METHODS OF MEASURING THE GENERAL CHARACTERISTICS OF THE SUN EMPLOYED AT THE SAYAN SOLAR OBSERVATORY

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ABSTRACT. A special telescope was developed for measuring the mean magnetic field of the Sun as a star, the distribution of background magnetic fields on the solar disk, large-scale line-of-sight velocities and global pulsations of the Sun. The instrument represents a double telescope consisting of two Jensch-coelostat and of two objectives. The optical axes of the two telescopes are parallel to each other. In measuring large-scale line-of-sight velocities light beams from the two telescopes pass through the spectrograph slit and get a mutually orthogonall linear polarization. Differential shift of spectral lines, as formed by the two telescopes, is measured. One telescope is defocused such that on the slit a small-size area is produced that is illuminated by all parts of the solar image. The other builds a solar image in the spectrograph slit plane while the guiding and scanning device provides raster displacement of the image on the slit. For investigation of solar pulsations, two telescopes make it possible to illuminate the spectrograph slit with portions of the solar image different in diameter in the range from tens of arc sec to full Sun's disk and to measure the differential shift of the lines from these two parts. This makes it possible to single out the various spatial harmonics of solar pulsations. The measurements of the magnetic fields have been carried out in the single-telescope mode. The results of the first observations are discussed.

МЕТОДЫ ИЗМЕРЕНИЯ ОБЩИХ ХАРАКТЕРИСТИК СОЛНЦА В САЯНСКОЙ СОЛНЕЧНОЙ ОБСЕРВАТОРИИ: Создан специальный телескоп для измерения среднего магнитного поля Солнца как звезды, распределения фоновых магнитных полей на диске Солнца, крупномасштабных лучевых скоростей и глобальных пульсаций Солнца. Инструмент представляет собой двойной солнечный телескоп, состоящий из двух Енш-целостатов и двух объективов. Оптические оси обоих телескопов параллельны друг другу. При измерении крупномасштабных лучевых скоростей световые пучки от обоих телескопов проходят через щель спектрографа и имеют взаимноортогональную линейную поляризацию. Измеряется дифференциальный сдвиг спектральных линий, сформированных двумя телескопами. Один телескоп дефокусируется так, чтобы на щели образовалась небольшая область, освещаемая всеми частями солнечного изображения. Второй телескоп строит изображение Солнца на щели спектрографа, с помощью системы гидирования и сканирования осуществляется растровое сканирование изображения Солнца. Для исследования солнечных пульсаций, оба телескопа освещают щель спектрографа концентрическими частями солнечного изображения различного диаметра от десятков угловых секунд до полного диска Солнца и измеряется дифференциальное смещение линий от этих двух частей изображения. Это дает возможность выделять различные пространственные гармоники солнечных пульсаций. Измерения магнитных полей выполняются в схеме одного телескопа. Результаты первых наблюдений обсуждаются.

METÓDY MERANIA CELKOVÝCH CHARAKTERISTÍK SLNKA V SAJANSKOM SLNEČNOM OBSERVATÓRIU: Špeciálnym dvojitým slnečným ďalekohľadom sú merané nasledovné veličiny: stredné magnetické pole Slnka ako hviezdy, rozdelenie veľkorozmerných magnetických polí na slnečnom disku, rozdelenie veľkorozmerných rýchlostí a globálnych pulzácií Slnka. Prístroj je zložený z dvoch coelostatov Jenschovho typu a dvoch objektívov. Optické osi obidvoch ďalekohľadov sú navzájom paralelné. Pri meraní veľkorozmerných radiálnych rýchlostí, svetelné lúče z obidvoch ďalekohľadov prechádzajú cez štrbinu spektrografa a majú navzájom ortogonálnu lineárnu polarizáciu. Meria sa diferenciálny posun spektrálnych čiar, sformovaných dvoma ďalekohľadmi. Jeden z ďalekohľadov je rozfokusovaný tak, aby na štrbine vznikala neveľká oblasť, osvetľovaná všetkými časťami Slnka. Druhý ďalekohľad vytvára obraz Slnka v rovine štrbiny spektrografu a pomocou systému pointácie a skanovania sa uskutočňuje rastrové skanovanie obrazu na štrbine. Pre štúdium pulzácií Slnka, obidva ďalekohľady osvetľujú štrbinu spektrografu určitými koncentrickými časťami obrazu Slnka. Koncentrické časti majú rôzny rozmer, od desiatok oblúkových sekúnd až po celý disk Slnka. Meria sa diferenciálny posun spektrálnych čiar od týchto dvoch koncentrických zložiek obrazu. Táto metóda umožňuje určovať rôzne periódy a priestorové vzťahy v pulzáciách Slnka. Merania magnetických polí sa uskutočňujú v schéme jedného ďalekohľadu. Diskutované sú výsledky prvých pozorovaní týmto ďalekohľadom.

