there is an overall tendency towards S-E orientation. At the W limb the polarization values are considerably lower (particularly in the SW quadrant) and the orientation of the polarization planes is relatively complicated, directions perpendicular to the radius being prevelant (particularly in the SW quadrant).

More detailed analyses, taking into account distribution of the computed lines of force of the coronal magnetic field and the computed polarization in the green line on eclipse day (House, 1974) is carried out in Sýkora et al. (1977). The comparison of our P_g- and φ_g- data with those computed data showed a qualitative agreement. But to find the quantitative data of this relation seems to be premature. The difficulties in computing the structure of the magnetic field in the corona, the uncertainty associated with integration of the polarization effect along the line of sight, which intersects complicated coronal structures (and, in this connection, also the difficulties in determining the real values of the local concentration and electron temperature in the corona) may cause any of all model computations to prove valueless in their final stage.

In connection with the said results on the green corona, when a substantially higher degree of polarization was recorded at the east limb than at the west limb, it seems worthwhile mentioning that the white light corona, photographed during the same eclipses, does not show any substantial difference of the polarization between E and W limbs (see also Sýkora, 1977). It is also meaningful to emphasize that the direction of the white corona polarization is tangential (the directions correspond to the electric wave vector) in agreement with the classical theory (thin strokes in Figure 1). Deviations in some cases reach 10°-15° and can be attributed to the errors of measurements. It is in contrast to the variety of directions of the plane of polarization for green line of the corona. It should be probably also mentioned that it was necessary to measure the polarization of white light corona to exclude from the measurements of the polarization in green line that part of polarization which was caused by the coronal continuum which have passed through the narrow passband filter.

Distribution of the polarization parameters P_g and φ_g in dependence from the structure of the coronal magnetic fields was analysed in details for the eclipse days. Except of that we have also discussed (Mogilevskij et al., 1977) more general questions connected with determination of magnetic field from the data on polarization in emission lines, namely the infrared lines and the far UV lines (e.g. Fe XV, Fe XVI, etc.). Oscillator strength in UV lines is 10^{-2} - 2 and this means that by analysis of the plane of polarization turning (Hanle effect) the magnetic field of the corona can be measured in limits $10^{-4} < B < 10^{-2}$T and not only at the solar limb but also directly on the sun's disk. We have also given reasons that in case of real coronal fields $B > 10^{-7}$T and of known oscillator strengt of the green line $f_{ij}= 7.10^{-7}$, it is possible from observation of the polarization of this line to determine very well the direction of the magnetic field, its character above active regions, "closeness" and "openess" of the magnetic structures important in relation to heliosphere, but it is not possible to determine directly intensity of the magnetic field.

b) Some physical characteristics of the coronal structures and their relation to the background magnetic fields.

The systems of loops were studied (Livshits and Sýkora, 1983) on eclipse 1980 and 1981 photographs taken in green-line light and their positions were compared with background magnetic fields measured at the Kitt Peak and Stanford observatories, as well as, with the synoptic H_α maps data. It was revealed that the systems of loops are clearly situated over the polarity borders of the background fields. The height of the systems was estimated to be up to 200000 km at the equator and up to 70000 km at $\varphi > 30^o$. It was further found that the volume emission measures EM (V) of these systems are of the order of 1.5×10^{48} cm^{-3}, which means that they are substantially lower than those obtained from X-ray data for the active regions. The combined investigation of data on radiation of the corona in the green line and in the continuum enabled us to determine the total extension of the radiating matter, $(0.5 - 1) \times 10^{10}$ cm, as well as, the density in the separate arches, $\approx 1.5 \times 10^9$ cm^{-3}. It is assumed that the background matter exists between the arches, its density was found to be near to that known for coronal holes.

