KODAIKANAL OBSERVATORY

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The Solar Magnetometer of Kodaikanal Observatory

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Abstract

An instrument capable of measurement of weak longitudinal component of magnetic fields on the sun has been designed and contructed for operation with the horizontal solar telescope and high dispersion spectrograph of Kodaikanal Observatory. Detailed features of the optical and electronic design have been discussed. The instrument uses the principle of the Babcock magnetograph and has additional facilities of simultaneous measurements of Doppler velocities and line core intensities. A photo-electric guiding attachment for the solar image has also been described. The performance of the instrument and reliability of the measurements have been discussed.

1. Horizontal Solar Telescope

The new horizontal solar telescope was installed in 1960 in Kodaikanal Observatory to facilitate detailed studies of the sun. The complete optical and electronic drive system was supplied by Grubb Parsons and consists of a three mirror coelostat arrangement feeding a 38cm, f/90 two element objective lens. A 35cm solar image is produced by the telescope which is followed in the optical train by a high dispersion spectrograph, that provides high resolution spectra for further refined measurements. The horizontal telescope is housed in a long underground tunnel to minimise the effects of temperature variation. The first two mirrors of the coelostat system are mounted on a tower 10 meters above ground level to avoid seeing fluctuations that originate near the ground.

2. The Coelostat System

The first mirror of the coelostat, an optical flat of fused quartz of aluminised surface 61cm in diameter, is mounted in a cell with equatorial mounting arrangement and is driven by a synchronous motor geared down in such a way as to follow the sun with high accuracy. The supply frequency of the synchronous motor is 47.333 cycles nominally, which is generated by a Wein bridge oscillator with its elements in a thermostatically controlled oven. A separate tuning unit provides small adjustments needed to cope with the variations in the sun's apparent motion. The oscillator output is phase split and amplified by three power amplifiers to produce a 3 phase 440V supply with a very stable frequency.

The second coelostat mirror, identical to the first is also equatorially mounted and has independent remote controlled slow and fast movements around two perpendicular axes, that enable the observer to move and centre any part of the solar image on to the spectrograph slit.

The third mirror located at the bottom of the tower is again a 61cm optical fused quartz flat, but fixed at an angle of 45° to the vertical so as to render the beam from the tower coelostat mirrors horizontal along the axis of the 60 metre long underground tunnel.

3. The Imaging System

The horizontal solar beam falls on a 38 cm diameter, two element achromat objective lens with a focal length of 36 meters. Anti-reflection coating of a thin film of magnesium fluoride is provided on the lens to reduce light loss by reflection at the two surfaces. The lens is mounted on a remote controlled traction carriage to enable carrying out small changes in focussing when working at extreme edges of the spectrum. To facilitate visual inspection, the solar image is focussed on a white metal screen, which forms the end plate of the 18 metre diffraction spectrograph.

4. The Spectrograph

The high dispersion spectrograph consists of a large plane reflection Babcock grating in a Littrow arrangement. The grating has an area of 153 mm × 203 mm, which 600 lines to the millimetre and blazed in the fifth order at 5000Å. The Littrow lens is a 20 cm, f/90 two element achromat with a focal length of 1800 cm, and is mounted on a remote controlled traction carriage. The dispersion and spectral resolution are extremely high; in the fifth order green, where it is blazed, a dispersion of 9 mm/Å is obtained with a resolving power of 600,000.

5. Theory of Measurement

The longitudinal component of solar magnetic field is measured from the Zeeman splitting of certain Fraunhofer lines. In the direction of the magnetic field, most of the spectral lines split up into two components, both circularly polarised, but in opposite sense. The shift in wavelength of each component is related to the magnetic field strength by the following relation :

$$\Delta\lambda = -4.67 \cdot 10^{8}\, g\lambda^{2}H \qquad \ldots \qquad (1)$$

where $\Delta\lambda, \lambda$ are in cms, H is in gauss and g is in the Lande' splitting factor for the particular line. The shift, as may be seen, is extremely small for small magnetic fields and cannot be detected photographically or even by the usual photoelectric arrangements. The two components remain unresolved even for moderately strong fields, and in that case, the line appears a trifle broadened. If, however, by introducing a quarter-wave plate and a polariser, one of the circuarly polarised components is removed, only the other component will be seen and the line will appear shifted.

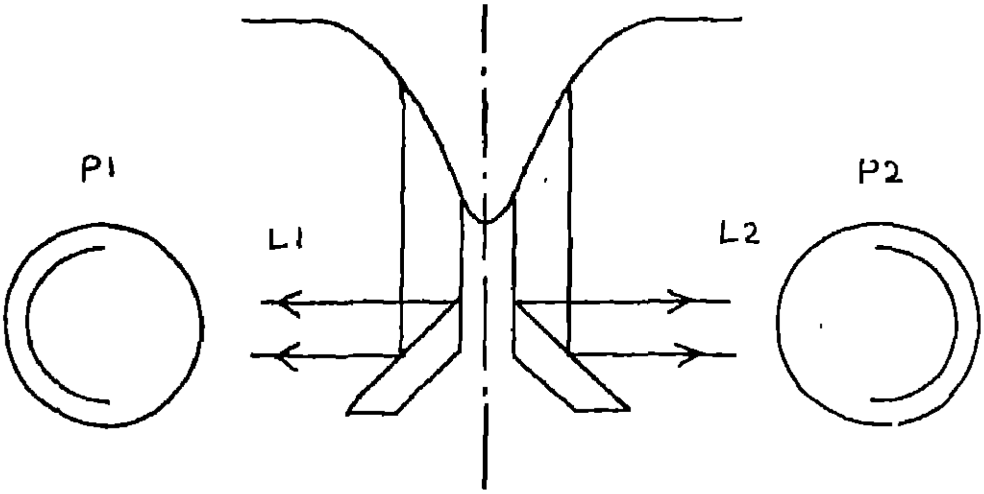


Fig. 1

If one sets up an arrangement as shown in Figure 1, which separates the light from the two wings of a line into components L_1 and L_2, the difference $\Delta L = L_1 - L_2$ will be zero if the line is properly centred, but introduction of a circular polarisation analyser will result in a fractional change,

$$\frac{\Delta L}{L} = 4.67.10^{-5} \frac{1-R}{1+R} \frac{2}{B} \quad g \lambda^2 H \qquad .. \qquad (2)$$

in a Zeeman affected line, R being the residual intensity at the centre of the line and B the half width of the line, assuming a straight triangular profile. If the light is received on two photomultiplier tubes of identical and linear response characteristics, then a small change in photomultiplier output current Δi should result with the introduction of a circular polarization analyser given by :

$$\frac{\Delta i}{i} = 4.67 \times 10^{-5} \frac{1-R}{1+R} \frac{2}{B} g \lambda^2 H \qquad .. \qquad (3)$$

where i is the mean current delivered by the photomultipliers receiving light from the wings of the spectral line under investigation.

The difference current Δi is extremely small for low values of magnetic field and cannot be unambiguously determined with the normal d.c. amplification techniques. Connecting two photomultipliers receiving light from the two wings in a differential arrangement doubles the difference, but even then the signal current is very small and completely submerged in the noisy photomultiplier output currents. To amplify the signal out of the noise background, a selective amplification technique is employed. To achieve this, an electro-optic modulation arrangement is used. A mounted crystal of ammonium di-hydrogen-phosphate (ADP) has the property of becoming birefringent when an electrical potential gradient is applied across it. When an appropriate voltage is used, the crystal behaves as a quarter wave plate. Used in conjunction with a polariser, it serves as a circular polarisation analyser. By reversing the polarity of the voltage, the combination changes from a right to left circular polarisation detector or vice-versa. If an alternating voltage of appropriate magnitude is applied across the ADP, the combination behaves as an oscillating circular polarisation analyser. When such a system is introduced in the beam the right and left circularly polarised light are cut off in alternate half cycles. The differential output of the two photomultipliers thus contains a single frequency signal whose amplitude is proportional to the longitudinal magnetic field. This when channelled through narrow band selective amplifiers, rises above the noise level and makes it possible for being recorded after suitable further amplification, filtering and synchronous detection.