1. INTRODUCTION

Regularities of the structure and dynamics of background magnetic fields, circulation and of convection in the Sun's atmosphere, and the global pulsations all refer to the general characteristics of the Sun. Interest to these problems being of crucial importance in solar physics has always attracted researches' attention; in the past 10 or 15 years, however, the study of the general characteristics of the Sun has received ever increasing attention.

This was stimulated by the discovery of sector structure of the interplanetary magnetic field and its association with the structure of the background magnetic field of the Sun (Wilcox, 1961; Severny et al., 1970; Wilcox, 1971) as well as of global pulsations of the Sun (Severny et al., 1976; Leighton et al., 1962; Deubner et al., 1979), zonal peculiarities of the differential rotation (La Bonte and Howard, 1982), and other phenomena.

The nature of background magnetic fields remains the subject of interesting discussion. During many years, the basic features of the dynamics of solar magnetic fields were interpreted within the context of the idea of solar magnetism, as advanced by Babcock and Leighton (Babcock, 1961; Leighton, 1964). It was thought that the background fields result from decaying magnetic fields of active regions and their dynamics is due to the action of "Leighton diffusion" mechanisms and differential rotation of the Sun. However, this idea was upset by the discovery of "sector" magnetism of the Sun - the properties of large-scale fields such as solid-body rotation, the impulsive character of the distribution of following-polarity magnetic field toward the polar regions, etc. Further observations of the background field dynamics on long time scales constitute an important problem of solar physics.

The limiting case of background magnetic field observation is measuring the mean magnetic field of the Sun as a star (Severny, 1969). Such observations allow us to look at the Sun as a variable magnetic star and provide a better understanding of the rank of the Sun amongst other stars as well as of other stars.

The Sun provides a unique possibility of comparing mean magnetic field measurements with magnetic field distribution over the surface; it permits us to extend a variety of analogies regarding the surface structure of magnetic fields to other stars. In addition, measurements of the magnetic field of the Sun as a star are of interest in connection with the discovery of its close association with the interplanetary magnetic field sector structure and with the cycle of solar activity. Magnetic field structure measurements in the solar photosphere are insufficient for solving the many problems of solar magnetism. Information on large-scale mass motions on the solar surface and, especially, in internal layers of the Sun is urgently needed. Helioseismology methods, developed in the last few years, have afforded a possibility in principle of determining the depth of the convection zone, the profile of differential rotation with depth, and surface flows associated with hypothetical giant convective cells. With the development of helioseismology, methods of accurate measuremen of spectral-line Doppler shift have been improving, and the sensitivity of line-of-sight velocity measurements on the solar surface has also improved.

The problems mentioned above, and also the related observational objectives require magnetic field strengths to be measured as accurate as 0.05 Gs well as line-of-sight velocities as accurate as 1 m s^{-1} or better.

For purposes of investigating a number of general characteristics of the Sun, at the Sayan solar observatory a specialized telescope was constructed and methods for measuring weak magnetic fields and differential methods of line-of-sight velocity measurement were developed (Grigoryev, 1983; Grigoryev and Demidov, 1983). The instrument was named the solar telescope of operative prediction because observational programs are directed not only at investigations in the solar physics proper but also at obtaining synoptic information on solar magnetic fields for direct use in forecasts of the interplanetary medium and magnetospheric disturbances.

2. GENERAL DESCRIPTION OF THE TELESCOPE FOR OPERATIVE PREDICTION

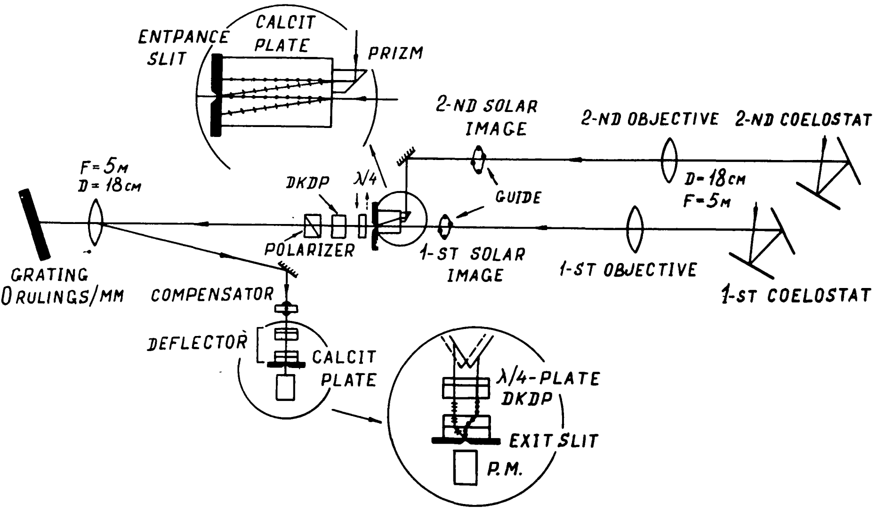

Fig. 1: Twin solar telescope system. The figure shows the light path in a calcite prism which serves to illuminate the spectrograph entrance slit with the light simultaneously from the two telescopes, as well as a scheme illustrating the principle of operation of the deflector.