In a latest work (Dzifčáková et al., 1986) the analysis of the photometric measurements (data from 1980 eclipse) by means of the motion equations applied to coronal gas led to the conclusion that the classical determination of the electron density distribution from the eclipse measurements, e.i. assuming the spherically symmetric and homogeneous corona leads to the principle inconsistence in physical interpretation of the results. Discrepancies can be partly suppressed if the expansion of the coronal matter is assumed in a relatively narrow streams the diameter of which firstly decrease with height (up to about 3 R_o) and then on the contrary increase. In the mentioned work the course of electron density, temperature, flow velocity and diameter are presented for such a stream. It is shown that the observed brightness of the K-corona can be always fitted to a proper combination of such streams and practically no existence of the background corona is necessary.

c) The solar activity on the disk and its response in the variety of the coronal structures.

This chapter is difficult to summarize because of rather extensive morphological description of the observed features and because of naturaly quite specific activity situation during each of the four eclipses. Above all, the white-light corona photographs were used to discuss relation of the disk and corona activities.

For example a narrov coronal ray, slightly curved to the equator was observed during 1973 eclipse (Rušin and Rybanský, 1979). A detailed analysis of

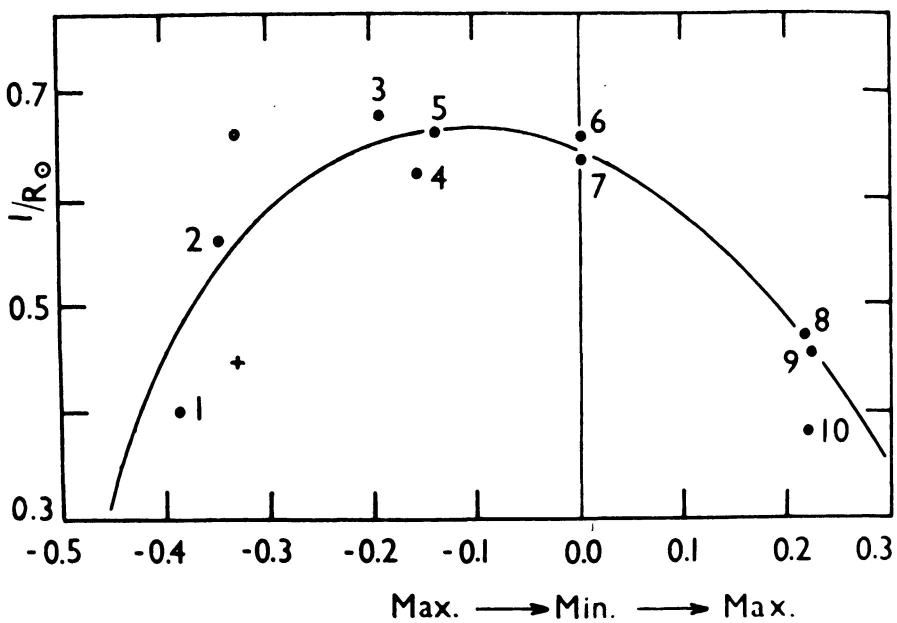

Fig. 3.: Variation in ℓ (at r = 1.0 R_0) with the solar phase (1 - 1952 Van Biesbroeck; 2 - 1962 Saito-Hata; 3 - no date, Campbell et al.; 4 - 1900 Van de Hulst; 5 - 1963 Stoddard-Carson-Saito; 6 - 1954 Wallenquist; 7 - 1954 Waldmeier; 8 - 1955 Saito; 9 - 1965 Saito; 10 - 1955 Waldmeier; + - 1973, our value for the rays in the NW quadrant, 0 - 1973, our value for the rays in other quadrants.

this ray (about 20000 km in width) with respect to the photospheric and chromospheric phenomena anabled to state that the ray was very probably a neutral sheet which separated the opposite polarities of magnetic fields in the corona. During the same eclipse a number of well developed polar rays were observed also (Rušin and Rybanský, 1976). The dependence of the slope of the polar rays on height was proved. The values of the length of a hypothetical bar magnet at 1.0 R_0 have been found ℓ = 0.46 in the NW quadrant and ℓ = 0.66 in the other three quadrants. Both values are not well fitted to the curve displaying the variation of ℓ with the phase of the solar cycle (Figure 3).

