SUMMARY LECTURE

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This has been a memorable meeting. First of all, we have had an opportunity of coming to India and getting to know some of its people. We have discovered how attractive Bangalore is and we have glimpsed a little more of Karnataka: none of us will forget the colossal statue of Gomateshvara or the temples at Belur and Halebid. Then we have had our scientific proceedings and contacts with colleagues from across the world. Here I appreciated the unusual distribution of people attending the Symposium. I was especially pleased to see such a high proportion of women present at the meeting and delivering excellent contributions. It was also a welcome change – reflecting the spirit of glasnost – to have more delegates from the Soviet Union than from the United States, including many young physicists whom I congratulate on their skill in speaking here in English. Above all, we had a chance of meeting so many bright young Indian astrophysicists, while they have been able to see us and to observe our shortcomings. I am sure that we are all impressed by the range of research institutes, in Bangalore and elsewhere in India, as well as by the quality of research being done in them. In particular, we learnt more about the Indian Institute of Astrophysics with its commitment to research in solar physics. As Professor Bhattacharya reminded us, it has a two-hundred year history, with a long and distinguished tradition of observations at Kodaikanal coupled to new standards being developed here in Bangalore.

As you all know, this meeting would never have taken place without the persistent efforts of Professor Vinod Krishan. Her original concept involved a much wider coverage of plasma astrophysics: this was cut down to solar physics by the IAU but something of the original scope remains. This range has been immensely stimulating and truly interdisciplinary but no-one, least of all me, could be familiar with all the topics covered. So it is impossible (and probably undesirable) to produce a systematic summary of what we have achieved. That can be gleaned from the Proceedings. What have impressed me most are the quality of research, the wide range of activity and the number of young scientists coming into the subject. In what follows I shall only offer a very selective personal response, with apologies to any participants who feel that their own work has been unjustly neglected.

E. R. Priest and V. Krishan (eds.), Basic Plasma Processes on the Sun, 527–532.

Recent Developments

First of all I want to draw attention to various recent advances and their future prospects, affecting observations from the ground and from space and their theoretical interpretation. I begin with solar observations, go on to the solar system and to other stars and then come round to theory.

Solar oscillations. Precise measurements of the frequencies of p-mode oscillations with periods around five minutes have been inverted to yield amazingly precise measurements of the variation of density, angular velocity (and perhaps magnetic fields) within the Sun. In the future, continuous worldwide coverage will be achieved by the GONG Network, which includes a station at Udaipur. So we expect to investigate fine details of the internal structure and properties of the Sun.

Neutrino flux. The discrepancy between solar models and the neutrino fluxes measured at the Homestake mine and Kamiokande still remain. Is this a problem of stellar structure or high energy physics? Will the apparent correlation with magnetic activity persist – or disappear, like correlations between the solar cycle and the weather? Here we must be patient and wait for results from the gallium experiments that are being prepared.

High resolution photospheric observations. Striking images are being obtained from new ground-based telescopes at La Palma and Tenerife and through improvements at the Pic du Midi and Sacramento Peak. The most important advance came through realising that images were distorted by effects on the Sun and not in the earth's atmosphere. Once the five-minute oscillations were filtered out subgranular scales could be observed with unprecedented clarity. The Lockheed group is now making simultaneous measurements of intensity, velocity and magnetic fields on scales much less than an arc-second. In the future, with adaptive optics and LEST, we can expect to attain even higher resolution.

Radio observations. Radio emission provides increasingly detailed information on flares, coronal mass ejections, type III and type IV bursts and also, through scintillation measurements, of interplanetary magnetic features. The resolution obtained with the VLA and the new millimetre array will be enhanced as other instruments, including the new GMRT near Poona, come into operation.

Rocket flights. The remarkable X-ray images obtained this year by Golub and his colleagues show magnetic features with amazing resolution. There is fine structure on all scales down to 0.1 arc-sec. This shows what can be achieved with new technology and augurs well for future X-ray satellites.