The instrument (Figure 1) is a twin solar telescope consisting of two Jensch-coelostats and two doublet objectives. The optical axes of the two telescopes run parallel to each other. Each of the objectives is installed on a separate carriage and is able to move on the optical bank along the telescope's optical axis. The instrument is operated in two regimes. In one regime, the main telescope is used for measuring background magnetic fields and the mean magnetic fields of the Sun as a star. In the second regime, both telescopes are employed to measure large-scale line-of-sight velocities and solar pulsations. The light beams from the two telescopes enter the spectrograph slit and have a mutually orthogonal linear polarisation. Measurements are made of the differential shift of spectral lines formed by the two telescopes. The operation mode of the instrument in the twin-telescope system will be examined in greater detail in Section 4.

The telescope objectives are 18 cm in diameter each and the focal length is 5 m. Tracking at hourly rate is effected by means of the coelostat main drive. Fine guiding, and also program image scanning are carried out with the aid of a photoelectric guiding-and-scanning system (a coordinatometer) and correction drives on the main mirror of the coelostat. The difference signal from two pairs of photodioedes positioned at opposite points of the solar limb, set the correction drive motors in motion. Programmed displacement of the carriage in the image plane by means of step motors allows the image to be scanned on the spectrograph entrance slit in E-W and N-S directions. The E-W directions is parallel to the solar equator and is achieved by rotating the carriage with photosensors relative to the center of the solar image. The coordinates of the origin of the scanning rates are related to the solar image center. Determination of the coordinates of the image center and of the orientation of the solar rotation axis, and also the corresponding setting of the coordinatomer carriage are effected automatically. The position of the carriage with respect to the spectrograph entrace slit is controlled by digital position sensors.

The spectrograph has been constructed according to the Littrow scheme. The spectrograph objective is 180 mm in diameter, with a focal length of 5 m. The spectrograph slit is followed by a circular polarization electrooptical analyzer. A magnetograph photometer is installed in the focal plane of the spectrograph. The photometer entrace slit is preceded by an electrooptical deflector which successively interrogates the wings of the spectral line as well as a spectral line Doppler shift compensator.

3. MEASUREMENT OF BACKGROUND MAGNETIC FIELD AND OF THE MEAN MAGNETIC FIELD OF THE SUN

In order to measure the mean magnetic field in a selected area of the solar surface requires that all points of this area of the image be involved with equal weight in the formation of the spectral line profile. For this purpose, a system designed to illuminate the spectrograph objective, as shown in Figure 2, is employed. A solar image is built at a distance S in front of the

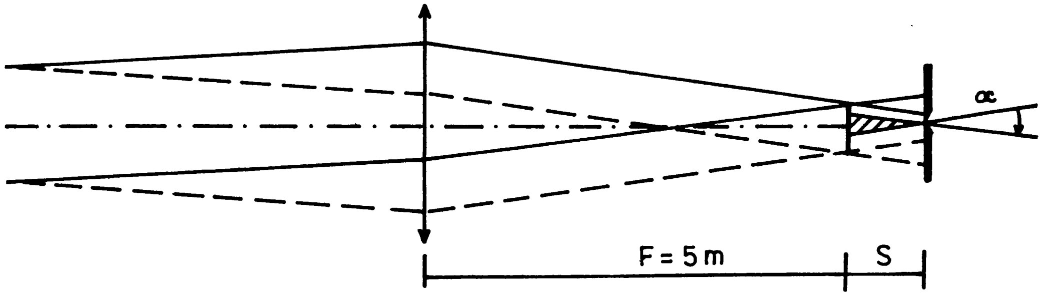

Fig. 2: Optical system designed to illuminate the spectrograph slit when measuring background magnetic fields at low spatial resolution.

spectrograph entrace slit. In this case the slit produces a mean-field spot from the solar image portion limited by the angular aperture of the spectrograph. The angular diameter, d', of the portion of the solar image, all points of which are with equal weight involved in the formation of the spectral line profile, is related to the degree of defocusing by

$$d' = \frac{\rho S}{D} \frac{d}{F + S}$$

where S is the distance (in mm) of the solar image from the entrace slit;

ρ is the angular diameter of the Sun (in arc min);

d is the objective diameter; and

D is the solar image diameter (in mm).

For background magnetic field measurements with a resolution of 2 ars min the defocusing is 97 mm.