A richness of coronal structures was observed during the 1980 eclipse which practically coincided with the maximum of the 21st solar cycle (Rušin and Rybanský, 1983a) (Figure 4). Broad coronal streamers, mostly of radial direction, were observed around the whole solar disk up to heights of about 6 R_0 with exception of the south polar region (P.A. 165°-180°) which is probably due to the non-uniform development of polar prominence zones in the individual hemispheres.

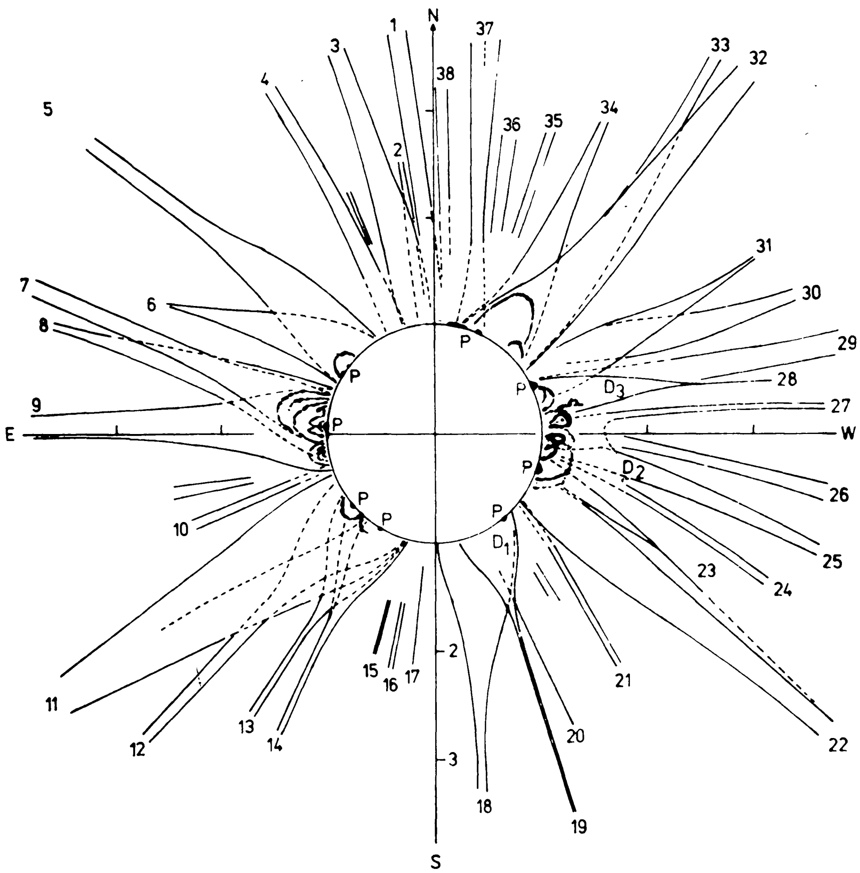

Fig. 4: Structure of the 16 February 1980 solar corona, outlined from the photograpf taken with a 20 cm lens of 304 cm focal length.

In the inner corona, above the W limb, a large number of the thin coronal loops were observed, which completely upset the compactness of the coronal rays observed at higher heights. Areas of lower intensity, about 10000 km in width in the shape of semi-arcs, were observed in two streamers above the W limb at heights of 1.5 and 1.75 R_o. At P.A. 282 and a height of 9.4 R_o the head of coronal transient was observed. The ascending velocity of this formations as compared to the observations made on the African continent was 610 ± 100 km s^{-1}.