6. The Magnetometer Detector Head

For measurment of weak solar magnetic fields, therefore, it is necessary to measure the wings of a Zeeman sensitive spectral line with a precise photoelectric set up. The high dispersion and spectral resolution required for this purpose is provided by the spectrograph. The photoelectric detector head consists of a combination of two adjustable slits S_1 and S_2, so that if a spectral line of proper width is allowed to fall on them, the wings will be reflected to two photomultipliers P_1 and P_2 while the core will pass through to the third photomultiplier P_3 as in Figure 2. The slit S_1 is a standard Hilger bilateral slit of length 18 mm and adjustable upto a maximum width of 1800 microns. The slit S_2 is a bilateral arrangement of two optically worked reflecting jaws of speculum, coated with Alumium in a vacuum deposition chamber at a precisely controlled rate. This is adjustable upto a maximum width of 1500 microns. S_2 is mounted on a table controlled by a precision screw which allows accurate alignment of the two slits in respect of the beam coming from the spectrograph.

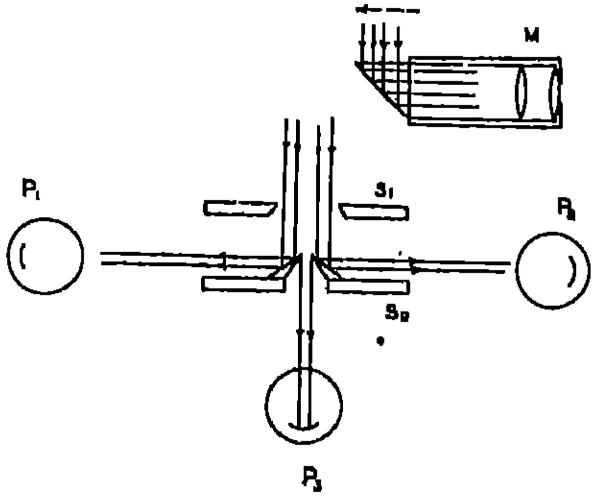

M
P_1
S_1
P_2
S_2
P_3

Fig. 2

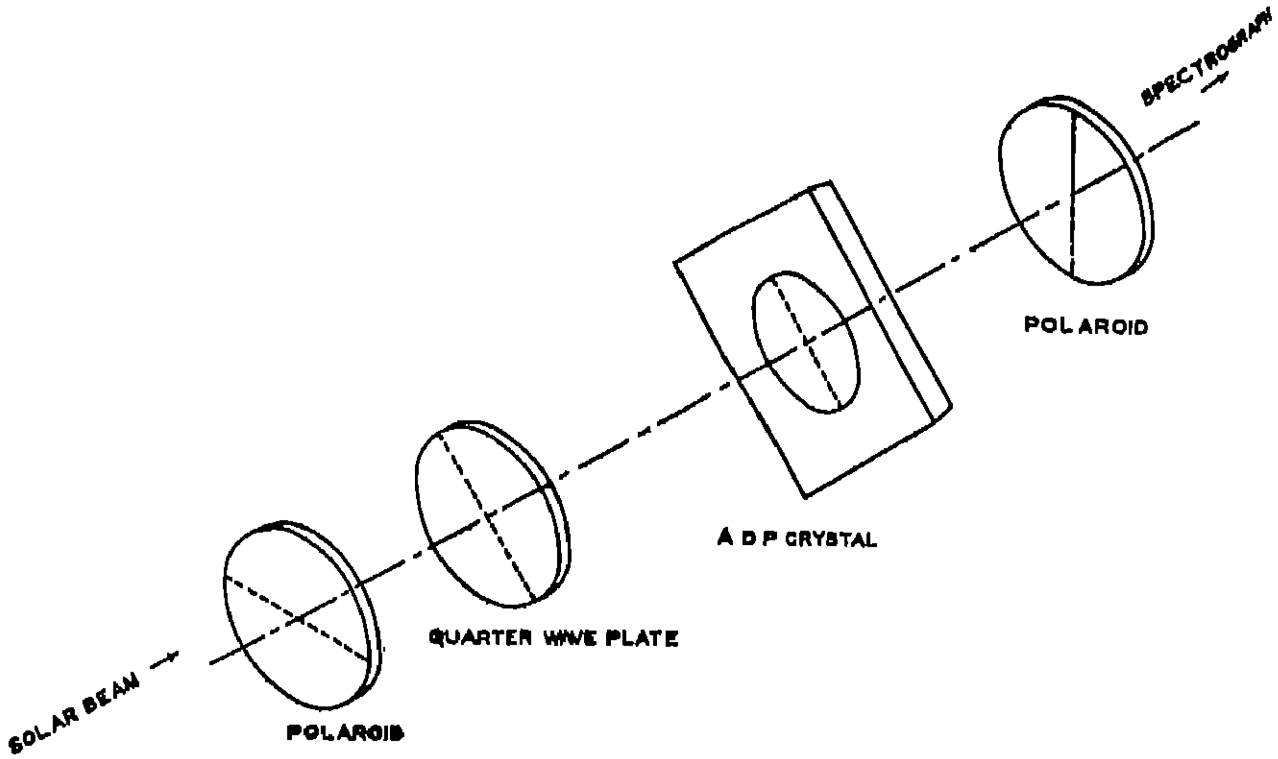

SPECTROGRAPH →
POLAROID
A D P CRYSTAL
QUARTER WAVE PLATE
SOLAR BEAM →
POLAROID

Fig. 3

The three photomultipliers P_1, P_2 and P_0 are RCA 1P21 photo tubes with S-4 cathode surfaces. The photomultipliers P_1 and P_2 form a matched pair selected from about 2 dozen tubes and show almost identical characteristics. To improve their signal to noise ratio characteristics, they are operated with double the normal stage voltages across the cathode and the first dynode and slightly reduced voltage between the ninth dynode and anode. The photomultiplier P_0 is provided with equal voltages at all stages, the potential divider chain being located at the base of the tube. But the supplies to tubes P_1 and P_2 are independently given to individual electrodes by means of multicore cables, voltage division being controlled by elaborate networks on the main instruments rack. The outputs of the two "wing" photomultipliers P_1 and P_2 are taken out by a pair of shielded cables for feeding into the difference amplifier. A small monitor viewer M, consisting of a total reflecting prism and an eye-piece, is mounted on a draw tube which can be brought in or out of the beam by manual operation. The monitor helps identification of the spectral region and approximate centering of the line on the slit combination.

7. The Electro-optic Modulator

The heart of the electro-optic modulator is a Baird Atomic mounted ADP crystal type AM-2 with optically transparent NESA electrodes. The mounted crystal is fixed on an adjustable stand and introduced in the solar beam just before the spectrograph entrance slit. A polaroid is also fixed on a rotatable frame following the ADP. The stand has facilities for accommodating a fixed circular polariser for converting the equipment for velocity recording and for calibrating the scale of the instrument as explained later. Two separate heavily insulated conductors supply the 2500 volt A.C needed for the crystal to switch $\pm\lambda/4$ retardation between the two polarised components of the light beam.

The emergent light is completely polarised in the direction of the polaroid axis; for the sake of optical efficiency it should be parallel to the grating ruling, which is vertical in our set up. The orientation of the polaroid is hence fixed, and the ADP crystal orientation adjusted with respect to this so that the direction of the optic axis of the crystal remains at angle of 45° to the polaroid axis. As the direction of the optic° axis of the crystal is known from the manufacturers specification as being parallel to one of the sides, the crystal is mounted with its sides at one angle of 45° to the vertical. A schematic arrangement of the different elements of the modulator is shown in Figure 3.