In measuring the background magnetic fields, use is made of the usual principle of longitudinal-field magnetograps based on recording the circular polarization in the wings of a magnetosensitive spectral line. Analysis of the polarized light is done by means of an eletrooptical DKDP crystal and a polarizer behind the spectrograph entrance slit and with an electrooptical deflector preceding the photometer slit. The electrooptical deflector consists of an electrooptical crystal and a calcite plate (Stepanov et al., 1975). The induced optical axes of the crystal are arranged at an angle of 45° with respect to the doubling plane of the calcite plate. The radiation incident on the deflector, is linearly polarised. With a zero phase on the deflector, the slit receives the radiation from one wing of the line while with a $\lambda/2$ phase, from the other wing. The distance between the portions of the line wings coming to the photometer slit, is determined by the thickness of the calcite plate. The electrooptical polarization analyzer and the deflector are controlled by square-form voltage of equal frequency but phase-shifted by 90°. During the pulse shaping process, the combined operation of the analyzer and the deflector discriminates the following four states:

State	Phase shift on polarization analyzer	Phase shift on deflector	Light intensity on photometer
1	$\lambda/4$	0	$1/2\ (I_o^b - V)$
2	$\lambda/4$	$\lambda/2$	$1/2\ (I_o^r + V)$
3	$-\lambda/4$	$\lambda/2$	$1/2\ (I_o^r - V)$
4	$-\lambda/4$	0	$1/2\ (I_o^b + V)$

Here I_o^b and I_o^r are the light intensities in the blue and red winds of the line, respectively, and V is the Stokes parameter. Composition of the signals in states (1), (3) and (2), (4) and then subtraction of the sums obtained yield a signal that is proportional to magnetic field strength. If the sum (2)+(3) is subtracted from the sum (1)+(4), we obtain a value proportional to the Doppler shift of the spectral line. The operations indicated are performed in a mini-computer.

Measuring weak background with low spatial resolution requires that the accuracy be 0.1 Gs or better for a dynamical range from 0.1 to 100 Gs. So high an accuracy is achievable provided the time of signal accumulation is considerably long, of order 10 sec. This problem is most easily solvable with a digital method of measurement. For that purpose, we have applied a current-frequency converter that converts the photomultiplier anode current into pulses whose repetition frequency is proportional to the input current. The converter consists of a current-voltage converter, a scaler and a voltage-frequency converter. The arithmetic unit accumulates digital information in four channels corresponding to the four states of the polarisation analyzer for a preset integration time.

A major difficulty involved in measuring the weak magnetic fields (of about 0.1 Gs) is the influence of the telescope's instrumental polarization upon the measured results. This introduces uncertainties in the determination of the zero level of the magnetograph signal. In order to check the signal zero level and to exclude the instrumental polarization effect, we utilize a $\lambda/2$ phase plate that is periodically installed in front of the coelostat. If the S-signal of the magnetograph is obtained without a phase plate and the $S\lambda/2$-signal is formed with a phase plate, then the signal from instrumental polarisation which is responsible for the shift od the signal zero level, is found from the relation

$$\frac{S - S\lambda/2}{2}$$

The background magnetic field observations at the Sayan observatory were begun in July 1982, initially with a spatial resolution of 3 arc min and since 1983 with 2 arc min resolution. In both coordinates the raster scanning steps are 99 arc sec. Signals at each point of the raster are integrated during 8 sec. During the transition from one point to the other, the signals are not integrated.

Figure 3 shows an example of a record of calibrations by scanning the solar image along the equator with the line-of-sight velocity compensator turned-off (Figure 3a) and by displacing the line through a rotation of the plane-parallel plate before the photometer by a preset amout (Figure 3b). The calibration was performed with the accumulation time, T = 0.01 sec and the scaling coefficient, A = 2, in the mode of measurement: T = 8 sec and A = 64. Figure 3c, d is a record of noise with no voltage applied to the polarization analyzer, as well as an example of one scan across the solar image. The rms magnitude of noise is about 0.1 Gs with the accumulation time T = 8 sec.

Figure 4 presents a series of magnetograms for the successive days of observation, showing stable large-scale structures of the background magnetic field.

Figure 5 shows the magnetograms taken at the Sayan and Stanford observatories. Good agreement between the magnetic field structures is evident on the magnetograms from both observatories.