Space missions. The next decade will see an impressive sequence. SOHO is a cornerstone of the ESA programme and will make a range of observations including measurements of solar oscillations. The USSR will launch the CORONAS mission in 1992 to make a suite of observations covering the solar atmosphere in a wide range of frequencies. The Japanese SOLAR-A mission will make uv and X-ray measurements and we expect NASA to launch OSL as a free-flyer, following up on Spacelab-2 with uv and X-ray observations as well as imaging with the Lockheed

SOUP device.

Solar wind and magnetosphere. Going beyond the Sun itself, we may learn from observations within the solar system. Continuing studies of interplanetary magnetic fields, of MHD waves and of reconnection near the magnetopause are improving our understanding of the solar wind and the earth's magnetosphere. Meanwhile, Voyager, Vega and Galileo have explored magnetic fields of planets and the plasma sheaths surrounding comets.

The solar–stellar connection. Although individual magnetic features can only be resolved on the Sun we can discover the effects of varying parameters, such as the rotation rate, by studying other stars. Their magnetic activity can be monitored by recording chromospheric Ca II emission, coronal X-ray emission or radio signals emitted by flares. In this way we have gained a much better understanding of cyclical activity and of the evolution of the Sun's magnetic field as it spins down owing to magnetic braking. Moreover, we can study a continuum of magnetic activity that extends from the Sun through active stars to white dwarfs and neutron stars, or from the corona through accretion discs to active galactic nuclei.

Numerical experiments and simulations. Moving to theory, we note the increasing role of computation. The availability of supercomputers has given a great boost to numerical modelling of plasma processes on the Sun. Until now much of the effort has gone into highly idealized models, many of them two-dimensional, but sophisticated three-dimensional simulations are now feasible. Current research is directed either at detailed atmosphere modelling, aimed at reproducing observations, or at probing turbulent convection in the solar interior.

Nonlinear dynamics. Recent mathematical developments have significant implications for processes in the solar atmosphere and interior. Nonlinear waves may propogate as solitons in flux tubes. The formalism of KAM theory, applied to chaos in Hamiltonian systems, can be used to describe the structure of magnetic fields or to discuss dynamo action by flows with chaotic streamlines. Bifurcation patterns associated with chaos in dissipative systems are also attracting considerable attention as part of a new approach to nonlinear convection and stellar dynamos. In addition, quantitative analysis of aperiodic behaviour is made possible by measuring Lyapunov exponents or computing the dimension of the attractor.

Modelling. These powerful new techniques are exciting in themselves and offer great new opportunities, since plasma processes are typically nonlinear. Nevertheless, they are only relevant in that they enable us to model and interpret the underlying physics of magnetic fields in the Sun. That understanding must be what we aim for.

Impressions.

It may be appropriate to begin by recalling the poster for this meeting. It shows the Sun with its atmosphere extending outwards and full of detail. We can observe this region over 10 decades in frequency, from X-rays to radio, and we know almost too much about it. So it is not surprising that it has received the most attention –

but it is as well to remember that the atmosphere contains only 10^{-10} of the solar mass. The structure of this atmosphere is dominated by magnetic fields which originate in the convection zone, containing $0.03M_\odot$. This can be probed directly, using magnetic flux tubes or solar oscillations. The radiative interior, where energy is generated, contains 97% of the mass and can only be explored with neutrinos or through helioseismology.

Solar interior. The internal structure of the sun can now be determined with extraordinary precision by inverting helioseismological data. Rotational splitting yields measurements of the internal angular velocity, as a function of radius and latitude, which have upset our preconceived ideas: the surface differential rotation apparently persists to the base of the convection zone, with a gradual transition to uniform rotation deeper in the radiative zone. The resulting shear must have a profound effect on the magnetic field.

Dynamo theory. This subject has grown more confusing in the last few years. We still need to establish the location of the solar dynamos and to construct a convincing phenomenological model. Mean field dynamo theory provides a convenient parametrized description of the generation process and some qualitative features can be studied with low-order nonlinear models. Some processes, such as magnetic braking or losses through magnetic buoyancy, can be isolated and studied in some detail but large-scale nonlinear calculations are still badly needed.

