Solar Physics

at

INDIAN INSTITUTE OF ASTROPHYSICS

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Acknowledgements

We decided to use the occasion of IAU Symposium 142 on " Basic Plasma Processes on The Sun " to present the work done by the solar physicists of the Indian Institute of Astrophysics to our colleagues from far and near who would be attending the symposium. This compilation is based chiefly on the inputs we received from J. C. Bhattacharyya, M. H. Gokhale, S. S. Hasan, K. M. Hiremath, J. H. Sastri, Ch. V. Sastry, J. Singh, and K. R. Sivaraman. We thank them for their efforts. We are very grateful to our Director, Professor J. C. Bhattacharyya for his support. We also appreciate the help rendered by the library staff, the academic office staff, as well as our colleagues at the computer centre. for preparing this report.

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PROLOGUE

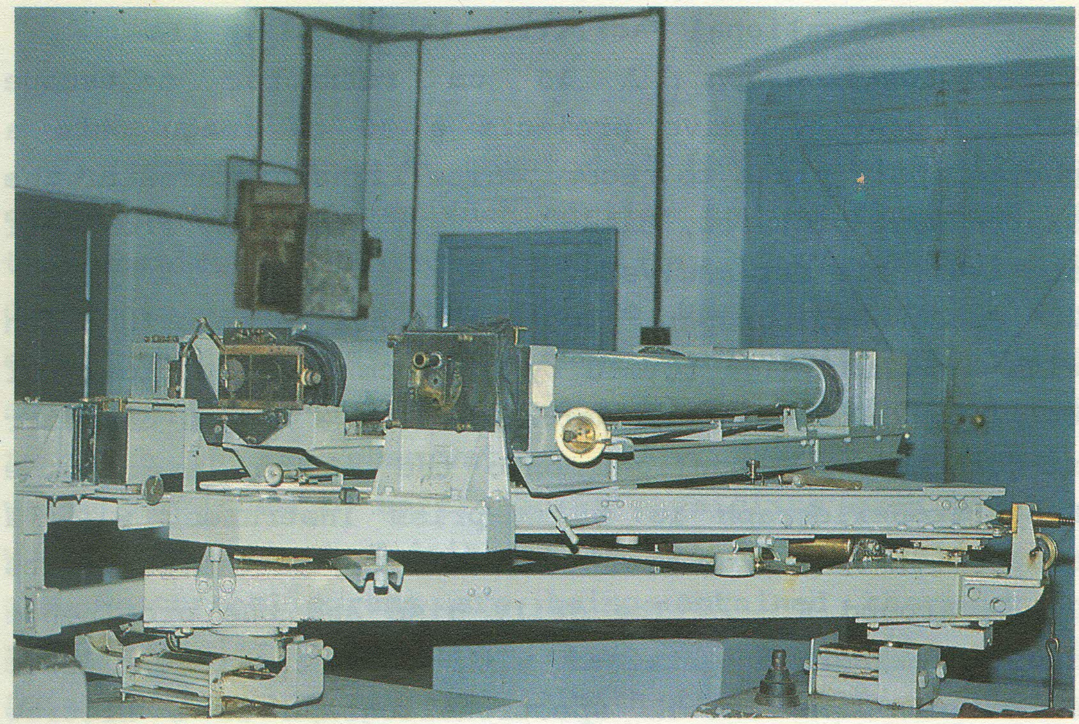
Research in solar physics at the Indian Institute of Astrophysics began much earlier to the formation of the Institute in its present form. The Kodaikanal Observatory, the predecessor to the Institute , was established in 1899. The then fashionable subject of solar physics was begun as one of the chief topics of research in the observatory. The Evershed effect , which continues to baffle solar physicists even today , was discovered at Kodaikanal in 1909. Photoheliograms and spectroheliograms are being obtained there on a regular basis to this day. These have provided material for contemporary research. With the formation of the Indian Institute of Astrophysics in 1971, the complexion of the research changed somewhat, owing to the gradual induction of people, who were not traditional astronomers, into solar research. A great majority of these people preferred to pursue theoretical solar research. Because of this reason, as well as due to the siphoning of funds meant for new solar experimental facilities into the extremely demanding activity of building a 2.3 m optical telescope for night time astronomy, the possibilities for observational optical solar astronomy have lagged behind present day standards. This has not prevented observational solar astronomers from going to modern telescopes elsewhere in the world to obtain data. Apart from that, low frequency solar radio astronomy has become one of the branches of observational solar physics in the Institute.

Observational Facilities Inherited by IIA

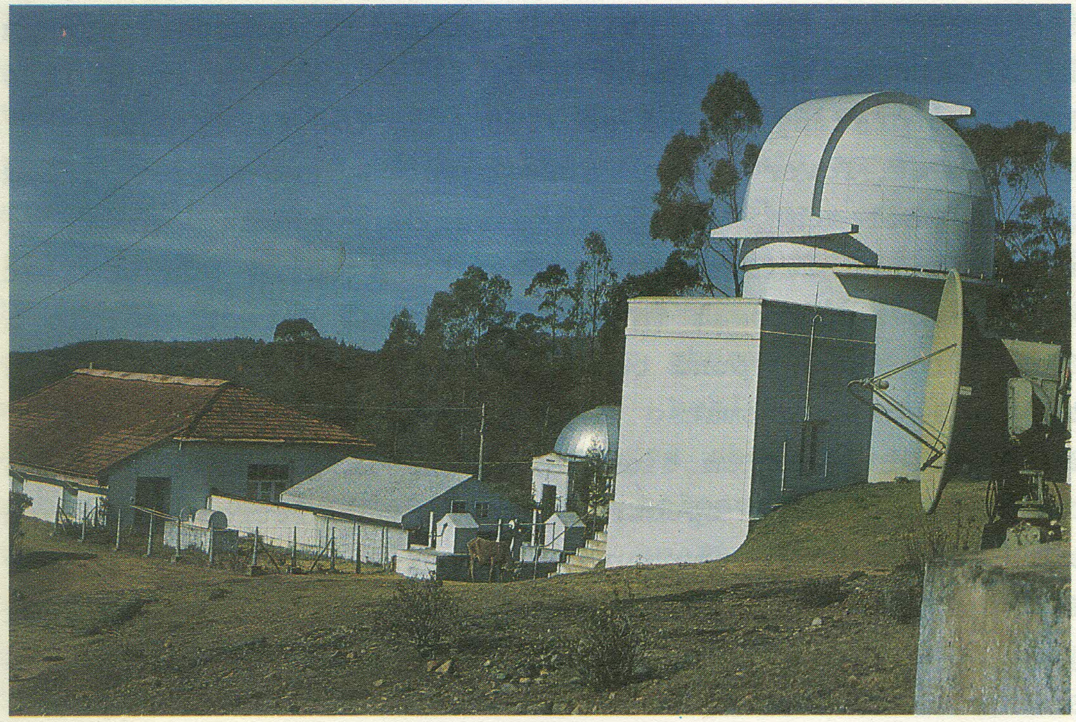
1. *Photoheliograph :* A 15 cm refractor telescope with a gravity drive projects a 20 cm image onto a photographic plate to record white light pictures of the Sun. These pictures, taken on every clear day from 1911 are available for analysis.

2. *Spectroheliographs:* Two spectroheliographs function with a 60 mm image formed by a 30 cm Cooke photovisual triplet. A Foucault siderostat with a 46 cm diameter mirror reflects sunlight onto the 30 cm lens. The K-spectroheliograph is a two-prism instrument with a dispersion of 7 A/mm near 3930 A. The exit slit admits 0.5 A around K_{232}. The daily disc and the prominence spectroheliograms obtained with this instrument date back to 1904. The Hα spectroheliograph is a Littrow grating instrument. The exit slit isolates 0.35 A about Hα and the daily series of pictures with this instrument go back to 1911. A third spectroheliograph is a Littrow arrangement of 3.43 m focus with a 1200 lines/mm grating blazed at 7500 A in the first order.

3. *Solar Tower-Tunnel Telescope*: A two-mirror fused quartz coelostat, 61 cm in diameter, mounted on an 11 meter tower, reflects light on to a third quartz flat which sends the beam in the horizontal direction into a 60 m long underground tunnel. The parallel light falls on a 38 cm achromatic objective of 36m focal length. This yields a 34 cm diameter solar image, with a scale of 5".5 $mm.^{-1}$ The spectrograph is of Littrow type and utilises a 20 cm aperture, 18.3 m focal length Hilger achromat in conjunction with a 6000 lines/mm Babcock grating of ruled area 200x135 $(mm)^2$, and blazed in the 5th order at 5000 A.



THE SPECTROHELIOGRAPH AT KODAIKANAL



THE TOWER/TUNNEL TELESCOPE AT KODAIKANAL

TWO DECADES OF RESEARCH IN SOLAR PHYSICS

1. Introduction

Solar physics research at the Indian Institute of Astrophysics has always been focussed on the observable layers of the Sun. Theoretical work on the solar interior, e.g. on the solar neutrino problem (Sivaram,C. :1989, *IAU Symp.* 142) has not received the attention it deserves. On the other hand, there are several examples where observable phenomena have been linked to the interior processes like the solar dynamo and solar convection. These will be described in later sections.

Even for the solar atmosphere, there does not appear to be any strong interaction between the observational and theoretical astronomers. The reason for this is obvious. "Fashionable" topics of research in the 70's and 80's have concentrated on the fine scale photospheric, chromospheric and coronal inhomogeneities which are far beyond the capabilities of the in-house observational facilities. However, a strong interaction exists between the observers and the theorists in solar radio astronomy.