8. The Electronic Design

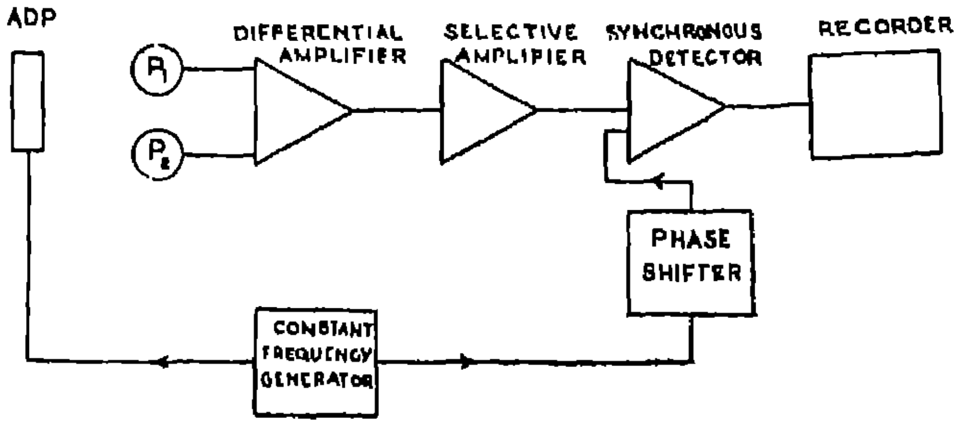


Fig. 4

The electrical arrangement for modulation, selective amplification and detection is shown schematically in Figure 4. The modulating frequency employed in this instrument is 125 Hz, obtained from a crystal controlled oscillator and a scaler chain. The constant frequency generator unit consists of a 100 KHz quartz oscillator, a buffer amplifier, two scaler units providing a scale of 800 and giving a square wave of frequency 125 Hz, an active filter comprising of a selective amplifier at 125 Hz and finally a push-pull Class AB power amplifier delivering 40 Watts at 115 volts. The whole set up is shown schematically in Figure 5. The output of this constant frequency generator feeds two transformers, the first one supplying 2500 V to the optical modulator and the second, chopper vibrator through the phase shifter unit.

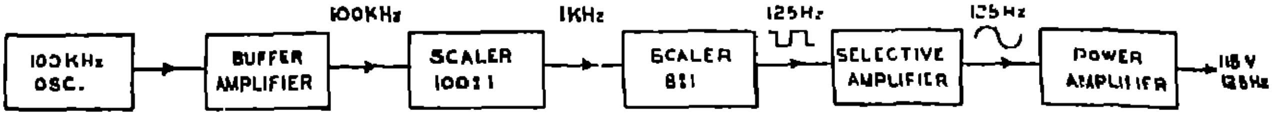


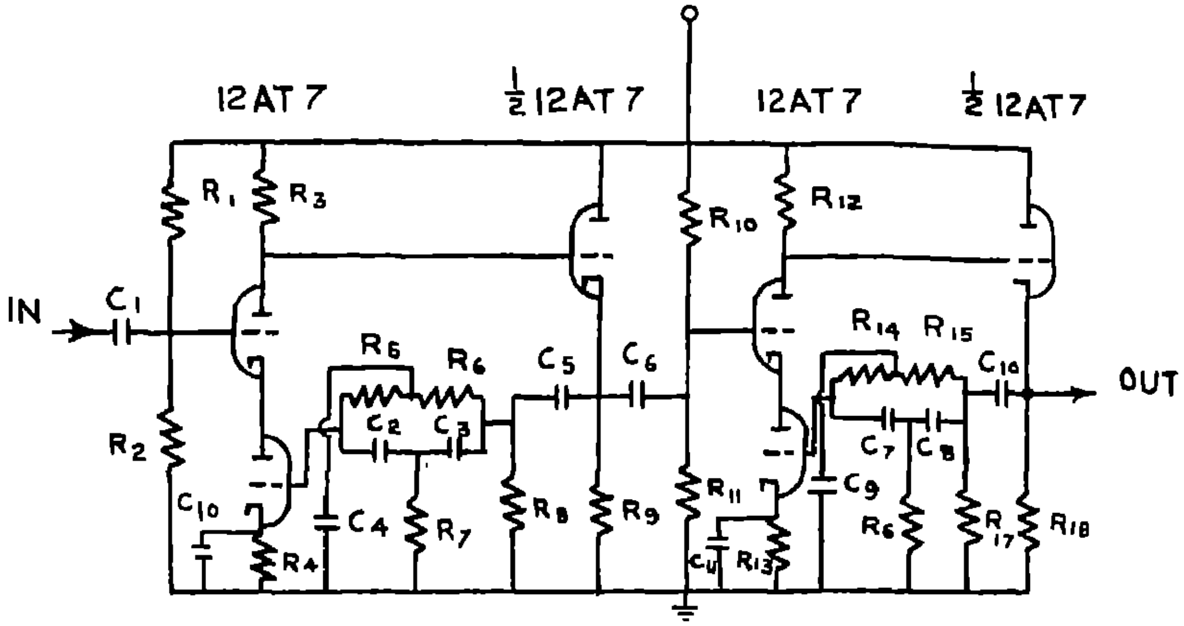
Fig. 5

The difference amplifier used is a DA-102 low level differential amplifier manufactured by EPSCO Inc. U.S.A. This accepts two inputs and amplifies the difference by means of a Wheatstone bridge network and a cascode input stage. For obtaining a flat response from DC to 200 KHz, it divides the DC and very low frequency signals from others and amplifies by a separate chopper stabilised amplification system. In the final output the two channels are combined together. Common mode rejection is high, the rejection ratio at 125 Hz being 50,000 to 1. Differential gain is adjustable from 100 to 2000 in five steps. The bandwidth is inversely proportional to gain, the gain band width product being equal to 20 MHz. The equivalent noise input being less than 3 microvolts r.m.s., the amplifier is ideally suitable for amplification of low photomultiplier signals. Simultaneous amplification of the DC with the 125Hz signal frequency permits D.C. to be separated at the output and is used for operating a servo system that keeps the line continuously centred on the double slit of the photomultiplier detector head.

The selective amplifier consists of two stages. The individual units are of a cascode input stage with a twin-T rejection network in its feed back loop. Figure 6 shows the circuit diagram of this stage. Use of a cathode follower in the feed back path improves the frequency response characteristics, the half power points being less than 5 Hz away from the centre frequency of 125 Hz. Use of high precision, high stability components in its construction has made the amplifier intrinsically very stable.

The phase sensitive synchronous detector employs an electro-mechanical single pole 2-way chopper driven at the synchronous frequency of 125 Hz. The circuit arrangements are shown diagrammatically in Figure 7. The four-pole, six-way switch can select 6 different R.C. combinations to vary the time constant of the synchronous detector. The values of the time constant which can be chosen this way are 0.3, 1.1, 2.8, 6.8 and 11 seconds. Feeding into the detector is done through a cathode follower stage with D.C. coupling and the output is obtained from a pair of balanced cathode followers in differential arrangement. The balance point is adjustable by a precision ten-turn helical potentiometer connected between the two cathode points and the ground.