Convection and magnetoconvection. These phenomena are thoroughly nonlinear. Several recent numerical simulations of three-dimensional compressible convection agree in showing a cellular structure at the surface, giving way to rapidly sinking isolated plumes below. These results are impressive but the deep structure remains mysterious. Most studies of compressible magnetoconvection have so far been confined to two-dimensional models. Careful treatments of MHD turbulence in incompressible fluids show that oversimplified models (and simplistic postulates) have limited validity.

Surface motions. Differential rotation and meridional flows provide large-scale effects. There is evidence for meridional circulations from sunspot proper motions, as well as for fluctuations in rotation rate over the solar cycle. On a smaller scale, behaviour of photospheric flux tubes is controlled by granular, mesogranular and supergranular velocities. High resolution measurements of granular proper motions have confirmed the existence of mesogranules but the underlying dynamics is uncertain: are they thermally driven or produced by self-organization from a nonlinear cascade?

Flux tubes. The formation of isolated flux tubes with intense magnetic fields is understood but has not yet been modelled in detail. Once formed, these tubes support waves whose properties have been thoroughly described. Moreover, these waves can maintain the supply of energy to isolated bright points in the chromosphere. Pores and sunspots appear deceptively simple and it has proved surprisingly difficult to model the overall structure of a sunspot.

Nonlinear waves. Nonlinear waves crop up in several contexts, in the photosphere and corona as well as in the solar wind. Solar physics provides examples of fundamental nonlinear behaviour: solitons travel along flux tubes and coronal wave interactions can lead to chaos. In addition there are physical processes involving resonance absorption and particle acceleration which need to be described.

Heating the solar atmosphere. Acoustic heating provides an omnipresent background but other processes have to be invoked. Is the corona heated by hydromagnetic waves or by magnetic dissipation? This remains a controversial issue though the argument has grown more tolerant. Perhaps a clue can be obtained by studying fine structure in the latest X-ray images of the corona and assessing whether filaments are heated by local electric currents or by waves travelling along them.

Reconnection. This subject began over 40 years ago with the pioneering work of Dungey and Sweet. Since then modelling of prominences and flares has become increasingly detailed and sophisticated but we still need mechanisms for *rapid* reconnection. (It seems frustrating when speculations are damped by excessive observational constraints: life might be easier for theoreticians if we only knew about stellar flares.) A crucial issue concerns the evolution of force-free fields in the atmosphere as photospheric convection moves the footpoints of the flux tubes. Does lack of equilibrium lead to current sheets or are there only intermittent but continuous structures, as suggested by numerical experiments? Finally, when catastrophic reconnection occurs, which of several mechanisms – strong electric fields, nonlinear waves or turbulence – leads to particle acceleration?

This selective catalogue could continue to include spectroscopy and space plasmas. I end, however, with two quotes. Vinod Krishan warned us: "Do not underestimate the unknown devil." At the time I wondered what she meant but then Franz Kneer reminded us of the distinction between theoreticians and observers: an observer trusts everyone's results except his own while a theoretician does not believe any results except his own. Perhaps that is what she had in mind. If so, you will have to decide for yourselves what to accept in my summary of the meeting.

Conclusion

This Symposium has certainly demonstrated the characteristic flavour of solar physics. Our subject differs from, say, extragalactic astronomy in that theoretical ideas are heavily constrained by detailed observations. Yet those observations are incomplete and a proper understanding can only be gained by detailed modelling. Although the plethora of observational constraints sometimes appears to hinder progress we must acknowledge that without such observations we could never have invented the rich behaviour caused by magnetic activity on the Sun: magnetic cycles, isolated flux tubes, sunspots, rapid reconnection, flares, coronal heating. What makes our subject challenging and fascinating is (to use Parker's words) that "Nature is cleverer than we are."

Finally, on behalf of everyone I thank all those who have made this meeting so successful. This includes our sponsors, especially the Indian Institute of Astrophysics and Professor Bhattacharya, and the Raman Institute and Professor Radhakrishnan, the Scientific Organizing Committee, the local Organizing Committee and the staff who have so efficiently looked after our arrangements. Above all, Professor Vinod Krishan deserves our thanks: she corresponded with us, organized the meeting, arranged our sessions, provided advice, settled problems and found time to present her own work. We are very grateful.