During 1981 solar eclipse the most interesting feature seen in the corona were two coronal voids at position angles 169° and 281° (Rušin and Rybanský, 1985), they extended to the height of 1.8 R_o and 3.5 R_o respectively. The voids are very narrow (10000 - 30000 km in width) "empty" formations which are related to the photospheric neutral lines. Generally, the voids can be quite

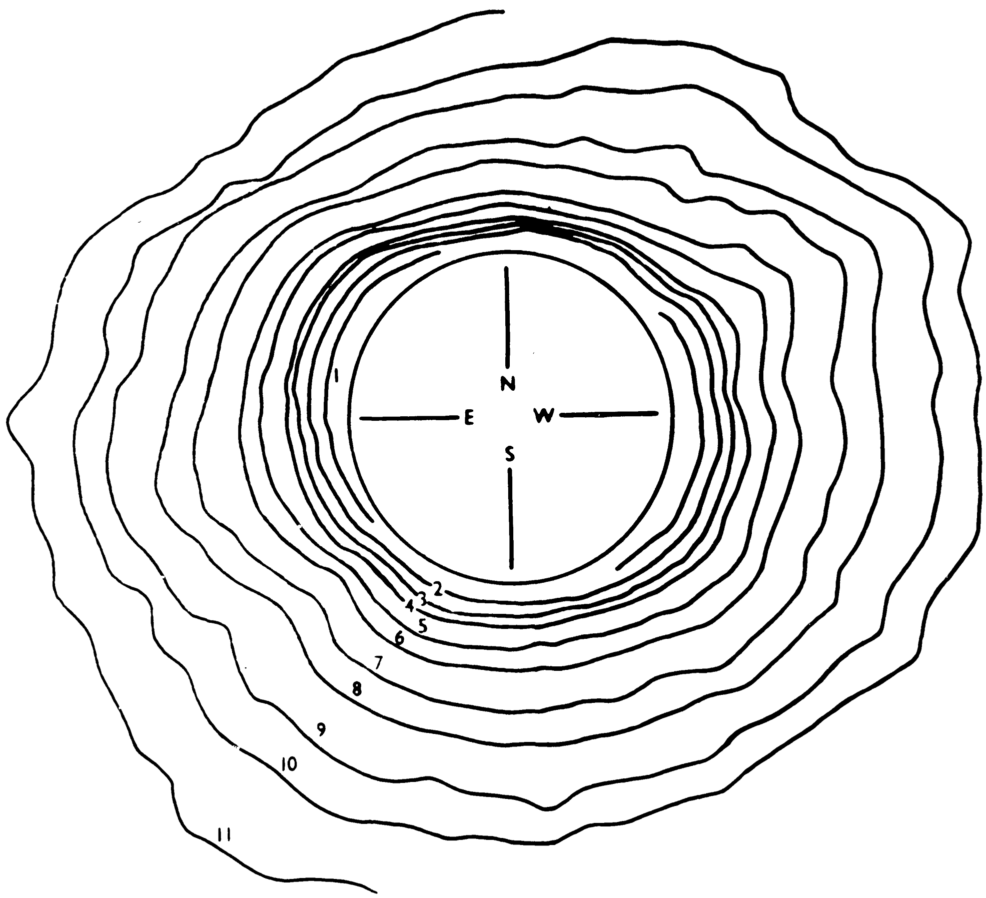

Fig. 5: Coronal isophotes of the intermediate type of corona 30.6.1973.

common feature in the corona but because of geometry they are very rarely observed. In opposite to the provious observations (Mac Queen et al., 1983; Wagner et al., 1983) we have not found any clear connection of the voids with presence of prominences at the base of the voids.

The structure of the white-light corona during the total solar eclipse of June 11, 1983 was of the intermediate type and displayed several different types of features: polar coronal holes, polar rays, mid-latitude und equatorial streamers, as well as, neutral sheet type rays (Rušin and Rybanský, 1985d). The dominating features were the helmet streamer in the SE quadrant, a system of loops and the coronal condensation above the W limb.

d) Absolute photometry, integral brightnes and flattening as a functions of the solar cycle phase.