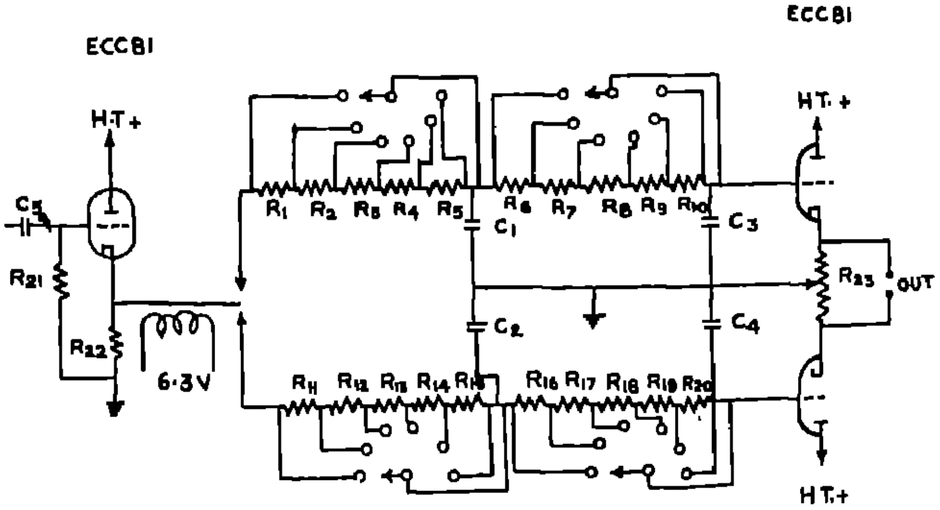
For proper adjustment of the phase sensitive detector a phase shifting arrangement for the driving voltage has been provided. The network is shown in Figure 8. The resistances are chosen in such a way that each step in the eleven point switch shifts the phase by 18°. The output impedance of the network is kept low, so that the connection of the chopper that draws about 100 MA at 6.3 volts does not affect the operation of the network.



R1, R10 = 2M
R2, R11 = 820K
R3, R12 = 150K
R4, R13 = 1 K
R5, R6, R13, R14, R15 = 10K+2K variable
R7, R16 = 5·1K+1K variable

C1, C5, C6, C10 = 0 11μF
C2, C3, C7, C8 = 0·11μF
C4, C9 = 0 22μF
C10, C11 = 100μF.12V.

Fig. 6



R1 R6 R11 R16 = 85KΩ
R2 R7 R12 R17 = 240 KΩ
R3 R8 R13 R18 = 470 KΩ
R4 R9 R14 R19 = 1 MΩ
R5 R10 R15 R20 = 1 MΩ
R21 = 1 MΩ
R22 = 8KΩ
R23 = 10K turn helipot

C1 C2 C3 C4 = 4μF
C5 = 0·1μF

Fig. 7

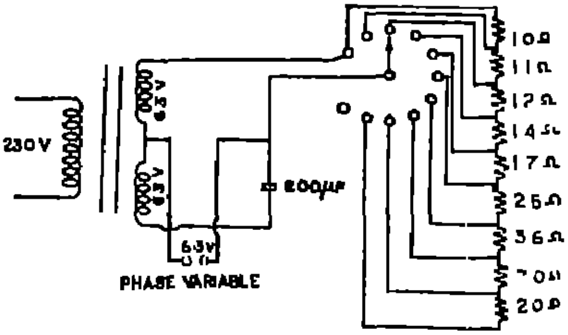


Fig. 8

9. Auxiliary Electronic Equipment

The recorder used is a Honeywell Brown potentiometric strip chart recorder with a standard resistance box connected across its input terminals. The recorder has a full scale sensitivity of 10mV with a response time for full scale deflection of 1 sec. The chart used is of standard 10 inch width being drawn at the rate of either 0.5 inch/min. or 2 inches/min. depending on the requirement. The output stage of the synchronous detector is kept slightly off-balance, so that the zero can be located at the centre of the chart.

The output of the central photomultiplier tube is amplified directly by a D.C. electrometer amplifier* and recorded on a second strip-chart recorder. To smooth out the noise fluctuations of the photoelectric output current, an R.C. network of time constant 1 sec. is introduced at the input of the amplifier.

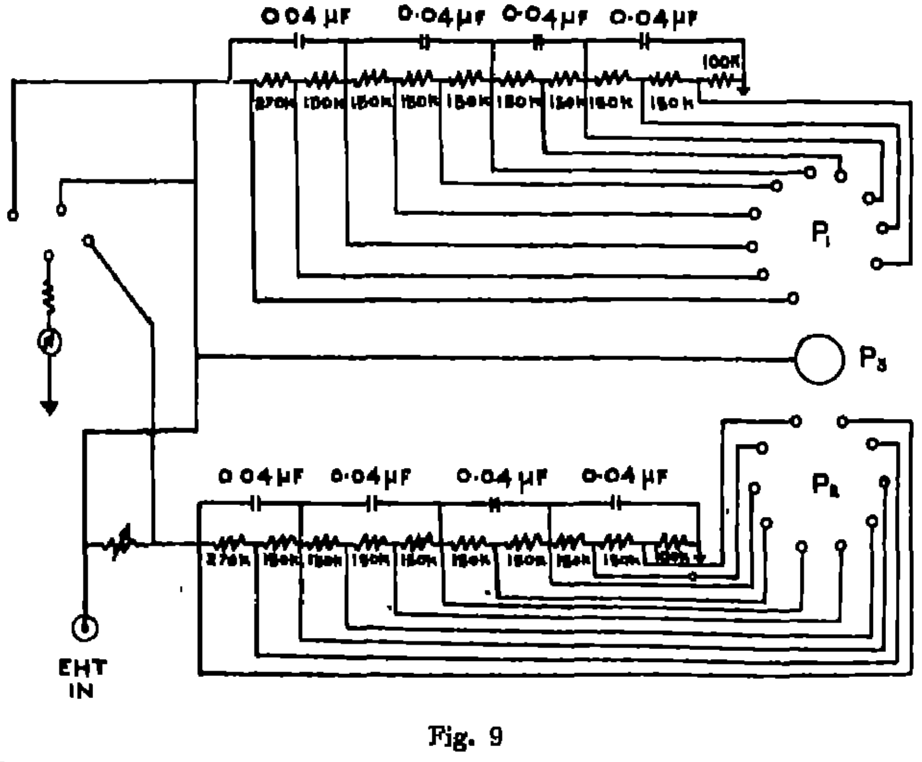


Fig. 9

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*Electrometer D. C. Amplifier and voltmeter type 1230A manufactured by Messrs. General Radio Co., U.S.A.

The H.T. supplies of the three photomultipliers are derived from a transistorised EHT unit with high stability*. The EHT is taken to a distribution panel where two stable resistance networks divide the voltage for application to different dynodes of the photomultiplier pair P_1, P_2. A variable resistance introduced in one chain allows small differential adjustment to be made between them, which may become necessary in course of aging of the two photomultipliers. A three way switch with a voltmeter enables the operator to check the voltages on the three photomultipliers independently. A circuit diagram of the EHT distribution panel is shown in Figure 9.

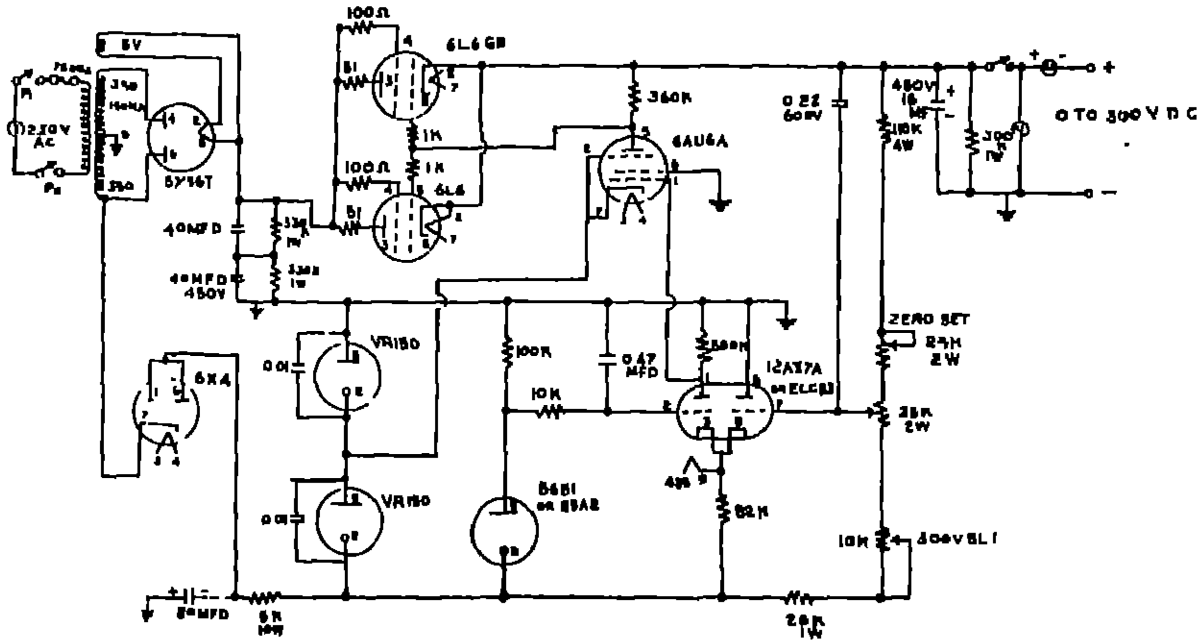

Fig. 10

All the essential controls for operation of the equipment have been brought out to a front control panel. The individual controls are : (1) The E.H.T. distribution check switch (2) Photomultiplier balance potentiometer (3) Synchronous detector zero adjustment potentiometer (4) The R.C. time constant selector switch (5) Phase control switch of the synchronous detector and (6) The light modulator on-off switch and indicator.