In what follows, we aim to highlight the contributions that the IIA solar astronomers have made towards the understanding of the Sun.

2. The Solar Photosphere

2.1 Interaction of velocity and magnetic fields:

Centrifugal Acceleration of Plasma Along Moving Field Lines

The interaction of velocity and magnetic fields in the photosphere leads to very curious phenomena. Magnetic fields which are weaker than those in equipartition with the velocity fields would be freely pushed around by these velocity fields. A convenient way of studying the resulting dynamics was evolved by casting the equations in a curvilinear coordinate system that moves with the field lines. Assuming a known form for the velocity of a field line, normal to itself, the MHD equations were solved by the method of characteristics to determine the vertical flow pattern and thermodynamic quantities along each field line. The chief outcome of this study was the discovery that plasma could be driven along the field lines in the direction of increasing lateral velocity of the field lines. This could be physically understood in terms of the centrifugal acceleration of the gas along the field line when it moves in a curved trajectory (Hasan,S.S. and Venkatakrishnan, P. : 1980, *Kodaikanal Obs. Bull. Ser. A.* 3, 6). In fact, this finding is a purely non -linear phenomenon and can result in a large net acceleration even in the case of a weak but persistent spatial gradient of the lateral velocity and even for temporally oscillatory motion (Venkatakrishnan, P. : 1981, *Bull. Astr. Soc. India*, 9, 214).

Downflow generated by granular buffetting.

The above mechanism was applied to the case of granular buffetting of magnetic flux tubes and significant downflow velocities was shown to be generated in the flux tubes (Venkatakrishnan, P. and Hasan,S.S.: 1981, *J. Astrophys. Astron.* 2, 133). This work was further refined by considering the back-reaction of the magnetic field on the flow. In spite of the back-reaction, a downflow of 700 m s^{-1} was expected for a typical granular shaking of magnetic field lines (Venkatakrishnan, P. : 1984 a, *Kodaikanal Obs. Bull*.4, 19 ; Venkatakrishnan, P.: 1984 b, Ph.D. Thesis, Bangalore Univ.). It must be remarked here that the centrifugal action of field line motion has been "rediscovered" recently by P. Ulmschneider and his group who have not noticed the earlier work done at Bangalore.

2.2 Intense flux tubes:

Non-Linear Resonance in IFTs

The slender flux tube approximation, suggested by Defouw and rigorously established by Roberts and Webb proved to be extremely useful in studying the interaction of the flux tubes with their environment. A non-linear investigation of the effect of pressure fluctuations on the dynamics of gas within the tube confirmed the existence of a resonance (first shown to exist in linear theory by Roberts) when the period of the fluctuations coincided with the time taken by a tubewave to traverse one wavelength of the spatial distribution of the fluctuations. The presence of radiative damping proved ineffective when the period of the fluctuations was very much different from the radiative time scale. These results on the resonance along with the absence of observational evidence for shock waves of five minutes period within flux tubes could perhaps put limits on the depths of the flux tubes that penetrate into the sea of eigen-oscillations of the Sun. (Venkatakrishnan, P. : 1986, *Solar Phys.* **104**, 347).

Convective Collapse of IFT's

The suggestion, first proposed by Parker (1978), that intense flux tubes on the Sun are created through convective collapse, was examined quantitatively. The mechanism essentially involves a convective instability, due to which a small downflow in a flux tube cools the tube's interior with respect to its surroundings, leading to an evacuation of the gas by gravity and the intensification of the magnetic field in it. The process was first examined for a polytropic tube (Venkatakrishnan, P.,: 1983, *J. Astrophys. Astron.* **4**, 135), and then for a realistic model for the flux tube embedded in the convection zone (Hasan,S.S. : 1984, *Astrophys. J.* **285**, 851).

The time-dependent response of the initial equilibrium to a small velocity perturbation was examined. It was found that when the perturbation was a downflow, convective collapse occurred for $\beta > 2$. An important finding to emerge was that the final state was not a steady one, but one with stationary oscillations.

The surface magnetic field in the final state had an average value of about 1400 G. Furthermore, there was oscillatory vertical flow, with a maximum amplitude of some 0.5 kms^{-1} and an average value almost zero (Hasan,S.S. 1984, *Astrophys. J.* 285, 851).

Overstable oscillations in IFT's

An extension of the above results for adiabatic flow to flows with radiative exchange was next considered which led to the very interesting result of overstable oscillations in the intense flux tubes (Venkatakrishnan, P. : 1984 a, *Kodaikanal Obs. Bull.*, 4, 19; 1984b, Ph.D. Thesis, Bangalore University; 1985, *J. Astrophys. and Astron.* 6, 21). This was confirmed in more detailed calculations for a slender tube embedded in the convection zone. In this investigation, the convective collapse of a vertical flux tube was analysed by (a) including heat exchange between the tube and the ambient medium and (b) allowing for a finite viscosity. Furthermore, hydrogen ionization and its thermodynamic consequences were also treated self-consistently. The main finding to emerge was that convective collapse once again produced kG field strengths and a final oscillatory state, but with the important difference that the oscillations were overstable due to lateral heat exchange of the tube with its surroundings. The amplitudes of the velocity oscillations were in the range 1-2 km s^{-1}. Some of the observational consequences of overstability in flux tubes were analyzed (Hasan,S.S. 1985, *Astron. Astrophys.* 143, 39)

Physical limits to the sizes of IFT's

The conventional wisdom (based mostly from ground based observations) has been that IFT's come in various sizes but they all have the same field strength in the region of 2 kilogauss. This value could be theoretically expected from the stability considerations of adiabatic IFTs. A re-examination of the stability criteria for radiating IFTs led to the concept of the radiative inhibition of the convective collapse of slender flux tubes. The inhibition increased with decreasing size of the flux tube. A comparison of the growth times of the instability with the externally dictated life time of the tube (e.g. by the granular buffetting) yielded a relation for the size of the IFT as a function of its field strength. This relation predicted two families of tubes. One family had a variety of sizes from that of pores to a few hundred kilometers, but a constant field strength of kilogauss intensity. Ground based observations, lacking great spatial resolution could well be picking out only these kinds of flux tubes. The other family consists of tiny tubes of constant size (few hundred kilometers) but has a broad range of field strengths from kilogauss to a few hundred gauss. The observations from space are expected to detect this new family of flux tubes (Venkatakrishnan, P. : 1986, *Nature*, 322, 156).

Heating of solar magnetic elements by downflows

The hypothesis, that magnetic elements in the photosphere are heated by downflowing gas, was investigated. Starting from a state of hydrostatic equilibrium, the temporal response due to the onset of a downflow in the tube was examined. After a transient phase, lasting some minutes, a stationary state developed that was substantially hotter than the ambient medium over a fairly large height range. Semi-empirical models for faculae could be reproduced fairly well by adjusting the mass flux entering the tube at the upper boundary (Hasan,S.S. and Schussler, M.: 1985, *Astron. Astrophys.* 151, 69).

Oscillatory motions in IFT's

The detailed nature of oscillatory motions in intense flux tubes was examined. Initial states of constant β were considered. Heat exchange between the tube and its surroundings was modelled using Newton's law of cooling. The linear stability of the equilibrium state was examined for (a) a polytrope and (b) a model atmosphere. Growth rates, oscillation frequencies and velocity amplitudes were determined for various values of β and the tube radius at surface. The height dependence of the eigenvectors (in general complex) and their phases were calculated. It was suggested that, although a comparison of the wave periods with observations was not possible, the phase relations for velocity-velocity and temperature-velocity functions offered greater promise (Hasan, S.,S. : 1986, *Mon. Not. Roy Astr. Soc.* **219**, 357).

Equilibrium of IFT's

The overall equilibrium of a thin isolated un-twisted flux tube in a stratified atmosphere implies an unbalanced force on the current sheath which will be upward or downward depending upon the field and density profiles across the current sheath (Gokhale,M.H.and Hiremath,K.M.: 1986, *Adv. Sp. Res.*, 6, 47). Upto the second order in the thinness parameter, the system of equations for equilibrium of a thin isolated force-free magnetic flux tube in a stratified atmosphere is mathematically closed (Prasannalakshmi and Gokhale,M.H.: 1987, *Solar Phys.*)

For a given amount of longitudinal magnetic flux and given initial conditions at a point on the axis the equqtions lead to a unique geometry of the tube with unique longitudinal variation of magnetic field and of differences between internal and external values of pressure and density (Prasannalaskshmi and Gokhale,M.H.: 1990, *Proc. Chapman Conf. on Magnetic Flux Ropes*).

Equilibrium of an IFT in the presence of energy transport

This investigation focused on the problem of constructing, in a self-consistent manner, an equilibrium atmosphere in a flux tube, when energy transport was taken into account. The energy budget consisted of contributions from radiation and convection. A new feature of the analysis was the use of the generalised Eddington approximation, in three dimensions, in modelling radiative transport in an axisymmetric flux tube. Convective energy transport was also included using a mixing length theory, with an additional parameter, which was crudely a measure of the magnetic inhibition of convection. Model atmospheres, corresponding to various values of β_0 where β_0 is a measure of the magnetic field strength at the top of the tube, were calculated. The results indicated that the temperature on the axis of a tube was generally lower than that in the ambient medium at the same geometric height, but higher at equal vertical optical depths. At optical depth of unity, this difference was typically some 500 K. However, in the optically thin layers of the tube, it was found that horizontal heat exchange was efficient and the tube temperature was insensitive to β_0 Finally, it was demonstrated that the equilibrium stratification was almost independent of the degree of convective inhibition (Hasan,S.S.:1988,*Astrophys.J.*,332,449).