Absolute photometry was possible namely for 1973 and 1980 solar eclipses,

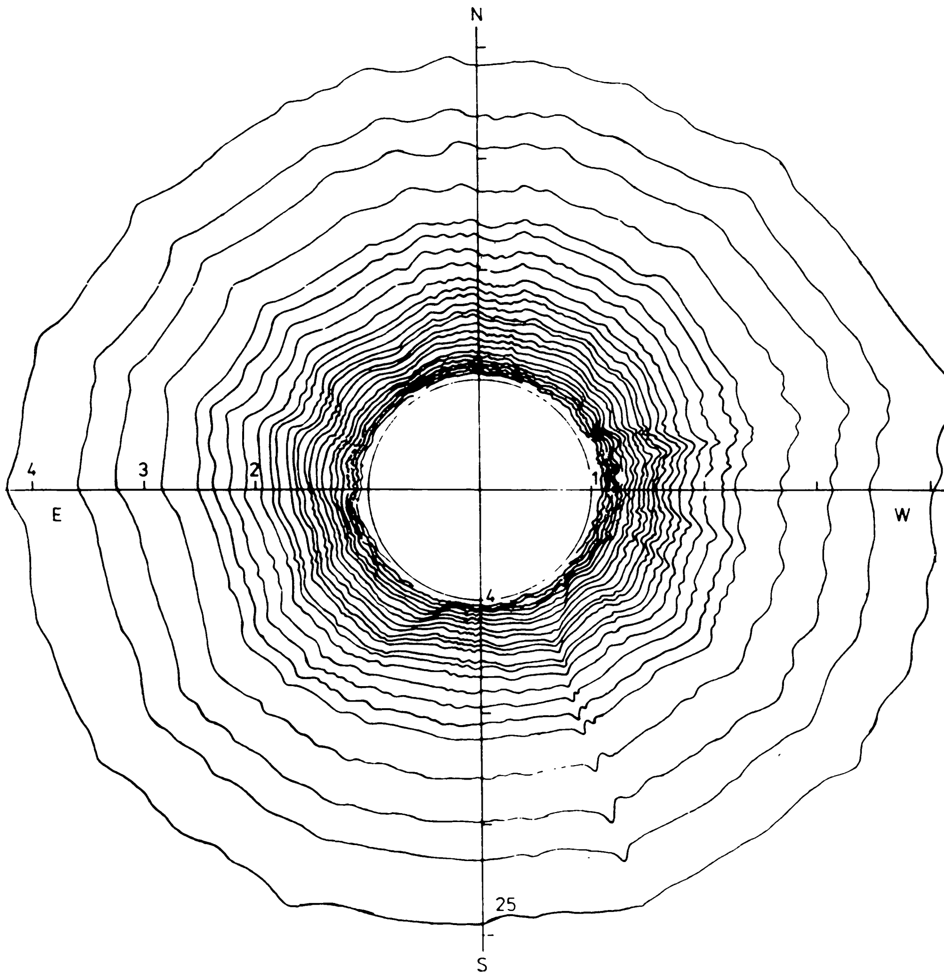

Fig. 6: Coronal isophotes of the maximum type of corona 16.2.1980.

when the observational conditions were fully favourable (Rušin and Rybanský, 1975a; Rušin and Rybanský, 1983b). Absolute intensities are tabulated with step of 5^{o} in position angle and 0.1 - 0.2 R_{o} in radial direction. Coronal isophotes constructed from the tabulated values are shown for 1973 eclipse in Figure 5 (intermediate type of corona) and with far better resolution up to 4 R_{o} for 1980 eclipse in Figure 6 (maximum type of corona). In the later case the Ludendorf's index characterizing the shape of corona is 0.027 and at the phase φ = 0.34 is one of the smallest in the history of eclipses. Nevertheless, a careful analysis shows (Figure 6) that at the south pole there is a conspicuous decrease of the K + F corona in comparison with the north pole - the ratio N/S amounts 4.39 at 1.1 R_{o}. The difference diminishes fully at 4 R_{o}, where