A cathode ray oscilloscope with associated amplifiers capable of D.C. amplification† has been included in the equipment to check several adjustments in the equipment. Besides the regular use as indicator in synchronous detector phasing and photomultiplier balancing, the oscilloscope is also used for initial signal tracing and in the calibration of the amplifier stages of the equipment. During observations the oscilloscope is used as a two dimensional indicator of image guiding system described in the next section. The power supply unit for operating the selective amplifier and cathode follower stages is a stabilised H.T. Unit of conventional design. Figure 10 shows the circuit diagram of this unit, which delivers H.T. voltages of excellent regulation and stability. To achieve further stability necessary for this equipment, a transistorised voltage stabiliser‡ employing saturable core action controlled by a sensitive amplifier loop is connected between the mains supply and the equipment.

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* EHT unit type HV 205 manufactured by Electronic Corporation of India.

† Dumont 301-A, D.C. Oscilloscope.

‡ Ether transistorised voltage stabiliser Model LT-T-1000

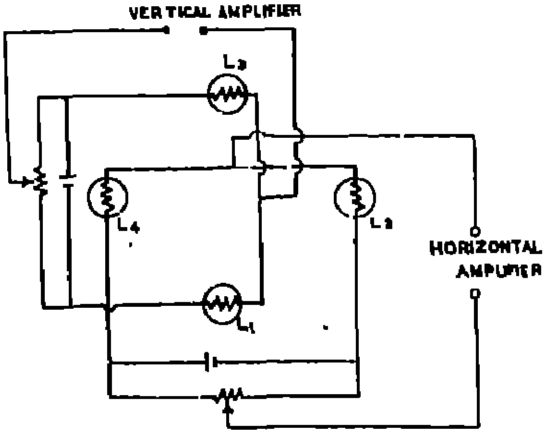


Fig. 11

10. The Photoelectric Guiding Attachment

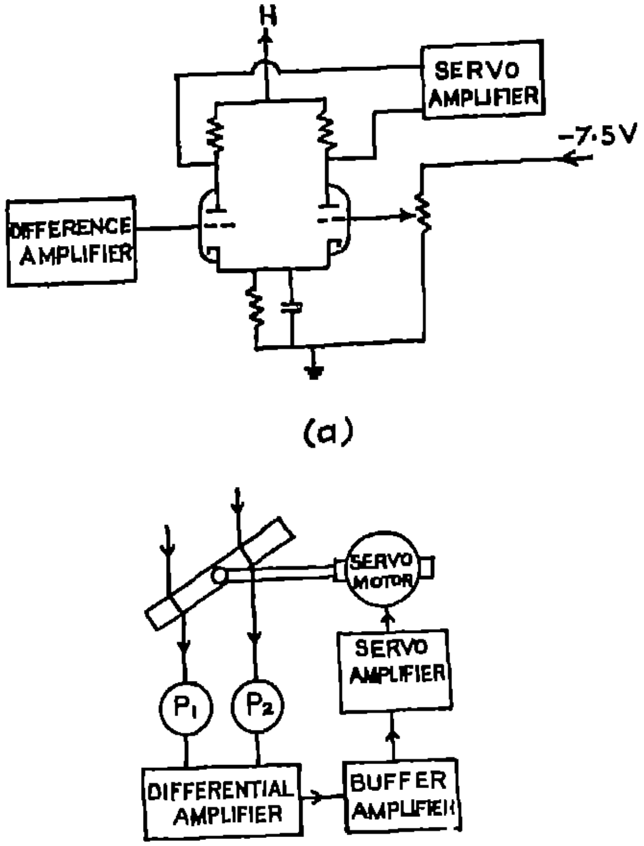
To facilitate accurate guiding of the solar image a photoelectric guiding unit is incorporated in the set up. The property of limb darkening gradient has been utilised for this purpose. Four light dependent resistors Philips type LDR are mounted behind a screen in such positions as to receive light from two perpendicular pair of diametrically opposite points near the sun's limb. Each pair of LDR is connected in a Wheatstone bridge arrangement as shown in Figure 11. After visual initial centering of the solar image, the two bridges can be balanced by using the respective potentiometers. The unbalance voltages are detected by the vertical and horizontal deflection amplifiers of the Dumount D.C. oscilloscope which deflects the cathode ray spot on the screen according to the unbalance voltages in corresponding directions. Because of strong gradients of solar limb intensities, any small shift of the solar image result in appreciable unbalance voltages, which can be corrected by recentering the image by operating the guide buttons of the coelostat arrangement.

The arrangement is useful in cases where observations are made not too close to the solar limb. The frame holding the LDRs do not permit the light from the limb to enter the spectrograph. The frame is capable of movement in two perpendicular directions controlled by two fine precision screws. Two calibrated sensitive dial gauges are used to determine the positions and movements of the frame, where such movements become necessary in cases of long continuous observations at a point, to compensate for solar rotation during the period of observation.

11. Automatic Doppler Compensator Unit

For measurement of longitudinal magnetic fields, it is necessary that the spectral line should remain properly centred on the double slit during observations extending over different parts of the solar surface and time. There exists considerable amounts of Doppler shifts of all spectral lines originating from different parts of the solar disc as a result of solar rotation and a variety of large and small scale motions. The quasi-periodic variations in Doppler shifts of lines originating from a fixed area is also well known. If not properly compensated, the spectral line is apt to get shifted from the central position during the observation, thereby introducing errors in the determined values. An automatic Doppler compensating arrangement is hence absolutely essential for operation and is provided in this equipment.

The basic component of the Doppler compensator is a plane parallel quartz line shifter mounted just before the focal plane of the spectrograph. The plate is optically worked to an accuracy of $\lambda/2$ and has a thickness of 3.085 mm. It is mounted on a rotatable axis which extends below through the metal frame meant for holding various attachments at the spectrograph focal plane and is connected to a two phase servo-motor.



(a)

(b)

Fig. 12

The servo-system driving the line shifter to compensate for any Doppler shift works in the following manner. Whenever the spectral line gets shifted a differential D.C. voltage is developed across the P_1, P_2 photomultiplier outputs. The EPSCO differential amplifier amplifies this difference along with any 125 Hz modulation present in the signal. At the output of the differential amplifier this amplified D.C. signal is separated, and fed into a servo amplifier through a D.C. buffer stage. The output of the servo amplifier drives the servo-motor controlling the line shifter. The arrangement is diagrammatically shown in Figure 12.

The servo amplifier used is a commercial unit employed in Honeywell continuous balance units in their strip chart recorders. The buffer stage is a simple D.C. differential amplifier whose balance can be adjusted arbitrarily. This has been found necessary while centering certain asymmetric lines of the solar spectrum and to compensate for small characteristic variation between the two parts of the double-triode used.