Dynamical effects and energy transport in an IFT

In this investigation, the previous calculations on convective collapse of an intense flux tube, were further refined to include energy transport. An initial atmosphere, which was in hydrostatic and energy equilibium, was first constructed. The temporal response of this equilibrium to a small down flow perturbation was considered. Although oscillatory behaviour was once again observed, the nature of the oscillations was found to be qualitatively different. The flow did not appear to have a simple sinusoidal form, but a fairly complicated one. The upflow and downflow phases were not symmetric. An important finding to emerge from the analysis was that vertical energy transport through radiation is very important, particularly close to continuum optical depth unity. A comparison with various semi-empirical models showed reasonable agreement (Hasan,S.S. 1989, in *AGU Monograph on "Physics of Magnetic Flux Ropes"*, eds. E. Priest and C.T. Russell ,in press).

2.3 Wave modes in a magnetised stratified atmosphere :

Classification of modes in a magnetically structured medium

The structure of motions that can occur in a vertical magnetic flux tube, with a rectangular cross-section, was examined. A polytropic stratification was assumed within the flux tube. Using a gauged version of Helmholtz's theorem, the perturbations were decomposed into irrotational (l) and solenoidal components. The latter was further split into the sum of poloidal (t) and toroidal (a) parts. The normal modes of the tube were determined using a Rayleigh-Ritz variational technique. This technique successfully isolated all the modes to high orders. In the absence of a magnetic field, the l and t modes were just the well known p and g modes. In a weak magnetic field, the l mode frequencies were found to be practically the same as those of the p modes, since these modes blended in with the fast mode spectrum. However, the nature of the g spectrum was greatly altered by the field - the t modes had now assumed the form of slow waves. The a modes could always be identified with Alfven waves. (Hasan,S.S. and Sobouti, Y.: 1987, *Mon. Not. Roy. Astr. Soc.* 228, 427).

Wave modes in thick photospheric flux tubes

The nature of wave motions in thick photospheric flux tubes was analysed. The aim of the study was to determine the normal modes of a stratified atmosphere with a strong vertical magnetic field. A diagnostic (ω - k) diagram was generated. An interesting feature of the solutions was the existence of 'avoided crossings', which occurred when adjacent order modes approached each other in the diagnostic diagram. Although such a phenomenon is encountered frequently in helio-seismology, its existence in the context of magnetoatmospheric (MAG) oscillations had not been noted earlier. The nature of the MAG modes was examined by decomposing the eigenvectors into longitudinal and transverse components. It was found that, in general, the character of the a modes changed with height in the atmosphere. The results were applied to umbral oscillations and it was found that oscillations with periods in the range 2-3min, corresponded to low order modes in the diagnostic diagram. For low horizontal wave number, the modes in the photosphere were found to have almost equal contributions from longitudinal and transverse components, whereas in the chromosphere,they were essentially transverse and could be identified with slow modes (Hasan,S.S.: 1989, in *AGU Mono- graph on "Physics of Magnetic Flux Ropes"*, eds. E. R. Priest and C.T. Russell, in press).

2.4 Solar Granulation

Nonlinear interactions between small fluid elements in an energetically open system facilitate the formation of large coherent stable structures. This is known as self-organization. We interpret solar granulation on all scales to be the result of self-organization processes occurring in the turbulent medium of the solar atmosphere. This mechanism provides explanations for the intrinsic weakness of mesogranulation and the rare appearance of the giant cells in addition to the sizes and lifetimes of these structures. The entire energy spectrum for the smallest granules to the largest giant cells brings out the prevalence of Kolmogorov's $K^{-5/3}$ law (Krishan,V. : 1989, *K.O.B.* 9.; 1989 in book on "*Solar interior and atmosphere*". Univ. of Arizona Press; 1989 *IAU Symp.* 138.)

Location of the foot points of sub-arcsec magnetic features

High resolution filtergrams in the core and in the wings of the Mg b line and of the granulation in the continuum in the quiet regions on the Sun were obtained using the Universal Birefringent Filter at the vacuum tower telescope of the Sacramento Peak Observatory. The bright points were identified in the Mg b core pictures and this identity was carried through the wing pictures. Finally a comparison of the wing pictures with those of the granulation in the continuum show that a majority (~80%) of the sub-arc second bright points (magnetic structures) fall within the dark intergranular lanes. Of the rest, about 13% tend to lie at the edges of the bright granules while, the remaining 7% coincide spatially with the bright central regions of the granules (Sivaraman,K.,R., Bagare,S.,P., and November,L.,J.: 1989, *IAU Symposium* 142).

2.5 Sunspots:

Oscillations in sunspots

In this investigation, the mathematical formalism developed in earlier papers, was applied to studying the detailed nature of oscillations in sunspots. An equilibrium stratification, based on a model atmosphere for the umbra of a sunspot was considered. Approximating the umbra as a thick vertical flux tube, its normal mode spectrum was determined. The modes were classified by decomposing the eigenvectors into irrotational and solenoidal components. It was shown that in certain limits, these modes could be locally related to the conventional fast and slow MHD modes in a homogeneous medium. A diagnostic diagram for a sunspot was generated and compared with observations. (Hasan,S.S. 1989, in *IAU Symp.* 138 ed. J.O. Stenflo, in press).

Variations in the rotational velocity of sunspot groups during their life times.

The question whether the rotation of sunspot groups about the Sun's axis is accelerated or decelerated during their life times is of considerable importance in studying the rotation of the solar plasma and magnetic structures underneath the photosphere. From the statistical analysis of the angular rotational velocities derived from Greenwich Photoheliographic Data, some authors have concluded that the rotation of sunspot groups is decelerated during their life times.

The mean values, the r.m.s. deviations and the standard errors of the mean, for differences between the initial, overall and final angular velocities of the rotation of sunspot groups which occurred during the solar cycles 1923-1933, 1934-1944 and 1945-1954 were determined. Sets of spot groups having their maximum areas (A_*) in the intervals 300-500, 500-1000 and 1000 millionth of the solar hemisphere, and occurring in different cycles, are considered separately and in aggregates defined by various combinations.

The following general trend was found that spot groups are accelerated during the early phase of their life time, and decelerated in the late phase, yielding a net deceleration over the whole life time. (Gokhale, M.H. and Hiremath, K.M. : 1984, *Bull. Astr. Soc. India* 12, 398).

Solar rotation from sunspot measurements

A study of the daily motions of individual sunspots and of sunspot groups has been undertaken using Kodaikanal and Mount Wilson white-light observations. The Mount Wilson measurements were completed several years ago, and the Kodaikanal measurements have recently been started, using a technique identical to that used for the Mount Wilson data. Both data sets started early in this century, and both have continued to the present time. Preliminary results of a comparison of the two data sets are presented which show a good agreement between them in spot areas and motions. Analysis of the combined data set for the years that are available so far indicates that many more spots are available in such a reduction because the 12-hour time difference between the two sites allows for a more certain identification of individual spots from one observation to the next than in the case when data from only one site are used. This greatly increases the number of sunspots available for motion studies, particularly the smaller sunspots. Preliminary rotation and latitude drift reduction from the combined data set confirm earlier results from the Mount Wilson data alone that small spots rotate faster than large spots and that the correlation between rotation residuals and latitude drifts of individual sunspots and of groups suggests a transfer of angular momentum towards the equator as a result of such motions (Howard,R., Sivaraman,K.,R., Gupta,S.,S., and Gilman,P.,I.:1989, *IAU Symposium* 142).

2.6 Sunspot Cycle

Based on some physical arguments a speculative model of the solar cycle had envisaged the following: (i) during each sunspot cycle new magnetic flux would be created near the base of the convection zone in the form of clusters of closed, strong (10^4G), thin (10^2 km diameter) flux tubes by some locally 'catastrophic' interactions of globally linear MHD oscillatons of the Sun, (ii) the faster rising parts of these flux 'loops' would provide strong activity in the central latitudes, and (iii) the slower rising parts would disperse and diffuse to provide the weak reversed field and the weak activity at all latitudes during the following cycle, and so on (Gokhale,M.,H.: 1977, *Kodaikanal Obs. Bull. Ser. A*,2,10; Gokhale, M.,H.: 1977, *Kodaikanal Obs. Bull. Ser. A.* 2, 19; Gokhale,M.H.: 1984, *Kodaikanal Obs. Bull.* 4, 25;Gokhale,M.H.: 1984, *II Indo-US Workshop on Solar Terrestrial Physics*, NPL Publication, New Delhi, 399). Consequences of the model were shown to be consistent with many observed characteristics of the solar cycle (Gokhale, M.,H. and Sivaraman,K.,R.: 1978, *Proc. IAU Coll. No. 44 on "Physics of Solar Prominences"*, 189.;Gokhale,M.,H.: 1979, *Kodaikanal Obs. Bull. Ser. A* 2, 217; Gokhale,M.,H.: 1979, *Kodaikanal*

Obs. Bull. Ser, A. 2, 221; Gokhale,M.,H.: 1979, *Kodaikanal Obs. Bull. Ser. A* 2, 222; Gokhale,M.,H. and Sivaraman, K.,R.: 1981, *J. Astrophys. and Astron.* 2, 365; Gokhale,M.,H.: and Sivaraman,K.,R.: 1982, *Bull. Astron. Soc. India*, 10., 154).

Spherical-harmonic fourier (SHF) analysis of sunspot occurrence probability yields mainly axisymmetric even degree modes of period 11 y. It was found that the amplitude spectrum and relative phases are approximately constant over several cycles. SHF analysis of the nominal toroidal field (defined by attaching sign to sunspot occurrence probability in occordance with Hale's laws of magnetic polarities) yields axisymmetric modes of odd degree and periods 22y. It has been found that the amplitudes and phases of these modes have remained approximately constant for 103 years and that the amplitude spectrum is similar to that derived from the magnetogram data during 1960-1985.