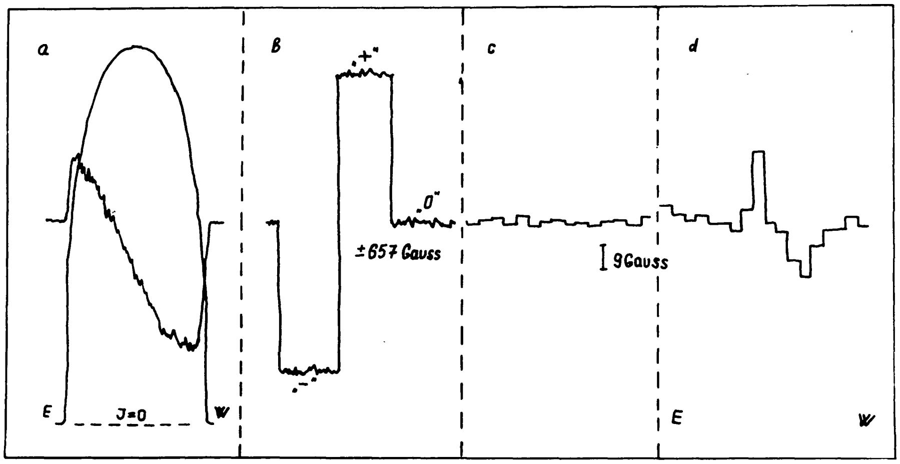

Fig. 3: An example of a record of signals: heavy line - brightness signal; thin line - magnetic field signal. (a) - calibration signal when scan are done in E-W direction along the solar equator; (b) - calibration signal by using a plane-parallel plate; (c) - record of noise with the polarisation analyser turned-off; and (d) - magnetic field signal when scanning the solar image.

Figure 6 illustates an example of a magnetogram reconstructed from harmonics of an expansion by spherical functions of the original magnetogram and magnetic field structure in the corona, as calculated in terms of a potential approximation (the calculations were done by D. Ponyavin, Institute of Physics, Leningrad University).

4. MEASUREMENTS OF THE MEAN MAGNETIC FIELD OF THE SUN AS A STAR

In observations of the mean magnetic field of the Sun as a star when all points of the visible solar disk ought to be involved in the formation of the spectral line profile, the objective is displaced 145 cm from the position in which the focus lies in the plane of the spectrograph slit. The solar image must be moved such a distance away from the slit that its angular dimensions seen at the slit, coincide with those of the objective; in this case, one beam will enter the slit from each image point and the light efficiency of the spectrograph will be used best.

As usual, the measurements are made in the λ 5250 Å line of Fe I; the accumulation time of signal, T = 100 sec, provides a sensitivity of about 0.05 Gs. In order to check the signal zero level, the measurements are made alter-

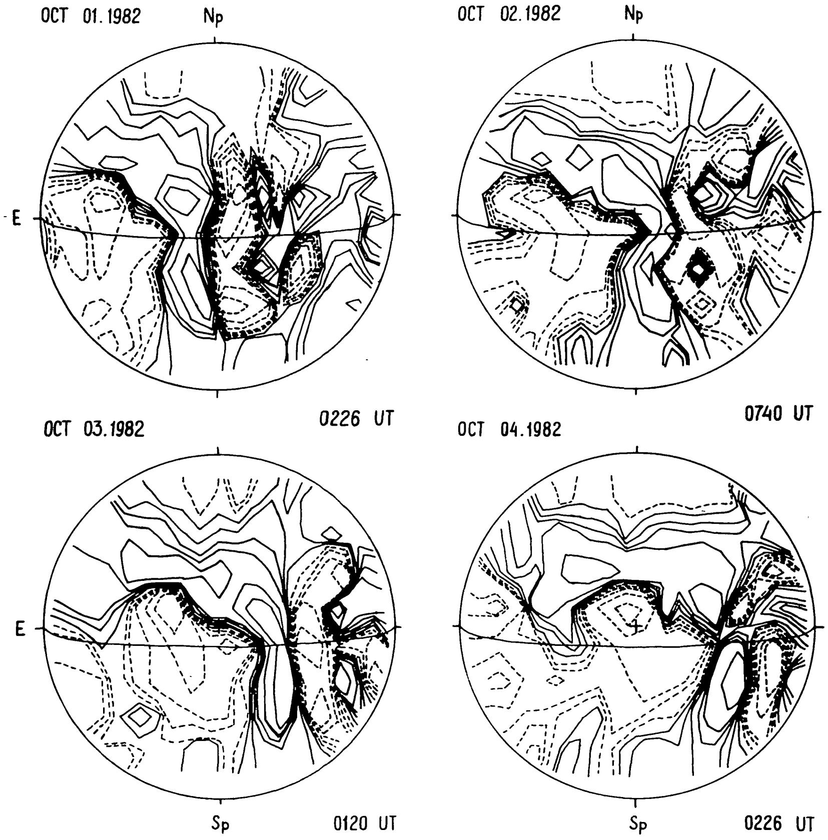

Fig. 4: A typical sequence of daily magnetograms taken with a resolution of 2 arc min.

natively with and without a $\lambda/2$-phase plate preceding the coelostat. Calibration is done with a special unit comprising a calcite plate and a $\lambda/4$-phase plate which is placed in the beam behind the spectrograph slit in front of the polarization analyzer. Such a unit imposes an artificial splitting of the spectral line into two components that are circularly polarized in opposite sense. This ensures a complete analogy with the measurement procedure and removed systematic errors inherent to other calibration methods.