12. The Doppler Recorder

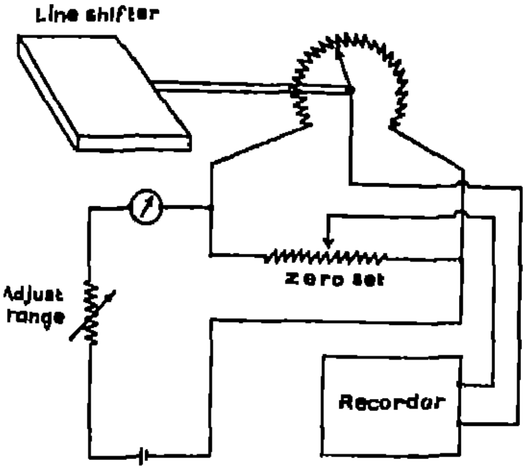


Fig. 13

A small attachment to the automatic Doppler compensator unit makes the simultaneous recording of the Doppler motion of the region possible. While the main unit determines the Zeeman splitting of the line, the automatic Doppler compensating unit keeps the line properly centred, by sensing the error voltage due to Doppler displacement and correcting the shift through a servo loop. A continuous record of this error voltage directly gives the Doppler velocity information.

The attachment basically consists of a good quality potentiometer rigidly fixed to the shaft carrying the line shifter plate. A precisely controlled current flows through the potentiometer, so that any minute movements of the slider results in small changes of the potential of the slider contact. These changes, which are proportional to the line shifter movement are recorded on a second potentiometric recorder. The electrical arrangement is illustrated in Figure 13.

It is obvious from the electrical arrangement that the scale of deflection is directly proportional to the current flowing through the potentiometer. This is of great advantage as extra amplification of the deflections can be easily achieved when recording velocity variations of small amplitudes. A simple R.C. filter is used at the recorder input to smooth out the fluctuations originating mainly from the seeing defects.

13. Reimaging Attachment

The solar tower equipment at Kodaikanal consisting of the horizontal telescope and the spectrograph is used on several different research projects on the sun. As such it would be difficult if the complex and heavy magnetograph head is designed to fit permanently in the standard focal plane of the spectrograph. This difficulty has been overcome by locating the magnetograph detector head at one side of the spectrograph and reimaging the spectrum on the analysing slit of the magnetograph. Changing over from the magnetographic mode of operation to the conventional photographic mode of operation requires removal of this reimaging attachment, and can be accomplished in a matter of seconds. A total reflecting prism placed just ahead of the focal plane of the spectrograph bends the beam at right angles and is reimaged by a lens of 20 cm focal length, without magnification. The lens position is adjustable for accurate focus, which can be monitored at the detector head on which the spectra are reimaged. A light tight mount for 5 cm × 5 cm is provided in this unit to enable working in the higher order spectra by interposing suitable filter combinations to cut out the unwanted overlapping orders.

14. Instrument Characteristics

For proper evaluation of the readings obtained by the instrument described above, a thorough controlled calibration and checking of various key units as well as the instrument as a whole is essential. The method and results of such operations are now described in the following paragraphs.

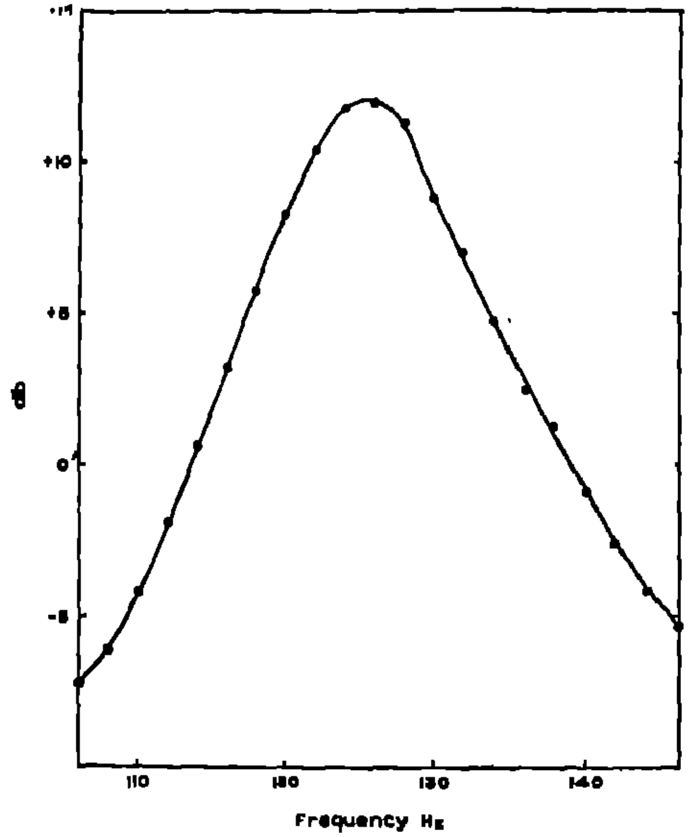


Fig. 14

The gain-frequency characteristics of the selective amplifier is a factor which determines the minimum signal detectable by the instrument. For the sake of proper maintenance of the instrument, it is preferable to have this checked periodically. Facilities are provided in the equipment for doing this. Output of a laboratory standard oscillator is fed through a calibrated attenuator to the input of the selective amplifier, the input from the differential amplifier being removed and the output measured directly on the cathode ray oscilloscope screen. An alternate path by-passing the amplifier is made for measuring the input on the same scope. The output/input ratios are measured at frequencies around the operating frequency. Figure 14 shows the gain-frequency characteristics of the selective amplifier used in our equipment.

The linearity characteristics of the entire amplifier-detector chain is extremely important, as variations in this may introduce large errors in our measurement. This is checked by the following arrangement. The input to the differential amplifier is removed and a small fraction of the generator voltage fed instead, through the calibrated attenuator. The output is directly measured on the recorder, taking care to kep the phase of the synchronous detector reference voltage properly adjusted. Measurements are done at various input levels and the input vs output characteristics determined. Reversing the input connections permits obtaining the points on the negative side. Any non-linearity, if obtained has to be corrected by adjusting the biases of the different amplifier and cathode follower tubes. This has been done by a trial and error method in the first instance, and use of high stability components has reduced the probability of shifts later. In any case the original linearity characteristics are kept as a reference and subsequent periodic measurements compared with the same. Figure 15 shows the linearity characteristics of the equipment.

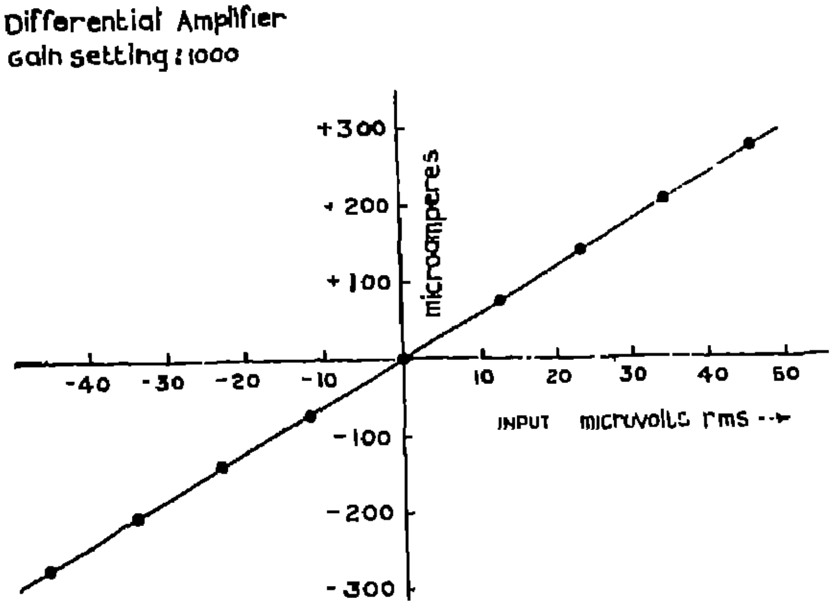


Fig. 15

The light passing through the ADP polaroid assembly is completely polarised and the final output has large variations for different orientations of the grating ruling and photo-cathodes. Since the orientation of the grating ruling is fixed with respect to the photomultiplier cathodes in our set up, it is necessary to know the variation of the photo-electric output for different orientations of the ADP-polaroid assembly, to enable one to adjust the instrument for optimum response. This has been done by noting the third photomultiplier response for different orientations of the assembly. Figure 16 shows the transmission characteristic for different orientations of the assembly; angles are measured from the vertical, and the response is symmetrical about this axis. The variation is quite large and is of the order of 40 per cent of maximum response between two extreme orientations at right angles. It may be noticed that the ADP-polaroid assembly blocks a major part of the incident light. The loss is inherent in the arrangement: the maximum transmission is only 44 per cent in the present set up.