A nominal 'toroidal field' defined as sunspot occurrence probability with signs attached according to Hale's law yields most of the power in axisymmetric odd degree modes of periods 22y with approximately constant amplitudes and phases during 1874-1976. The amplitude spectrum w. r. t. *l* is similar to that derived from the observed 'poloidal' magnetic field during 1960-1985 (Gokhale, M.,H. and Javaraiah, J.: 1990, *Mon. Not. Roy. Astr. Soc.*).

Using the H-alpha spectroheliograms of Kodaikanal, synoptic charts were constructed for the years 1915-1982 and used to derive the poleward migration of the filament bands a few years ago (Makarov V.,I. and Sivaraman,K.,R.:1983, *Solar Phys.*,85, 227). This poleward migration of filaments (or the magnetic neutral lines) establishes the poleward migration of the unipolar regions which effects the reversal of the magnetic polarity at the N and S poles on the Sun. Submerged in these large scale unipolar regions are the polar faculae (seen in the photoheliograms and in the Ca K spectroheliograms) in the zones of latitudes $>40^{\circ}$ and the sunspots in zones of latitudes $<40^{\circ}$. A study of the polar faculae for 4 cycles (1940-1985) show that they appear at latitude zones 40°-60° in the north and south hemispheres immediately after the reversal of the field at the poles and the zones of appearance migrate progressively and reach higher latitudes (70°-80°) in the course of 10 years as the solar cycle progresses. The polar faculae in general appear in pairs with polarities characteristic of the next following sunspot cycle. After 4-5 years from the appearance of the polar faculae, the sunspots of the new cycle make their appearance at latitudes $\pm 40^{\circ}$ and the zones of sunspot appearance proceed towards the equator giving rise to the well known butterfly diagram. What was not known before this investigation is the pattern of migration of the polar faculae towards the poles in the two hemispheres on the Sun. The picture that emerges from this study is as follows: The global solar activity commences soon after the polar field reversal in the form of two components in each hemisphere. The first component (brought out by this study) is the polar faculae with poleward migration and the second and the more powerful component, the sunspot with equatorward migration. The two components occur at different latitude belts with the polar faculae leading the sunspot of the same cycle by 5-6 years. Thus the solar cycle, which should be counted from the first appearance of the polar faculae to the last appearance of sunspots, lasts for 16-18 years as against the traditional value of 11-years which has come about only from the sunspots. In addition, it has been shown in this study how the two components (polar faculae and sunspots) match with the pattern of the coronal emission in 5303 A line recorded for several solar cycles by French astronomers and also with the pattern of excess shear associated with the torsional oscillations on the Sun. This study thus provides a unification between the torsional oscillations, 5303 A coronal emission and global magnetic activity (Makarov,V.,I. and Sivaraman,K.,R.: 1989, *Solar Phys.*, in press)

2.7 Magnetic Field Measurements:

A Babcock type magnetograph was built in 1966 to measure the line-of sight component of the magnetic field. The main results that were obtained using this instrument are: (i) the 5-minute oscillations seen in velocity fields do not have a corresponding effect on the fluctuations of the magnetic field (ii) sudden large changes in the apparent Doppler velocity have almost a one to one correspondence with sudden changes in magnetic field and (iii) both magnetic and velocity fields vary coherently with approximately 500 seconds period, but this coherence could well be "seeing" induced (Bhattacharyya,J.C.: 1969, D. Phil

Thesis Univ. of Calcutta; 1972, *Solar Phys.*,24, 274).

An attempt was made to measure all three components of sunspot magnetic fields using the Kodaikanal Solar Tower / Tunnel telescope. The instrumental polarisation of the three-mirror system was theoretically modelled. Seasons of small declination and times of small hour angles were seen to produce the minimum instrumental polarisation. Various terms of cross talk between the Q, U, and V stokes parameters were identified (Balasubramaniam,K.S., Venkatakrishnan,P., and Bhattacharyya, J.C.: 1985, *Solar Phys.*, 99, 33).

Actual observations on a sunspot group KKL 18313 (NOAA AR.4811) were converted to vector fields after a long process of photographic reduction and iterative inversion of the resultant stokes profiles for two positions of the slit on the sunspot (Balasubramaniam,K.S. 1988 Ph.D. Thesis, Indian Institute of Science). However several pitfalls exist in the whole process of analysis which must be removed before the procedure can be standardised into a vector magnetographic routine.

Some experience on vector magnetogram analysis was obtained using data from the MSFC vector magnetograph. The problems of evaluation of magnetic shear in vector magnetograms obtained off the disc centre were examined in detail and some techniques were developed to tackle these problems (Venkatakrishnan,P., Hagyard,M.J., and Hathaway,D.H.: 1988, *Solar Phys.*, 115, 88;

Venkatakrishnan,P. and Gary,G.,A.: 1989, *Solar Phys.*,.120, 235; Venkatakrishnan,P., Hagyard,M.J., and Hathaway,D.H.: 1989, *Solar Phys.* 122, 215) The results of these techniques were applied to a particularly active region (AR 4474) which produced a white light flare on 24 August, 1984. It was seen that the extent of shear was longer for 2 gamma ray flare sites than for 2 non gamma ray flare sites (Hagyard, M.J. Venkatakrishnan,P., and Smith,J.B. Jr,: 1989, *Astrophys. J. Suppl. Ser.*)

2.8 Five Minute Oscillations

The 5-min oscillations in the photospheric velocity fields were studied in detail from measurements on 14 absorption lines from 3 time sequences of high quality spectrograms . The lines cover a range of heights in the solar atmosphere from log τ =+0.2 to -1.2. Regions oscillating coherently are seen to have an average dimension of 8000 km and the oscillations in general last for 2 to 3 periods. Power spectrum analysis of high resolution enabled to determine the period of oscillation at each level very precisely. The period decreases with increase in height, being 304 s at the level log τ = 0.2 and 295 s at the level log τ = - 1.2. The low level lines possess considerable power in the low frequency range representing the convective overshoot from below. The oscillatory power remains substantially constant in the heights studied. The intensity fluctuations in the continuum, the line wing and core of Fe I 6358.695 A have also been studied. The continuum power spectrum has practically all the power near the zero frequency range, with a very weak oscillatory component. The line wing intensity fluctuations resemble those in the continuum, whereas the line core clearly shows an oscillatory component similar to the velocity oscillations. (Sivaraman,K.,R.: 1973, *Solar Phys.* 33, 319.)

The coherence and phase spectra between velocity oscillations in different pairs of lines have been studied. The oscillations in the high level lines are found to lag behind those in the low level lines in general. There is coherence between oscillations at the different levels. The phase differences between the velocities have insignificant values in the resonance range. This is taken to mean that they are standing waves. In the high-frequency range the phase difference observed is appropriate for the propagation of sound waves. The coherence and phase spectra of (i) the continuum brightness with the line wing and core brightness of Fe I 6358.695 A, and (ii) the continuum, line wing and core brightness of Fe I 6358.695 A with the velocity fluctuations in the same line, have been studied. The core brightness leads the continuum by 57° in the resonance range. The intensity oscillations in the core lead the velocity oscillations by $93^{\circ}.5$. This is taken as an additional evidence for the existence of standing waves (Sivaraman,K.,R.: 1973, *Solar Phys.* 33, 333.).

3. The Solar Chromosphere

3.1 Calcium Bright Points:

A two dimensional image of the Sun in the Ca II K line under high spatial resolution shows that the three agencies responsible for the emission are the bright points, the network and the plage areas. The bright points populate the interior of the network and have dimensions of 1-2 arcsec. From several excellent spectra over a quiet region on the Sun, the Ca II K line profiles of a large number of bright points as well as over the emission features residing on the network boundaries were derived. The width of the emission at the half intensity level (between K_2 emission peak and the K_1 absorption) for these bright points have a mean value that is the same as the value of the width in the Wilson-Bappu relation for the Sun as a whole after correction for the solar rotation. This demonstrated that the bright points of K emission are the principal contributors to the line width - absolute magnitude relation or in other words, it is these bright points that enable the Sun to follow the line width absolute magnitude relation of Wilson and Bappu. From the analysis of the time sequence spectra a well as from the spectroheliograms, we find that the bright points have a life time of about 200 secs. The boundary of the Ca K network (which is cospatial with the supergranulation) has enhanced emission with a two fold contribution. The fine mottles are there too in very quiet regions on the Sun, and some of them clump together to form the coarse mottles of size about 7000 km. Another aspect of the line profiles of the bright points is the ratio of the emission peaks I_{K2V} and I_{K2R}. In the quiet region most of the peaks have the emission in the violet greater than in the red ($I_{K2V} > I_{K2R}$), but about 20% of the cases have $I_{K2V} < I_{K2R}$. A new component of absorption in the solar chromosphere was detected, viz.,the 'dark condensation' which have sizes of about 5000 km. In all the profiles associated with the dark condensations, a large redward shift of 5 - 8 kms^{-1} in K_3 over and above the normal one was found, which was interpreted as representing the downflow of the dark condensations with these velocities and causing the extreme cases of $I_{K2V} >> I_{K2R}$ or, even at times, profiles with $I_{K2R} = 0$ (Bappu,M.,K.,V. and Sivaraman,K.,R.: 1971,*Solar Phys.* 17, 316)

Another interesting aspect about these bright points seen in the Ca II K line is their association with the photospheric magnetic fields. The large amount of simultaneous high spatial resolution observations of spectroheliograms in K_{232} obtained at the McMath telescope and the magnetograms with the vacuum solar telescope of the Kitt Peak National Observatory provided the material for this study. From a detailed comparison between the K spectroheliograms and the magnetograms involving a sample of hundreds of bright points, we find that the bright points located in the interior of the network are co-spatial with the sub-arcsec magnetic structures within the network. Using the time sequence of CaII K images and the corresponding magnetograms, it was possible to establish that this correspondence holds true even during the dynamical evolution. The bright points follow a light curve with period of 180-200 secs. The bright points are present only on those locations where the magnetic points are also present but bright points have no preference for either polarity. The field strengths associated with the bright points cluster around a value 10-20 G although there are examples of associations with field strengths as high as 70-80 G. It was also seen that a bright point shifts its position to the new location of its associated magnetic point (when swept by horizontal flows) to maintain the co-spatiality. This leads to the conclusion that the presence of the concentrated magnetic flux is an essential precondition which decides the location of the bright point within the network (Sivaraman,K.,R. and Livingston,W.,C.:1982, *Solar Phys.*,80,227).