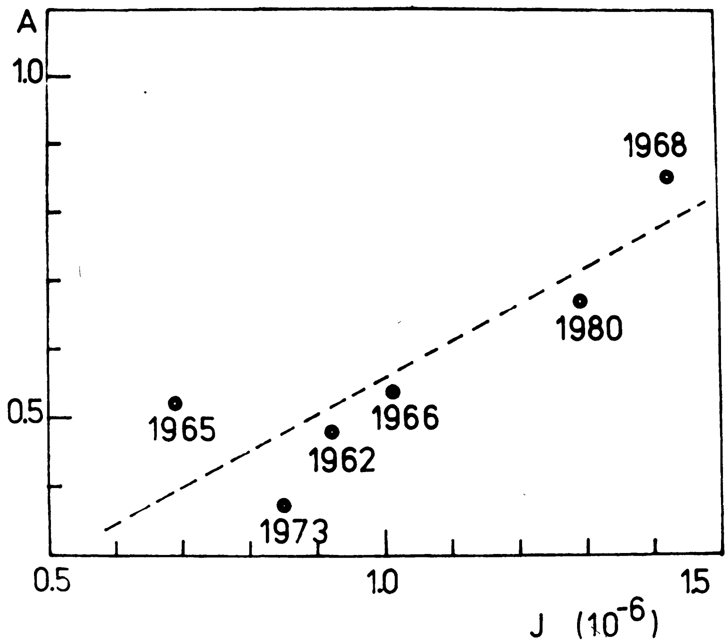

Fig. 7: Comparison of the values of the total brightness of the solar corona and of A values.

dust F corona (constant during solar cycle) prevails. It is assumed that such decrease is probably due to presence of a coronal hole at the south pole.

In the next, it was natural to determine the total brightness of the corona from the carried out absolute photometry. The method is shortly described in Rušin and Rybanský (1975b) and in some modified form in Rušin and Rybanský (1985a). If the unit of brightness (J) is taken to be 10^{-10} of the brightness of the centre of the solar disk (J_D), then for intermediate type of corona of 1973 the authors obtained the value $J = 0.84 \times 10^{-6} J_D$ and for maximum type of corona 1980 the value is $J = 1.288 \times 10^{-6} J_D$.

In both cases the total brightness of the corona was calculated also for the individual position angles and regions above the solar limb. It is interesting to comment that in spite of the nearly spherical appearence of the 1980 white-light corona at the solar maximum, still the maximum of radiation is produced by the equatorial region ($\pm$ 45°). If the ratio A = N+S/E+W is introduced, the boundaries being at $\pm$ 45° of latitude, then for 1980 eclipse A = 0.66 is found. Taking into account the A values for several past eclipses (Figure 7) the linear dependence between A and J can be expressed: $A = 0.497\ J + 0.051$. This is valuable relation because, if necessary, the relative photometry can be indirectly calibrated by it.

Using all the available observations of the total brightness of the

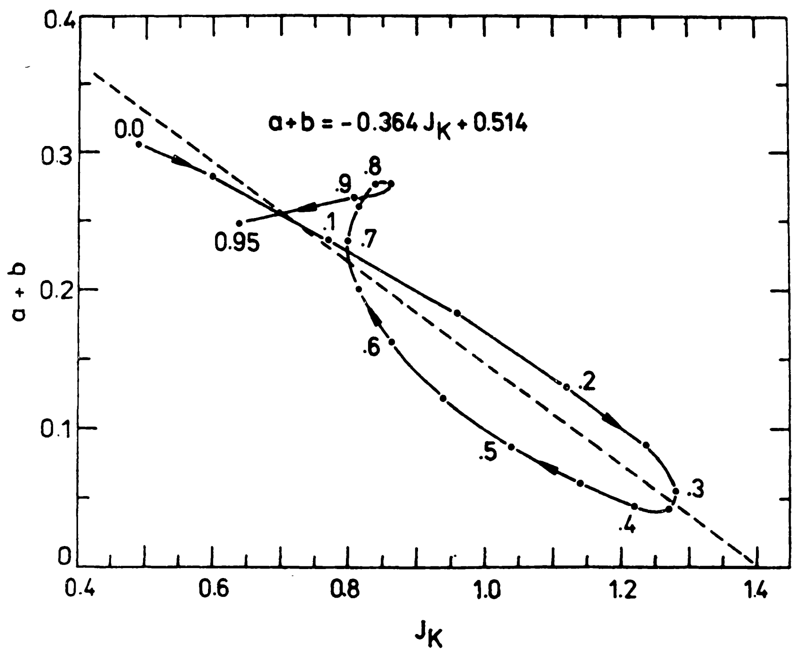

Fig. 8: Relation of the total brightness of the white-light corona and ellipticity. The numbers indicate the phase of the solar cycle