For accurate measurements, it is essential that the linear drift of the output should be a minimum. From systematic studies it has been seen that the equipment almost completely stabilises after half-an-hour's warm up time. During observations, care is taken not to record data before such stabilisation is achieved.

Stabilisation of the photomultipliers, however, is much more difficult to obtain. There is a tendency for large differential drifts to occur after the EHT is switched on, which may require hours to come down to a reasonable value. To avoid such drifts the photomultiplier voltages are kept on during the observing period lasting over days. The photomultiplier pair is balanced at the beginning of each observation by focussing a portion of the continuum on the slit pair, and the balance checked at the end of observation.

Adjustment of the reference voltage phase can be done without ambiguity by looking at the G.R.O. waveforms at the electromechanical chopper outputs. The phase once adjusted does not require frequent changes. The phase need be checked at the beginning of a day's observation or when optical adjustments are altered.

15. Doppler Mode Operation

The electronic amplification and detection arrangement is extremely sensitive to even a trace of the signal modulated at the operating frequency. By a simple optical arrangement it is possible to introduce signal frequency modulation to any spectral line, irrespective of whether Zeeman polarisation of the wings is present or not. When a fixed circular polariser is placed in front of the ADP-polaroid assembly, the light falling on the electro optic modulator is totally circular polarised, and the effect of the oscillating detector is to modulate the total light falling on the spectrograph. When a symmetrical spectral line is properly centred the differential output of the two wing photomultipliers is zero. A slight shift of the line produces a non-zero output, as explained earlier. When the total light is modulated at the signal frequency, as a result of putting a fixed circular polariser ahead of the ADP-polaroid assembly, the differential output is also modulated. This is amplified by the selective amplifier and detected by the synchronous detector, with extreme high sensitivity. The equipment, under these conditions, is said to operate in the "Doppler mode". Even a minute shift of the line is detected and recorded by this arrangement.

The shift of any spectral line results in a differential output of the two photomultipliers that receive light from the wings. The proportionate change in the differential photomultiplier output is given by:

$$\frac{\Delta i}{i} = \frac{v\lambda}{c}\,\frac{1-R}{1+R}\,\frac{2}{B} \qquad \ldots \qquad (4)$$

where v is the line of sight component of velocity of source and c is the velocity of light expressed in the same units; the other symbols representing the same parameters as in Equation (3).

16. Calibration

The possibility of operating the instrument in the Doppler mode provides a convenient way of calibrating the records. The sun's disc as imaged by the telescope can be used for this purpose. It is known that the axial rotation of the sun on its equator results in a linear velocity of 2 Km/sec. On the east limb this results in a blue-shift of the lines of equivalent amount and on the west limb it results in a red-shift and of equal magnitude. If any spectral line is centred on the double slit illuminated by the light from the centre of disc, and the instrument is operated in the velocity mode, the output would be zero, nominally. If, now the image is moved so that a point on the east limb illuminates the spectrograph slit, some non-zero detector output will be obtained. By moving the image similarly in the other direction, an output of equal magnitude, but of opposite sign should result. On the recording chart the pen will deflect from one side to another for such movements of the image and the difference between the two deflections will be equivalent to a Doppler shift of 4 Km/sec. This can be used as the calibration standard provided certain other difficulties are properly taken care of.

The first difficulty one encounters is the random shifts of the spectral lines, resulting in an unsteady output. The effect is most pronounced at the centre of the solar disc, but very much less at the limbs, at least for some lines. For such lines one can get reasonably steady deflections for the two limb positions. For others it is necessary to take a large number of readings at the two positions to work out a mean value.

The fall in light intensity near the limbs also require correction. The electrical signal as per equation (4) is proportional to the product of the Doppler shift and the mean intensity. To compensate for this it is also necessary to know the proportionate reduction of intensity in the nearby continuum at the calibration points on East and West limb positions. In the present equipment, facilities already exist for measuring the line core intensity simultaneously and this can be utilised for applying this correction. The centre to limb variation of the line profile can be neglected without much loss in accuracy for most of the Fraunhofer lines.

With the above two corrections, it is possible to determine the scale coefficients of the instrument for individual lines. The deflection 'd' obtained in our instrument can be represented by a general equation :

$$d = K.\ v.\ I \qquad .. \quad (5)$$

where v is the line of sight velocity, say in meters/sec., I is the intensity of the adjacent continuum and K is the instrument constant working under certain conditions. Suppose D is the difference of the two deflections at the calibration points which are taken close to the limb on the solar equator, and whose theoretical Doppler velocities differ by M meters/sec. (which is close to 4000 meters/sec.) and I' is the intensity of the adjacent continuum at those points, then

$$D = K.M.\ I' \qquad .. \quad (6)$$

Eliminating K, between equations (5) and (6) one gets,

$$v = M.\ \frac{I'}{I}\ \frac{d}{D}\ \text{meters/sec.} \qquad .. \quad (7)$$

The value of M can be calculated from the geometry of the calibration positions and the previously determined values of solar rotation. The ratios I'/I and d/D can be directly measured and thus the value of v for different deflections calculated.

The direction of the velocity vector component can be determined by noting that the velocity of a point on the east limb is approaching the observer on earth and may be taken as negative and that of the point on west limb as positive. The deflections on the chart can thus unambiguously indicate the direction of the velocity component.

The same value of calibration constant can be used for magnetic field measurements. Only it is necessary to know the equivalence of the Doppler and Zeeman shifts of particular lines. Also, because in the Doppler mode an additional fixed circular polariser is introduced in the team, its transmission properties are also to be taken into account.

The line generally used for the magnetic field measurements is the FeI line of $\lambda =$ 5250.218A with a Lande' factor of 3. Substituting these values in equation (1) the separation of the two longitudinal Zeeman components becomes :

$$\begin{aligned}\Delta\lambda_{//} &= 2\,(4.67.10^{-13} g\,\lambda^{2} H)\\ &= 7.72 \times 10^{-5} H\end{aligned} \qquad .. \quad (8)$$

where $\Delta\lambda_{//}$ is expressed in Å and H in gauss.