The K_2 widths measured at the half intensity points for plages was found to be far less than those for the bright points. This would mean that the K_2 width of the Sun viewed as a star during solar maximum would be less than that during the solar maximum. Extending this argument to Sun like stars, the integrated spectrum of the star would represent a weighted mean of the bright points contributions as well as those originating from the active regions on the stellar surface and hence the K emission width of this star would be lower than that derived from the Wilson Bappu relation based on the quiet Sun alone. From the several K-line profiles of bright points on the Sun, it was seen that the situation $I_{K2V} >> I_{K2R}$ arises due to the dark condensations and all such profiles show a large K_3 redward shift (5-8 km s^{-1}). Extending this to Sun like stars we have examined the K profiles of 41 stars with a view to relate the K_{2V}/K_{2R} asymmetry with the K_3 displacements. In a large majority of the cases, K_3 has large redward displacement and K_{2v} >> K_{2R}, in conformity with the expectation from the example of the Sun. This method can therefore be used to infer the presence of dark condensations in the chromospheres of stars (Bappu,M.,K.,V. and Sivaraman ,K.,R.: 1977, *Mon. Not. Roy. Astr. Soc.*, 78, 279).

3.2 Luminosity variation of the Sun as a star in the Ca K line:

The program to examine the luminosity variation of the Sun as a star in the K line of ionized calcium, started in 1969 using the solar tower telescope at Kodaikanal, has now covered the span of more than one complete solar cycle. Ten parameters were evolved, which would characterise the mean K line profile and enable the study of the temporal changes in the profile over the time scale in view. The main findings are: (i) The K_3 absorption brighten up by almost 40% with the increase in plage coverage. (ii) The emission line width at half power point increases in phase with solar activity showing the increased weighted contribution from the plages and their influence on the width of the K line profile in the integrated light from the Sun. This would provide a valuable clue in inferring the nature of the magnetic structures in other sun-like stars whose K line profiles have been determined. (iii) There is clear evidence to indicate the oscillation of the temperature minimum region in the solar atmosphere and that the phenomenon is related to the solar cycle. (Sivaraman,K.,R., Singh,J., Bagare,S.,P., and Gupta,S.,S.: 1987, *Astrophys. J.*,313,456).

3.3 Calibration of Ca Flux To Estimate Magnetic Flux:

The intimate association between the surface magnetic fields and the Ca II K-line emission known to exist on the Sun, holds a promise for using this property to detect the presence of global magnetic fields on the Sun - like stars. We have obtained a large number of K-line profiles over a variety of plages on the Sun and related the 1 A emission flux centred at the K_3 minimum for these profiles with the corresponding values of the longitudinal component of the magnetic field. This provides a calibration for detecting and estimating the surface magnetic fields on stars (Sivaraman,K.,R., Bagare,S.,P,. Gupta, S.,S., and Kariyappa,R.: 1987, in *"Cool Stars, Stellar Systems and the Sun" Proc. Fifth Cambridge Workshop* Boulder, Colorado, July 7-11, 1987, p.47).

3.4 Supergranulation Size:

Calcium K spectroheliograms obtained from Kodaikanal and spread over seven solar cycles have been analysed to investigate the variation in supergranular size with the phase of solar cycle. It was found that the calcium network diameters are smaller by 5% at solar maximum than at minimum. The average cell size at minimum is 22115 $\pm$ 99 km. The average size at solar maximum is 20920 $\pm$ 112 km, though individual maxima perform differently from each other depending probably on the dispersed remnant magnetic fields. The change in size of the network is interpreted in terms of changes in the size of the supergranular convective cell. It has also been noticed that average cell size is smaller than hitherto believed. (Singh,J. and Bappu,M.K.V., 1981, *Solar Phys*, 71, 161).

3.5 Rotation from Plages:

The appearance and disappearance of extensive plages with phase in the sunspot cycle makes the Sun appear as a variable star in the CaII K light. In addition to this, the plot of the calcium plage areas on the visible hemisphere of the Sun as measured from K spectroheliograms shows the rotational modulation very well. Similarly, the Sun-like stars, if monitored in the Ca II K light, would show the rotational modulation and this method can be used to measure a star's rotational velocity. The demonstration of this method has prompted Wilson and his co-workers at Mt.Wilson to monitor Sun like stars in the K-line and determine their rotational periods as well as detect solar like cycles in them (Bappu,M.,K.,V. and Sivaraman,K.,R.: 1971, *Solar Phys.*,17, 316).

It is difficult to derive the chromospheric rotation rate from the individual plages because of the uncertainty in identifying a particular region of the plage on the Sun from one time to the next due to changes in the shape and size of the plages. Therefore, a simple technique of power spectral analysis of plage data was adopted to determine the chromospheric rotation rate at different times. This was done for the period 1951-81 at the latitude belts 10°-15°S and 15°-20° S and also the entire visible solar disc. The mean rotation periods derived from 10^{o}-20^{o} S, total plage area and sunspot numbers were 27.5, 27.9 and 27.8 days (synodic), repectively. A power spectral analysis of the derived rotation rate as a function of time indicates that rotation rate in each latitude belt varies over time scales ranging from the solar activity cycle, down to about 2 years. Variation in adjacent latitude belts are in phase, whereas those in different hemispheres are not correlated. The total plage areas, integrated over the entire visible disc of the Sun shows a dominant periodicity of 7 years in rotation rate, while the other time scales are also discernible (Singh,J. and Prabhu, T.P.: 1985,*Solar Phys.*, 97, 203). It has been shown further that the existence of the 13 day periodicity at certain epochs is due to the occurrence of enhanced activity at two different longitudes, approximately 140-170 degree apart. At other epochs the relative error in the 13 day peak exceeds 0.50 and therefore, may not be real. (Singh,J. and Jain,S.K., 1989, accepted in JAA). It has also been found that solar rotation rate at different epochs, derived from Ca K index in integrated sunlight, does not coincide with the rotation rate of the dominant activity zone for the short interval of 18 months studied. (Singh,J. and Livingston,W., C.: 1987, *Solar Phys*. 109, 387).

3.6 Spicule Flow:

A time-dependent model for flow of gas in a spicule was proposed. In this model, the flow occurs in a magnetic flux sheath. Starting from hydrostatic equilibrium, the flux sheath was allowed to collapse normal to itself, thereby generating a vertical flow. This flow was identified as a spicule. a variety of sheath geometries and velocity patterns for the normal flow were considered. It was found that a large curvature in the field geometry and a large initial normal velocity were necessary to achieve typical spicule-like velocities. It was proposed that the initial rapid collapse occurred during an 'impulsive spicule phase', lasting only some seconds. The subsequent gradual relaxation of the flow, on a time scale of a few minutes, could be related to the flow observed in spicules (Hasan,S.S. and Venkatakrishnan, P. 1981, *Solar Phys.*, 73, 45).

3.7 CO instability in the solar chromosphere:

I. Linear analysis

The linear stability of cool flux tubes in the solar chromosphere was examined. Owing to the presence of carbon monoxide (CO), it was found that there exists a narrow region near the temperature minimum, where the temperature gradient became steep enough to drive a convective instability. Assuming a flux tube, initially in radiative equilibrium, the thin flux tube equations were solved in the linear approximation. Radiative heat exchange between the tube and the ambient medium was incorporated in the analysis. Results were presented for various values of β (the ratio of thermal to magnetic pressure), assumed constant with height at the initial instant. Overstable oscillations were found to occur for β <7, with periods in the range 300-600 s. At

β =5.7, a bifurcation occurred into two purely growing modes. It was suggested that overstable oscillations should invariably be associated with cool flux tubes (Hasan,S.S. and Kneer,F.: 1986, *Astron. Astrophys.* 158, 288.)

II Nonlinear dynamical behaviour

The previous linear calculations on cool flux tubes in the solar chromosphere were extended to the nonlinear regime. The time evolution of the instability was examined by solving the MHD equations in the thin flux tube approximation. Energy exchange with the radiation fields was included in the analysis. During the first few hundred seconds, large amplitude chaotic motion were set up, with a periods of around 200 s. In the top layers (z = 1500 km), the amplitudes of the temperature and velocity fluctuations were found to be 1500 K and 4-5 km s^{-1} respectively. These simulations of a flux tube, with a transmitting upper boundary condition, showed that on average the energy flux in the oscillations was inadequate for chromospheric heating. However, the oscillations revealed several interesting features, which were noteworthy in themselves (Hasan,S.S. and Kneer,F.: 1989, *Astron. Astrophys.*, submitted).