The more-or-less regular series of mean magnetic field observations covers the period from Jule 1982 through October 1984 and includes 279 measurements. Part of the overall data set that refers to the first half of the period indicated, is shown in Fifure 7. For comparison, this figure also presents data from the Stanford University observatory. It is evident that despite some exceprions, there is a well-defined general similarity of the two series whereas the amplitudes show a systematic difference. A complete compa-

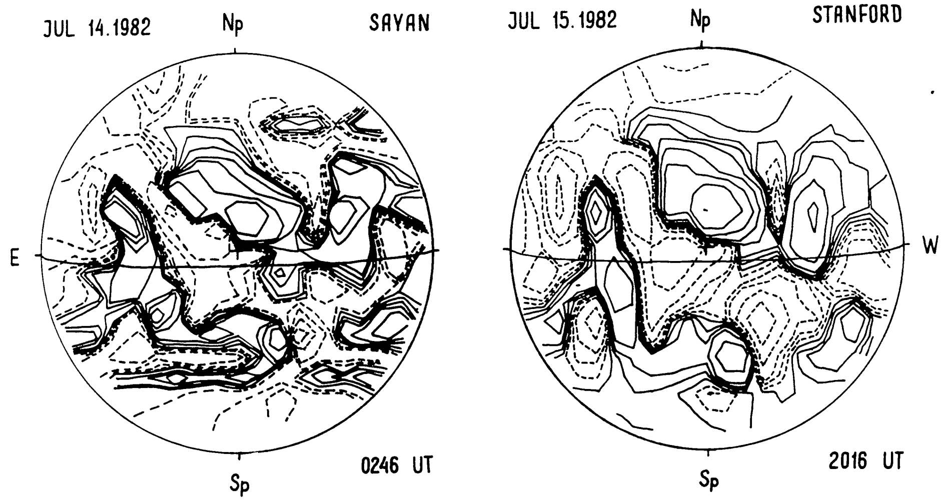

Fig. 5: An example of the comparison of magnetograms from the Sayan and Stanford observatories.

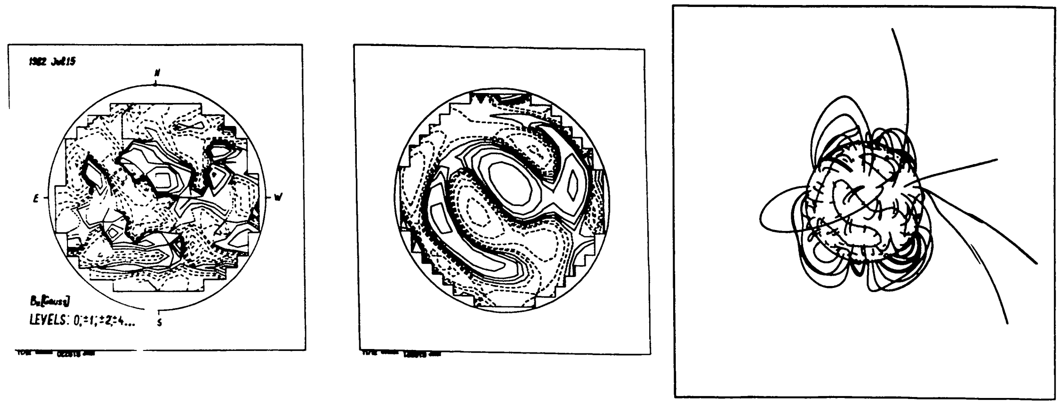

Fig. 6: An example of the original magnetogram, reconstructed using nine harmonics of an expansion by spectral functions and magnetic field structure in the corona, as calculated in the potential approximation.