The Doppler shift of the same line is related to the line of sight velocity by the relation,

$$\Delta\lambda_v = \frac{\lambda}{c}\ v$$
$$=1.75.10^{-5}v \qquad .. \qquad (9)$$

where $\Delta\lambda_v$ in Å and v is in meters/sec. So other things remaining equal, the equivalence between the Doppler and longitudinal Zeeman shifts is given by,

$$1.75.10^{-5}\,v = 7.72\times10^{-5}\ H$$
$$\text{or, } H = 0.225\ v \qquad .. \qquad (10)$$

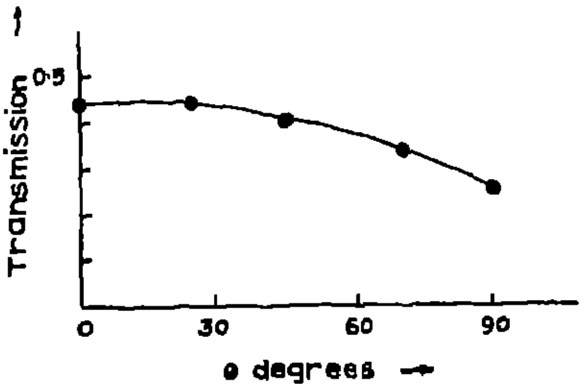


Fig. 16

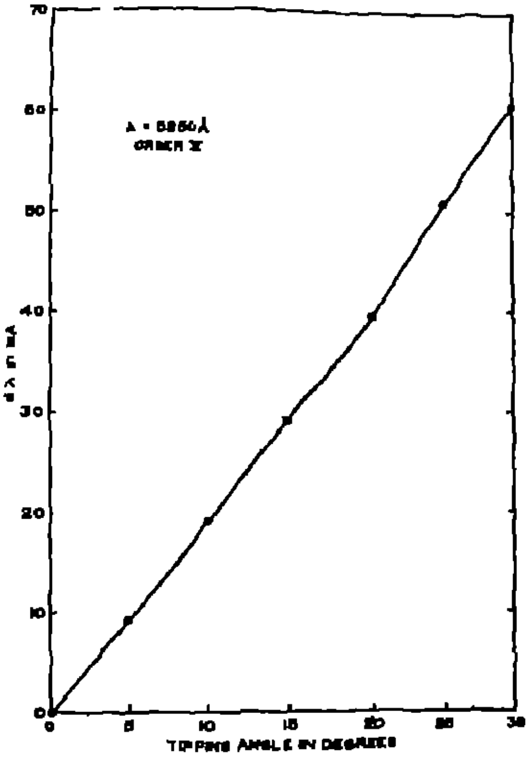


Fig. 17

But as we have to introduce a fixed circular polariser in front of the electro-optic modulator, the light transmitted in the Doppler mode is usually a fraction of that in the magnetic mode. If we designate this fraction as p the final relation between the two quantities will be given by :

$$H = 0.225\ p.v. \qquad (11)$$

H being obtained in gauss when v is in meters per sec.

It may be mentioned that the value of this fraction p is highly dependent on the relative orientation of the two polaroid axes. To avoid any error due to this, the value of the transmission fraction is determined separately for every magnetic record by noting the third photomultiplier readings with and without the circular polariser and actual orientation of the two elements in the optical modulator.

An alternative method of calibration is by the use of the parallel plate line shifter employed in the automatic Doppler compensator unit. The lateral shift δ of an image by a tipped parallel plate is given by the expression :

$$\delta = t \sin i \left[1 - \left(\frac{1-\sin^2 i}{\mu^2 - \sin^2 i} \right)^{\frac{1}{2}} \right] \qquad .. \qquad (12)$$

where t is the thickness of the parallel plate, μ its refractive index and i the angle between the normal to the parallel plate and the direction of light beam. The thickness and the refractive index of the parallel plate is known, and the tipping angle can be accurately measured on the scale provided. Thus it is possible to produce known shifts of any spectral line by manipulating the line shifter. Since the linear dispersion of the spectrograph is known with high precision, the lateral shifts can be converted into equivalent wavelength shifts of any particular line. A plot of the wavelength shifts for different tipping angles for the line FeI 5250.218A is shown in Figure 17.

The procedure for calibration is as follows:

By using an auxiliary lens the solar image is defocussed so that the light entering the spectrograph does not exhibit the granulation stimulated periodic component of Doppler motions. The equipment is run on the Doppler mode with automatic Doppler compensation unit disabled and the spectral line in question is centred on the double slit as judged from the null output on the recorder. The line shifter is then tipped by a known angle and the resulting deflection on the chart noted. The third photomultiplier reading is also noted for the purpose of the computation. The process is repeated for several tipping angles, and results plotted. The plot indicates the scale of deflection for different wavelength shifts which can be converted into equivalent Doppler velocities. From these values the instrument constant K can be directly calculated, enabling one to estimate values of Doppler velocity directly from the chart readings.

17. Sensitivity

The sensitivity or the minimum signal detectable by the instrument is basically noise limited. But apart from the noise, there are certain factors limiting the maximum value of amplification. The photomultiplier stage voltages are decided mainly from the noise considerations. The gain of the differential amplifier is adjusted on the basis of signal available. At a gain setting of 1000, for example, non-linearity sets in beyond an input 50 microvolts. The input resistance to the potentiometric recorder is adjusted to give full scale utilisation with available signal strength. It is, however, useful to have an idea of the sensitivity of the instrument under typical condition. Substituting the following typical values in equation (7) $M=4000$, $I'/I=0.5$, $D=90$, the minimum detectable signal for $d=1$ works out to be 22 meters/sec. With an equivalent noise input over the instrument pass band as 0.5 microvolt r.m.s., the root mean square fluctuation due to noise in the output is 3 microamperes, giving a deflection of less than one division on the chart. Under these conditions, a 2.8 second time-constant in the output circuit produces smooth records.

The above figures are, however, for favourable working conditions and in actual practice several other disturbing factors limits the accuracy of measurement. These are discussed in the next section.

Under favourable conditions it is theoretically possible to increase the sensitivity by as much as a factor of 10. With the differential amplifier gain setting of 100, it is possible to get a full scale deflection for some strong spectral lines, between the East-West calibration positions. After that the instrument gain can be increased to 1000 and a sensitivity of 2.2 meters/sec per division on the chart can be obtained. The noise is somewhat higher, but can be smoothed out by 6.8 seconds network combination to an r.m.s. fluctuation of the order of one division.

For records on low magnetic fields, it is the latter combination which is usually used in this equipment. The typical value of p in equation (11) is about 0.4 so that in the most favourable conditions, an accuracy of 0.2 gauss per division can be obtained with noise fluctuations of the order of 1 division. It may be noticed that under these working conditions the instrument is capable of measuring upto ±25 gauss before non-linearity sets in and the measurements become unreliable.

18. Accuracy and Limitations

The noise introduced by our amplified-detector chain is extremely small. By proper choice of tubes and voltages dividing network the two photomultipliers also introduce very little dark noise, the individual dark currents at the operating voltage of 900 V being about 2.10^{-9} A. But it is the random nature of the photo-electron cascades which limits the ultimate accuracy of the measurements. The scale of the solar image in the optical set up is 5".6 per mm. and a standard spectrograph slit of width 250 microns and 1 mm length is normally used. The angular dimension of the solar disc covered by the slit is thus 1".4 × 5".6. At the detector head slit pair, the spectrum is reimaged without magnification and to quote a typical dimension, the wing photomultipliers view a portion of spectrum 1mm × 350 microns each. In the fifth order, where it is mostly used, the dispersion is extremely high and the level of illumination at the photomultiplier cathodes is low indeed. In the Doppler mode with the fixed circular polariser introduced in the beam, a typical order of photomultiplier output current is 10^{-8}A. At this level of illumination, the random nature of the photo-electron pulses dictates the limits of gain and resolution that can be achieved in the present set up.

A good spatial resolution, which is a major objective of the instrument is thus limited by the availability of the light flux. In the f/90 system used the standard slit size of 1".4 × 5".6 has been chosen after several series of experiments as the optimum dimensions seeking a compromise between spatial and time resolution and the noise error which can be tolerated. For measurement on certain weak spectral lines, it is necessary to widen and increase the slit size at the cost of resolution.

Another limiting factor encountered at Kodaikanal is the seeing at the observation site. Owing to its location on a high peak surrounded by uneven terrain, the period of good seeing at Kodaikanal is limited to only an hour or so after sunrise. For long continuous records, observations have to be carried out when the seeing was no better than 2-3 seconds of arc. Lowering the slit dimension under such conditions is obviously useless.

For experiments requiring scanning over an extended area, the rate of scan has to be chosen consistent with the time constant of the detector. Higher time constants have to be employed with higher amplifier gain, which may be necessary for weak signals, thus requiring slower rates of scan. The spatial nature of certain time varying features of weak intensity can thus be studied with limited accuracy.

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