3.8 Dynamics of Large Scale Magnetic Regions On The Sun:

H-alpha synoptic charts for the period 1904 - 1982 were produced using the H-alpha spectroheliograms from

Kodaikanal archives and the Kislovodsk solar station. These charts, which depict the formation and evolution of the large scale magnetic fields on the Sun, provide the migration trajectories of the filaments, which represent the neutral line dividing the large scale magnetic regions of opposite polarity. The filament bands migrate polewards and cause the field reversal at the poles. Since the migration is not identical in both the hemispheres, the polar field reversal does not take place synchronously and this leads to the monopole situation on the Sun. The migration of the filament bands takes place in the form of two or sometimes three waves, reaching the pole one after another. The amplitudes of these waves seem to be directly related to the magnetic activity in the respective cycles. The poleward drift velocity of the filament bands ranges from 4 to 30 ms^{-1} and shows a dependence on solar activity (Makarov,V.,I., Fatianov,M.,P,. and Sivaraman,K.,R.:1983,*Solar Phys.*, 85, 215; Makarov,V.,I. and Sivaraman,K.,R.: 1983, *Solar Phys.*,85, 227).

4. The Solar Corona

4.1 Coronal Heating:

The release of energy through X ray bright points was proposed as a means of heating the solar corona (Gokhale, M.,H.:1975, *Solar Phys.* 41, 381). Spatial resonance of Alfven waves is one of the several ways by which the corona can be heated. It was found that the presence of twist in the magnetic field enhances the dissipation rate of Alfven waves. This enhancement is due to the availability of a finite resonance region (Krishan,V : 1981, *J. Astrophys. Astr.*,2, 379.) In situ generation of mhd waves by thermal overstability of surface mhd waves was considered as a possible source of waves to heat the corona (Joarder,P.S.,Gokhale,M.H. and Venkatakrishnan,P. 1987, *Solar Phys.*, 110, 255). To compare the significance of the overstability with the condensation mode, a flux sheath was next studied (Joarder,P.S. and Venkatakrishnan,P.: 1990, *Solar Phys.*) which showed that the condensation mode dominates. The formation of the condensations, therefore, impedes the heating process.

4.2 Flares:

The acceleration of particles to KeV energies in solar flares was considered, by invoking the presence of a double layer close to the apex of a flare loop. A theory of a warm collisionless double layer was developed, using a kinetic approach to treat electrons and ions. The model included both free and trapped particles. Using the Vlasov equation, critical conditions for the existence of a double layer were examined. The theory was applied to solar flares. It was suggested that high-energy particles with powerlaw energy distributions could indeed be produced through acceleration in a double layer. (Hasan,S.S. and ter Haar,D.: 1978, *Astrophys. Sp. Sci.*, 56, 89).

The impulsive release of large amounts of energy in a flare is associated with the anomalously large reduction in the conductivity of the plasma which in turn is a consequence of the plasma turbulence. The knowledge of turbulent conductivity is very crucial for this. Plasma acquires anomalous conductivity in the presence of ion-acoustic turbulence. Three different mechanisms are suggested for the non-linear saturation of the ion-acoustic instability. These include the indirect wave-particle interaction, the scattering on density fluctuations and the effects of energy renormalization of the particles. The estimate of magnetic field gradient, based on the resulting anomalous conductivity, agreed well with Skylab data (Krishan,V.:1978, *Solar Phys.*, 29). It was shown that high-m drift tearing modes can be excited under the condition prevalent at the solar flare site. Since the growth rate of the high-m tearing modes is larger than that for low-m macroscopic instability, these modes warrant accommodation in the scheme of instabilities possibly operating in the hybrid model of solar flares suggested by Spicer. (Krishan,V: 1982, *Solar Phys*. 80, 313).

Recent observations of the fast time variability in the hard x-ray emission from solar flares were interpreted in terms of plasma disruption. The fast spikes are assumed to be superimposed on the thermal X-ray emission. The rise and fall of a spike are caused by disruptions in the plasma. The rise time represents the impulsive heating time and the decay or fall time represents a quick cooling of the plasma due to the accelerating growth rate of the m=1 tearing mode. The estimated characteristic time durations of the spike were found to be in a good agreement with the observed ones (Krishan,V. IAU Symp. 107, 299).

It was shown that magnetic tension vanishes at regions of large magnetic "shear" on the polarity inversion line. These tension-free fields being sensitive to the density of the medium are prone to instabilities that change the density. These instabilities, in turn, could evolve to result in flares. The observation that solar flares tend to occur at regions of large magnetic shear on the polarity inversion line, have thus been explained (Venkatakrishnan,P.: 1990, *Solar Phys.*, submitted).

A clue to the preflare configuration of a magnetic loop was obtained based on Taylor's hypothesis that the decay of energy to a minimum with magnetic helicity remaining constant leads to a force free state. Previous numerical investigations indicate that a high energy and nearly force free state of the plasma decays to a minimum energy state with a release of energy via magnetic reconnection processes. For the typical parameters of flaring plasma, an energy dissipation rate of 10^{29} ergs/sec was estimated which compares well with the observed rate. The final relaxed state conforms to the minimum configuration. This minimum energy state has been studied in earlier papers (Krishan 1983, 1985) and has been used to model the pressure of the cool core and hot sheath type of loops. The calculated spatial profiles of the UV lines excited in these loops agree well with the observed ones. Thus it was seen that there are sufficient reasons to believe that the preflare configuration of the plasma corresponds to a nearly force-free high λ configuration. (Krishan,V,: 1986, *Plasma Physics and Controlled Fusion*, 28, 509).

4.3 Coronal Structures:

A coronal spectrogram obtained qt the March 7, 1970 eclipse showed the emission lines of the Balmer series, of Helium D_3, and of Calcium H and K. Detailed analysis of the intensities of these lines seen in emission shows that these could not originate from the scattering in the earth's atmosphere. It was suggested that these emissions originate from the cool columns embadded in the hot corona (Bappu,M.,K.,V., Bhattacharyya,J.,C., and Sivarman,K.,R.: 1972, *Solar Phys.*, 24, 366). This was the first time the emission in H-alpha had been detected in the coronal spectrum. The French, Japanese and Russian astronomers detected H_α emission in the subsequent eclipses and confirmed this finding. The June 11, 1983 eclipse again showed the emission conspicuously.

The solar corona was photographed at an effective wavelength of 6300 A during the eclipse of 1980 February 16 . Coronal pictures were also obtained in polarized light using a quadruple camera for four polaroid orientations. These observations were used to derive the coronal brightness and polarization and, from these the electron densities in the corona were estimated out to a distance of about 2.5 R_o from the centre of the Sun. The coronal brightness matches well with that of the corona of 1958 October 12 (Sivaraman,K.,R., Jayachandran,M., Scaria,K.,K., Babu,G.,S.,D., Bagare,S., P., and Jayarajan,A.,P.:1984,*J.Astrophys.Astron.*,5,149).

High resolution multislit spectroscopy of the solar corona was done during the total solar eclipses of 1980 and 1983 to study the temperature, and velocity structure in the solar corona. It was found that turbulent velocities of 30 km s^{-1} and 16 km s^{-1} need to be invoked to explain the enhanced line broadening for the 1980 and 1983 corona respectively. The observations showed that corona does not show any localized differential mass motion and that it co-rotates with the photospheric layers. (Singh,J., Bappu,M.K.V. and Saxena,A.K. 1982, *J.Astrophys.* 3, 249; Singh,J. Sivaraman,K.R. and Rajamohan,R. 1989 in press). The line and continuum intensity ratios indicates that collisional excitation is the predominant mode for R/R_o < 1.2. Collisional as well as radiative excitation is equally important for 1.2 < R/R_o < 1.4, whereas, beyond 1.4 R_o, radiative excitation becomes dominant (Singh,J.: 1985, *Solar Phys.* 95, 253).

The steady-state pressure structure of a solar coronal loop was discussed using the theory of magneto-hydrodynamical turbulence in cylindrical geometry. The steady state is represented by the superposition of two Chandrasekhar-Kendall functions. This representation, in principle can delineate the three dimensional temperature structure of the coronal loop. A two dimensional modelling was done since only this structure submits itself to the scrutiny of the available observations. The radial as well as the axial variations of the pressure in a constant density loop were calculated. These variations are found to conform to the observed features of cool core and hot sheath of the loops as well as to the location of the temperature maximum at the apex of the loop. These features are not present uniformly all along either the length of the loop or across the radius. The associated time periods of the possible oscillatory pressure variations have been estimated. The spatial profiles of line flux for the lines CII, CIII, OIV, OVI, NeVII, and MgX were determined and found that the hotter lines which are emitted near the surface of the loop have larger spatial extents compared to the lines originating in the cool core of the loop, in agreement with the observations (Krishan,V.: 1983, *Solar Phys.*,88,155; *ibid*,1985,97,183).

Distribution of the coronal velocity and magnetic field fluctuations was studied by formulating their statistical mechanics in a phase space whose coordinates are the expansion coefficients of the fields. The plasma subjected to the conservation laws emerges in a most probable state which is described by an equilibrium distribution function containing a Lagrange multiplier for every invariant of the system. The Lagrange multipliers are determined by demanding that the measured expectation values of the invariants be reproduced. For a numerical exercise, some probable values of these invariants were assumed. The total energy of a coronal loop is estimated from energy balance considerations. Doppler widths of the UV and EUV lines excited in the coronal loop plasma give a measure of the root-mean-square velocities. For analytical progress, two limiting cases are studied out of which one represents the equipartition of energy and the other represents the dominance of magnetic energy over the kinetic energy. More quantitative insight into the distribution of magnetic and kinetic energies for a general case can be obtained by resorting to numerical methods. This study has, however contributed in a positive manner in delineating the probability distributions of the magnetic fluxes and the total energy of the system. This study on the one hand proves the validity of the statistical treatment of magnetohydrodynamical turbulence and predicts the values of the invariants which cannot be measured at present. Once the probability distributions are known one can proceed to study the evolution of fluctuations and their correlations. The role of these fluctuations in producing large scale coherent structures is one of the most important revelations of the MHD turbulence theory. The availability of data for the solar corona similar to that obtained for solar wind could scrutinize some of these theoretical concepts. This could further lead one to consider stellar atmospheres where such data may never be available. (Krishan,V. 1985, *Solar Phys.*,95, 269).