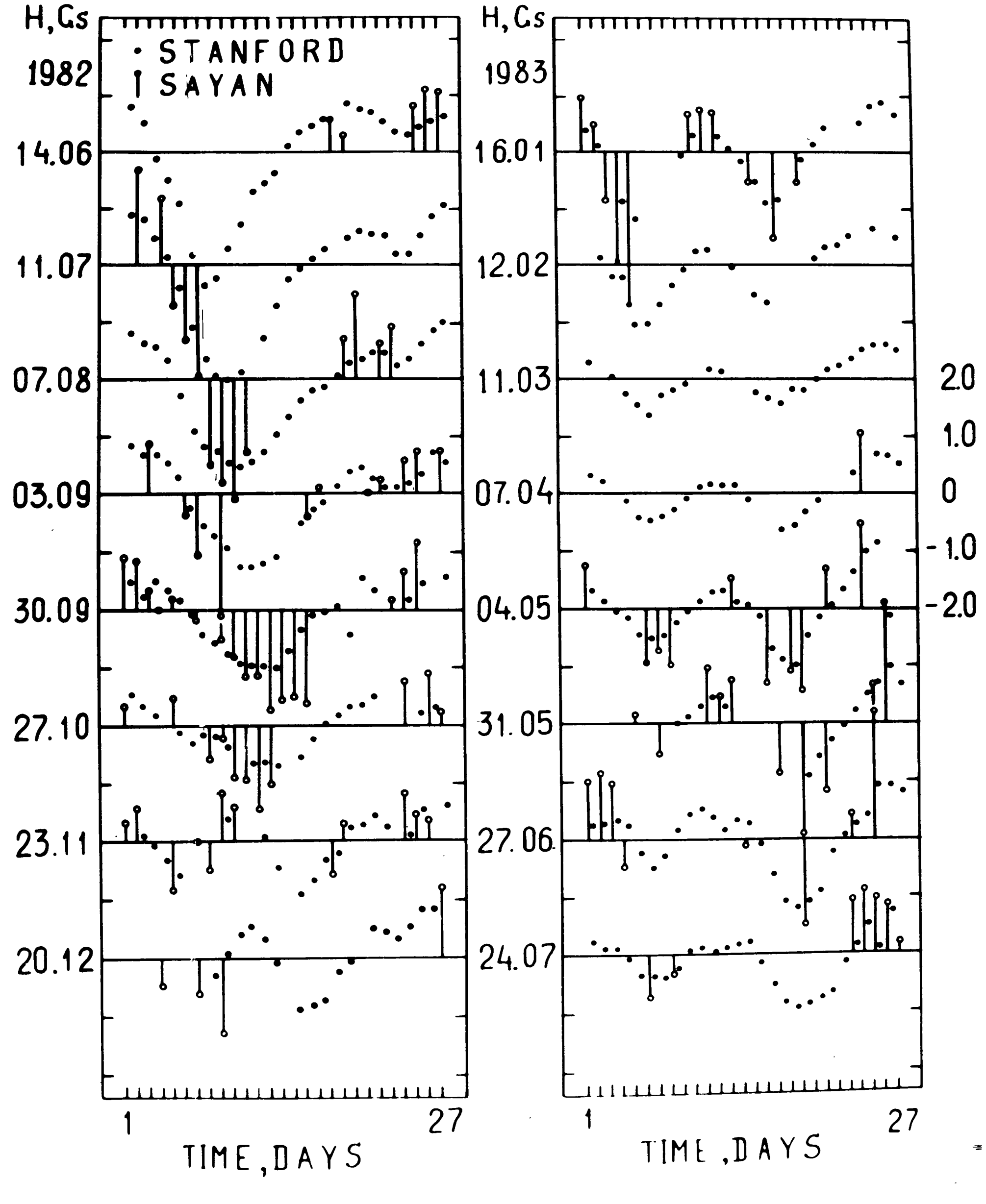

Fig. 7: The measured results on the mean magnetic field at the Sayan and Stanford observatories.

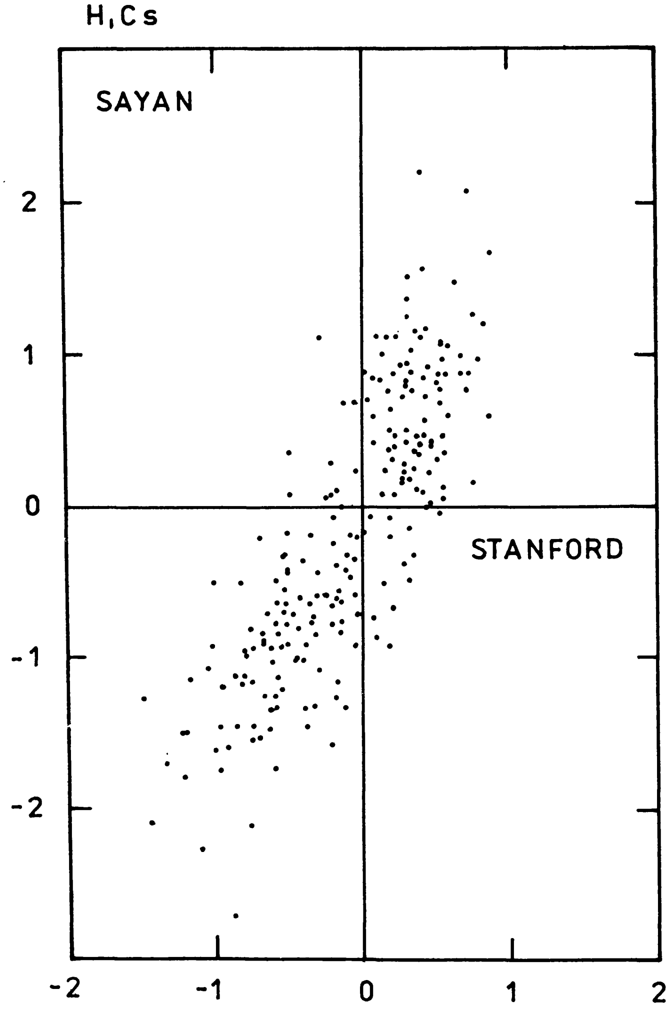

Fig. 8: The comparison of mean magnetic field measurements at the Sayan and Stanford observatories.

rison of the two observational sequences is given in Figure 8; 228 days were used in which time- coincident observations were made at the Sayan and Stanford observatories. A linear regression equation for the data sets has the form

$$H_{Sayan} = 1.51\, H_{Stanford} + 0.01$$

and the correlation coefficient is 0.88.