white-light corona made during this century, Rušin and Rybanský (1985b) were able to draw statistical relation showing clear dependence of the total brightness and ellipticity E (defined by Ludendorff, 1928) of the corona on the phase of the solar cycle. Their mutual relation is shown in Figure 8. In the first approximation it is linear and can be expressed as $E = - 0.364\ J_K + 0.514$. Based on this relation the total brightness can be again derived from the uncalibrated isophotes.

e) Eclipse observation solve the obscured cause of the highest geoactivity in 1981 ?

The last decade of July 1981 was characterized by exceedingly high geoactivity (Sýkora et al., 1986). Although that time there was on the sun's disk a well developed Hale region No. 17751 which kept its typical δ-configuration of the magnetic field for several days, which displayed the whirl chromospheric structures, changes of the magnetic flux, large horizontal gradients of the magnetic field and remarkable vertical motions of the chromospheric matter (Ioshpa et al., 1982; Ioshpa et al., 1984), still no large manifestations of the eruptive activity were observed. No flare of importance larger than 1 was detected; of about 60 flares only 4 were of importance 1, other were subflares.

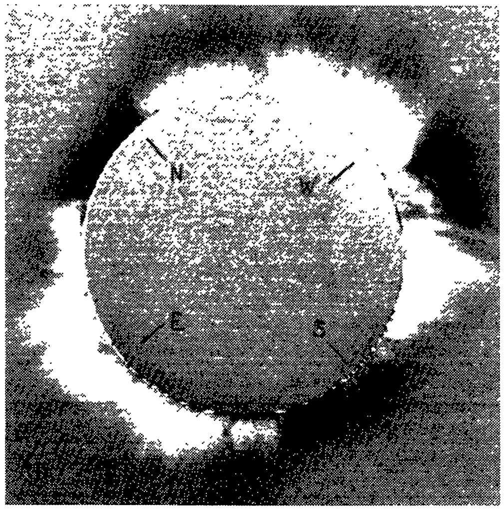

Fig. 9: The pictures taken in green 530.3 nm and red 637.4 nm lines were combined to this resulting picture by the digitalization technique. Hypothetical low-latitude coronal hole is the dark region on the west limb (30.7.1981).

It seems that our observation of the solar corona carried out in the light of the spectral lines Fe XIV 530.3 nm and Fe X 637.4 nm offer some reasonable explanation of the high mentioned geoactivity in the absence of the eruptive processes on the Sun (Sýkora, 1983). After processing, the eclipse's original images by the digitalization technique and subsequent subtraction of the "inactive" component (637.4 nm) from the "active" component (530.3 nm) we have obtained Figure 9. From this figure it is evident that emission 637.4 nm (dark) prevails at both poles of the sun (in fact, it probably identifies areas familiar to the polar coronal holes), but at the same time there is clear absence of the active (hot) corona near the equator, just at the place where the AR 17751 set behind the sun's west limb.

Taking the said facts into account, we are of the opinion that the so-called low-latitude coronal hole, located in the vicinity of the AR 17751, was very probably a source of the conspicuous geophysical disturbances. Thanks to the favourable circumstances (observation of the eclipse from two points distant by about 1 hour in time) it was also possible to look for motions of some structural details of the corona (Delone et al., 1983). Also this analysis shows absence of some outstanding eruptive processes in the region in question. Green corona loop and a small condensation moved with a velocity of about 10 km s^{-1} which is quite usual for the green corona structures as for example Kleczek and Topolová (1984) have shown.

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