Dynamics of magnetic and velocity fields in coronal loops was studied when the loop plasma is represented by a superposition of the three lowest order Chandrasekhar-Kendall modes. The temporal evolution of the fields in each of these modes was determined using ideal MHD equations under two simplified cases viz (i) allowing small departures from the equilibrium (ii) the pump approximation. In the first case the system exhibits sinusoidal oscillations with a period which depends upon the equilibrium values of the fields. In the second case the fields develop large gradients and under specific conditions show simultaneous reversals (Krishan,V. Berger,M. and Priest,E.R.: 1988, *Proc. Ninth Sacramento Peak Summer Symposium* Sunspot). Further, it is shown that the period of a loop can be expressed in terms of the total magnetic helicity and toroidal and poloidal magnetic fluxes, the invariants of the system. Thus the magnetic helicity which cannot be directly measured in the corona, can be estimated using the observed values of the periods (Krishan,V. and Priest,E.R.: 1989, *IAU Symp* 142).

A linear stabilty analysis of radiating magnetic flux sheaths embedded in a radiating magnetised plasma showed that the eigenfunctions "penetrate" into the ambient plasma. The penetration length was seen to be independent of the thickness of the magnetic structure. The observed structures could thus be a result of such a "penetrative" instability although only a non-linear analysis can predict the end-state of these instabilities (Joarder,P.S. and Venkatakrishnan,P.: 1990, *Solar Phys.*).

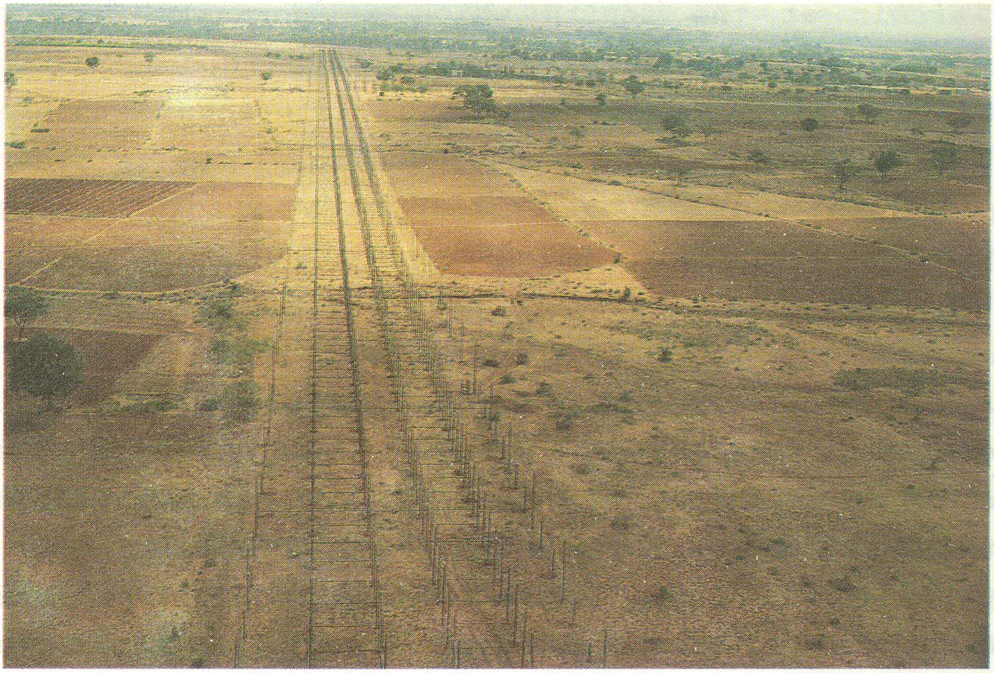
It was shown that the global kinematical properties of the coronal magnetic fields can be interpreted as a consequence of a continuous flow of strong thin flux tubes up across the photosphere and away from the Sun (Gokhale,M.H. and Venkatakrishnan,P.:1978, *Pramana*,547).

4.4. Coronal Radio Emission:

During the late sixties pioneering work on the fine structure in time, frequency and polarization of solar decameter radio bursts was carried out at the Astrophysical Observatory, Kodaikanal. Large antenna arrays in conjunction with high time and frequency resolution radiometers and polarimeters were used. The resolution in time was of the order of 15 milliseconds and that in frequency was 100 KHz. The major thrust of this work was on determining the durations, time frequency profiles, and polarization characteristics. From the observed characteristics like the ratio of intensities, the dependence of the time interval on the total duration etc, it was shown that the well known double peaked time profiles were not due to propagation effects like echoes in the solar corona. The polarization structure showed that the time splitting was not a magneto-ionic effect. Many interesting types of fine structures including spike bursts were detected in these studies (Sastry , Ch.,V.:1969,*Solar Phys.*, 10, 432; 1971,*Astrophys. Lett*,8, 115; 1972, *Astrophys. Lett* 11, 47; 1973, *Solar Phys.*, 28, 197).

The Decametre Wave Radio Observatory at Gauribidanur

Radio emission at decameter wavelengths is a good diagnostic tool for coronal plasma parameters like electron density, temperature and magnetic field between $1R_o$ and $2R_o$.The Indian Institute of Astrophysics and the Raman Research Institute are jointly operating a decametre wave radio observatory at Gauribidanur,



Karnataka (longitude 77^{o} 26′ 07" E and latitude 13^{o} 36′12" N). The main facility at the Observatory is a 'T' shaped array with a 1.38 km east-west arm and a 0.34 km south arm. The total number of dipoles in these arrays is one thousand and they accept east-west polarization. A full reflecting screen of area 60,000m^{2} is mounted below the dipoles. The entire structure is supported by a grid of 3500 wooden poles of varying lengths and heights up to 10 metres to compensate for the terrain. The dipoles of the array are phased in the field by remotely controlled phase shifters and are combined using a binary branching feeder network. The outputs of the east, west and south arms are carried separately by co-axial cables to the main observatory building. The signals are amplified and the sum of the east and west signals is correlated with that of the south arm. This produces a single beam of 26 arcmin x

40 arcmin at the zenith which is normally used for observations of pulsars, scintillations etc. Multiple beams are also formed using two different techniques. In one of them the response of the telescope is steered rapidly in the N-S direction by a special purpose digital control system which supplies switching voltages to the phase shifters. The time required to change the beam from one position to another is of the order of a few millisec. The number of declinations through which the beam is cycled can be varied from one to sixteen. The other technique measures the complex correlations between the E-W array and each one of the 90 rows of dipoles in the south arm. This is accomplished using 128 channel digital correlation reciver. Multiple beams can be formed by Fourier synthesis of the measured correlations. In the present case the number of independent beams is 90 in declination, and a region of the sky $+50^{o}$ of zenith angle can be mapped at any given time. The earth's rotation is used to cover the sky in the E-W direction. The effective area of the telescope is approximately 20,000 square metres at 34.5 MHz. The mean sky brightness at this frequency is about 10,000 K and so the minimum detectable flux density is of the order of 10 Jy (1 Jy = 10^{-26} watts m^{-2} Hz^{-1}) with an integration time of 24 s and a bandwidth of 400 KHz. The minimum detectable brightness temperature variations are of the order of 1000K. The presence of many unresolved sources in the main beam results in a confusion limit of the order of 10 Jy for the 'T' array. It is therefore not possible to decrease the minimum detectable flux limit by increasing the integration time. In order to increase both the resolving power and

the sensitivity, an array of 64 yagis have been added to the 'T'. This array is located at a distance of 0.45 km from the centre of the E-W arm of the 'T'. The beam of this array can be pointed anywhere within + 50^{o} of the zenith on the meridian using diode phase shifters and a digital control system. The sum of the outputs of the north and south arrays can be multiplied with the E-W array to produce a beam of 26 arcmin x 20 arcmin at the zenith. High resolution one-dimensional observations are made with a compound grating interferometer with an E-W fan beam of three arcmin. It consists of four grating units placed at intervals of 1.4 km (length of the E-W array) on a E-W base line starting from the western end of the E-W array. Each grating unit comprises of 8 yagi antennas and the outputs of each one of them is multiplied with the EW array output to synthesize the fan beam.

Broadband Array For Solar Observations

There is also a broadband array usable in the frequency range 30 MHz to 70 MHz mainly for solar observations. The basic element of this array is a biconical dipole with a VSWR 2 in the above frequency range. The array consists of 64 elements arranged in a matrix of 4 x 16 along E-W and N-S respectively. The dipoles are placed inside a corner reflector and accept N-S polarization. The array is split up into northern and southern groups of eight rows each. The eight rows of each group are combined in a branched feeder system and delay shifters are introduced at appropriate places, to steer the response of the array to $\pm 45^{o}$ of the zenith in the N-S direction. The position of the beam formed is independent of frequency allowing simultaneous observation of a radio source over the full bandwidth of the system. This array is also used in transit mode and the available observing times range from 26 minutes at 65 MHz to about an hour at 35 MHz. The effective collecting area is about 2000 m^2 and the sensitivity is better than 100 Jy at 65 MHz for a bandwidth of 1 MHz and 1 s integration time.