The interval of observation indicated above (1982-1984) is a period of declining solar activity, with its maximum falling into 1981. Therefore, a decrease in the amplitude of the annual mean strength of the mean magnetic field of the Sun should be expected. Indeed, a treatment of data from the Sayan observatory reveals that the value of $|\bar{H}|$ decreases from 0.50 Gs in 1982 to 0.41 in 1983 and to 0.38 in 1984.

A study of the periodical variations of the mean field by the method of correloperiodogram analysis using a number of measurements at the Sayan observatory, revealed that the main period of variation is 26.8 and the other significant periods are $24^{d}_{.}67$, $25^{d}_{.}76$, $28^{d}_{.}05$, and $29^{d}_{.}25$.

Periods of 36^{d}, 42^{d}, 82^{d} and 124^{d} are identifiable in the range of large periods which are no longer associated with the solar rotation. Long-time continuous observations (of several hour-duration) revealed short-period oscillations in the magnitude of the mean field with a period around 1 hr. Their origin is not clear yet.

5.THE METHOD OF MEASURING GLOBAL OSCILLATIONS OF THE SUN AND LARGE-SCALE MOTIONS IN ITS ATMOSPHERE

This method relies, in principle, on the same adea as realized in papers by Kotov et al. (1978), Scherrer et al. (1980) and Kobanov (1983), namely the modulation of light emission from different areas on the solar surface and measurement of relative line-of-sight velocities with a magnetograph. The optical system in our case is such that the spatial size of regions being observed are able to very over broad ranges, from 40 arc sec to the size of the solar disk. This has been achieved by developing the design of the solar telescope for operative predictions into a twin solar telescope (Figure 1).

One of the objectives is on the optical axis of the spectrograph; the light from the other objective, placed at 70 cm from the first objective axis, is directed into the spectrograph slit by means of a diagonal mirror and a prism that is cemented onto a calcite plate. The light beam from each objective, after passing through calcite, splits into two orthogonally linearly polarized beams. The calcite plate and the prism are adjusted so that only one beam should pass from each objective into the spectrograph slit. After passing the /4-plate placed behind the entrace slit, these beams acquire an orthogonal circular polarization and the on-giong measurements are similar to those of the longitudinal component of the magnetic field.

Since each objective is capable of displacing, independent of the other, along its own optical axis, then by selecting some or other position of the objectives with respect to each other, it is possible to achieve virtually any mode of measurement of differential line-of-sight velocities, right to the observation of localized velocities with the Sun as a star. An example of a record of the oscillations, taken with such a scheme, is shown in Figure 9; the integration time of the signal is 32 sec, and the sensitivity of measurement is 3 $\mathrm{m\ s^{-1}}$.

A combination of the telescopes' entrance apertures that represent concentric zones, makes it possible to perform a spatial filtering of the modes of the global oscillations of the Sun with different degrees 1.

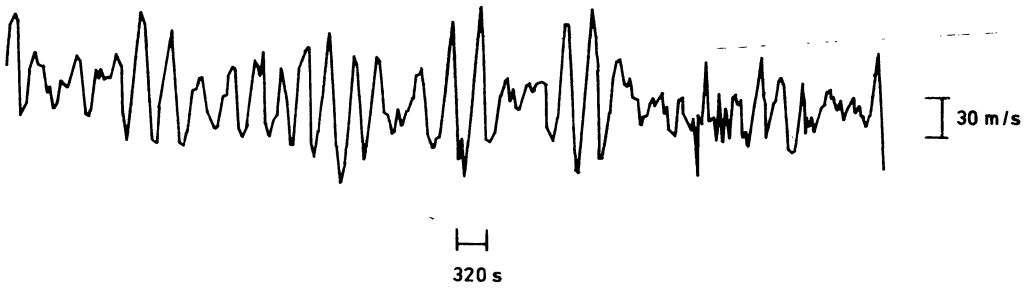

Fig. 9: A record example of 5-minutes oscillations of the Sun as obtained with the twin solar telescope.

In order to measure large-scale line-of-sight velocities and the rotation of the Sun, the second telescope illuminates the slit with the light from the entire solar disk while the first telescope is defocused to the spatial resolution required by the measurements. The image constructed by the first telescope, is being scanned with the aid of a photoelectric guiding and scanning system. This permits the local line-of-sight velocities to be measured with a preset spatial resolution with the Sun as a star.

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