Acousto-Optic Spectrograph

An acousto-optic spectrograph (AOS) provides high time and frequency resolution for studies of radio bursts from the Sun. The AOS has a bandwidth of 30 MHz with 1760 channels, the frequency resolution is about 30 KHz. The spectrograph is interfaced via an A/D converter and a memory bank to VAX 11/730 computer. All its 1760 channels are scanned every 250 millisec and the data is recorded either on the userdisk of the computer or magnetic tape unit. Software has been developed for processing the data and provides 3-D plots of the radio bursts (frequency, time and intensity), contour maps and drift rates etc.

Data Acquisition System

A microprocessor-based data acquisition and recording system enables analog signals of bandwidths up to 30 KHz with 12 bit digitization to be acquired and recorded on magnetic tape units. The system can accept data up to 64 single ended channels (32 differential) at a maximum rate of 25 microsec per channel. The system software allows interactive programmning of various features like sampling rate, number of channels, and error logging etc. Diagnostic software is available for board-level diagnostics.

Computer System

The VAX 11/730 system is available for off-line processing and data acquisition with the AOS system. It is supported by a 32 bit high memory speed microprogrammed central processing unit, 1 Mb RAM memory, 4 K ROM memory for control programs and two cartridge tape drives. Two drives of 20 Mb virtual memory and a tape drive which records at densities of 800/1600 bytes per inch are also available.

Solar Physics With The Decameter Telescope

The slowly varying component of solar radio emission was observed at a frequency of 34.5 MHz with half power beam widths of 26′/40′ in the east-west and north-south directions, respectively. It was found the observed brightness temperatures vary within the limits of $0.3x10^{6}$ K to $1.5x10^{6}$ K, and the average half power widths of the brightness distribution on the Sun is about $3R_{o}$. Thermal emission from dense coronal regions was shown to account for the observed brightness temperatures (Sastry,Ch.,V., Dwarkanath,K.S., Shevgaonkar,R., K., and Krishan,V.: 1981, *Solar Phys*,. 73, 363).

Type III b - Type III radio bursts were observed with high time and frequency resolution during the period of January 1971 to March 1972 using an antenna system of about 25 db gain and a four channel receiver. The centre frequency was 25 MHz and the bandwidth and the time constant was usually 100 MHz but can be varied from 20 MHz onwards. The average duration and the average time profile of the elements of type III b radio bursts were measured. The nonlinear evolution of an electron beam magnetoplasma system was studied in order to interpret the characteristics of type III b solar radio bursts. The treatment of electric field corresponding to the beam plasma electrostatic instability in this interpretation, differs in an essential way. In contrast to the earlier theory, where the electric fields interacts with the normal modes of the plasma, the electromagnetic modes of the plasma, immersed in the electric and magnetic fields, were found. The electric field enters at the single particle level and therefore is accounted in a more exact manner. In addition, the direction of propagation of the type III b radio busts is very clearly dictated by this interpretation. (Krishan, V., Subramanian, K.R. and Sastry, Ch. V. : 1980 *Solar Phys*, 66, 347.)

The strong correlation between the decay constant and the exciter duration normally observed for isolated type III radio bursts, was found to be absent for those type III radio bursts which are preceded by type III b radio bursts. This may result due to the different nature of the exciter in the two cases. The isolated type III bursts have an exciter which is more or less of uniform density and speed. In this case the decay constant and the exciter duration both are functions of only one set of parameters like density and speed and hence there is correlation between the two. On the other hand the associated type III busts have an exciter which is of highly non-uniform nature. The decay constant being mainly the function of the front end and the exciter duration being chiefly due to the larger rear end, the two are weakly correlated for associated type III radio bursts (Subramanian,K.R., Krishan,V. and Sastry, Ch.V. : 1981, *Solar Phys.*, 70, 375.)

The pulsation pattern in the time profile of short duration solar radio bursts at decameter wavelengths were observed and interpreted. The pulsations were found to be present predominantly in the saturation phase of the burst. The basic system responsible for these modulated bursts is an electron beam-plasma system. This system has been shown to support positive as well as negative energy waves. Their coupling gives rise to an explosive instability where the amplitude can become infinite in a finite time, although due to various non-linear effects, the growth of the amplitude will be arrested. The initial growing phase of the burst could be attributed to this explosive instability. Since the background level of emission over which the burst is superimposed is very high, the conditions for the explosive interaction of the waves are satisfied. The time of explosion is a function of the initial amplitude. The saturation of the explosive instability was shown to be due to the nonlinear complex amplitude - dependent frequency shift caused by three wave coupling. Further, the nonlinear frequency shifts combined with the linear dissipation effects set the saturation stage into an oscillatory mode (Sastry, Ch.V., Krishan,V. and Subramanian,K.R. : 1981, *J. Astrophys. Astr.*,2, 59.)

The excitation of electromagnetic radiation near the harmonics of electron plasma frequency was explored in an electron beam - magnetoplasma system. The electron beam is replaced by the electron plasma electrostatic wave generated by it. Under the combined influence of this electrostatic field and the magnetic field, collective motion of plasma particles gives rise to electromagnetic modes at $0.5(n_1 + n_2)(\omega_0 \pm K_0.u_e) + 0.5.(l_1 - l_2).\omega_{ce}$, where, n_1,n_2,l_1,and l_2 are integers, $\omega^2_0 = \omega_{pe}{}^2 + 3K^2_0.v^2_{th}$, ω_{pe} is the electron plasma frequency, K_0 is the wave vector, v_{th} is the thermal velocity of electrons, $u_e = (eE_0/m\omega_0)$ is the given velocity of an electron in the field E_0 of the electrostatic electron plasma wave and ω_{ce} is the electron cyclotron frequency. This mechanism explains various observed features of the type III solar radio bursts. The calculated values of the frequency driftrate and the characteristic rise time agree very well with the observed (Krishan,V.: 1980, *Plasma Physics*,22, 163; *ibid.*, 1980, 22, 787; *ibid.*, 1982, 24, 31).

Parallel acceleration mechanism essentially amounts to the calculations of the trajectory of a particle under the action of an electric field parallel to the magnetic field. This mechanism was reconsidered including the spatial dependence of the electric field of the form exp (iq.r) since the idea is to consider the acceleration of the particles by electromagnetic waves, a situation likely to be present in many astrophysical contexts. The results were applied to account for the sporadic solar radio emission in the form of type III and III b radio bursts. The frequency spectrum was found to agree well with the observations. In addition to relaxing the dipole approximation, the particle trajectory was determined to a higher approximation which admits harmonic generation (Krishan,V. and Sivaram,C: 1983, *Solar Phys.*, **84**, 125).

5. Solar Wind

The transient response of the solar wind to changes in geometry was examined. An initial stationary flow in a configuration diverging as r^2 was assumed. This state corresponds to the usual solar wind solution. The effect of gradually varying the field geometry, so as to mimic the form of the flux tube area dependence in coronal holes, was considered. It was found that a variety of asymptotic (in time) solutions were possible, including those exhibitng shock-like discontinuities. The potential of this study in modelling flows in evolving coronal holes was pointed out (Hasan,S.S. and Venkatakrishnan,P.: 1982, *Solar Phys.* **80**, 385).

Solar wind acceleration is one of the outstanding problems in solar physics. The characteristics of the non-transient related low-speed solar wind namely, the one that prevails around stream-free sector boundaries (reversals in the azimuthal component of interplanetary magnetic field that are currently considered as heliospheric current sheet crossings at Earth), were recently examined using the interplanetary plasma data base compiled from near-earth spacecraft measurements. (Sastri,J.H. :1987, *Solar Phys*., 111, 429). This study showed that the well-known positive dependence of the proton temperature (T_p) on the wind speed (V) is weaker and the recently evidenced negative relationship of T_p with momentum flux density (NV^2) is stronger in the flow around stream-free boundaries than in the other types of solar wind studied earlier. It was also found that the proton number density (N) varies as the inverse cube of the flow speed indicating an invariance of kinetic energy flux density (NV^3) to the velocity structure in the flow around stream-free boundaries. These relationships, which are not affected by interplanetary dynamical processes, are in good agreement with the predicted consequences of sub-sonic addition of momentum and energy in the corona. The results thus provide further support to the current views of the relevance of sub-sonic coronal processes to the low speed state of solar wind at 1 A.U.

EPILOGUE

What does the future hold for solar physics at the Indian Institute of Astrophysics ? The preoccupation of the Institute with night time astronomy will continue, thereby straining the resources potentially available for solar astronomy. Ambitious plans, however, are afoot to build a new facility (The National Solar Vacuum Telescope) at a yet unknown but obviously excellent site. Apart from this, modernisation of the existing facilities are being planned. The first step of course is to change over from photographic to CCD detection. New programmes, e.g. the measurement of all three components of the magnetic field are happily underway. New techniques of data reduction (even photographic data) are being employed as is evidenced in the reduction of stokes profiles using packages developed for stellar spectroscopy.

Literally new frontiers will be explored by the Institute's scientists this austral summer at Antarctica where they will study the evolution of supergranules in Ca emission. This experience might even urge some of us to enter helioseismology via Antarctica!

The theorists now have access to bigger computers than what was available in the late 70's. Many are now taking note of new developments in plasma physics and will hopefully introduce new concepts into traditional solar physics.

Bob Rosner (Univ. of Chicago) is known to have asked why solar physics has lost its charm. This question need not be asked for several more years in the Indian Institute of Astrophysics.