SUMMARY OF THE FINAL DISCUSSION ON AUGUST 29

(Chairman: G. Newkirk)

B. R. DURNEY, P. A. GILMAN, and M. STIX
National Center for Atmospheric Research, Boulder, Colo. 80303, U.S.A.

The aim of this summary is to convey to the reader only the highlights and the 'spirit' of the discussion. We have decided, therefore, to give an assimilated version of the discussion and realize that in doing so we have perhaps introduced our personal opinions; we have tried, however, to give due prominence to ideas different from our own.

As was pertinent to a symposium dedicated to the Basic Mechanisms of Solar Activity, much of the discussion was centered about problems concerning the solar dynamo and differential rotation. In relation to the Sun's differential rotation those problems relevant to theories of the solar activity cycle were especially emphasized.

Whereas the most favored explanation of the Sun's activity cycle is based on a dynamo theory of this phenomenon, this explanation is not accepted by everybody. The main objections are two-fold:

(a) There is not conclusive observational proof that turbulent diffusivity of the magnitude required by dynamo theories is present in the Sun;

(b) Dynamo theories describe magnetic fields that vary slowly in space and time whereas the observations show that most of the solar magnetic field is concentrated in small bundles of high field strength; how then can one talk about a mean magnetic field so essential for dynamo theories? These represent the most outstanding difficulties which have led some scientists to doubt the validity of dynamo theories. Others can also be found; for example:

(c) The variations of the angular velocity with depth and latitude are not known; and the dynamo responds in a complicated way to this dependence. In particular, most dynamo models require that the angular velocity *increase* with depth, while most theories of differential rotation predict that the angular velocity should *decrease* with depth because rotational constraints tend to make the angular velocity constant on cylinders;

(d) It appears that the toroidal magnetic field must be amplified *deep* inside the convection zone, because elsewhere (in the convection zone) magnetic buoyancy is so strong that it does not allow fields to remain long enough to be amplified to the strength observed at the surface. Such a location of the amplification zone could make the dynamo sensitive to the structure of the deep solar interior which the neutrino deficit emphasizes as a poorly understood region.

(e) Statistical averages play an essential role in the development of mean field electrodynamics, and the relation to the observational averages is not straightforward;

(f) Second-order terms in the equation for the fluctuating magnetic fields are neglected with only marginal justification;

(g) The variation within the Sun of the parameters α or R, which describe the regeneration of the poloidal magnetic field (from the toroidal magnetic field)

Bumba and Kleczek (eds.), Basic Mechanisms of Solar Activity, 479–481.

depends on the form of the convective motions, rotation, shear and density stratification; to calculate the values of these parameters one must make simplifying assumptions which are not always justified.

Some of the difficulties listed above are readily acknowledged and even put forward by proponents of the dynamo theory; the existence of such dilemmas merely indicates that our knowledge of this complex phenomenon is far from complete. Models of the solar cycle should therefore be developed more as a way to understand the physical processes leading to the solar activity cycle than to exactly reproduce observed details. The main difficulties (a) and (b) are answered by supporters of the dynamo theories as follows:

(a) The existence of turbulent diffusion can be derived from Maxwell's equations with the help of reasonable approximations; therefore, to doubt the existence of turbulent diffusion is to doubt the validity of Maxwell's equations. Ohmic dissipation, or field line reconnection, *will* take place at small scales, probably assisted by dynamic effects such as Petschek's mechanism;

(b) No matter how concentrated the magnetic filaments are, the mean field can always be defined. It is the average of the whole field, filamentary *and* (if there is any) interfilamentary.

Whereas there can be no doubt about the existence of the magnetic filaments, it is not understood how they are formed (a convergent velocity field is not sufficient). Do they exist throughout the convection zone as some observers argued? Or, is the large flux density limited to the surface as is, perhaps, more plausible? The persistence of these filaments is also difficult to understand; to achieve equilibrium an efficient cooling mechanism is needed; and one would expect the equilibrium to be rapidly destroyed by exchange instabilities. The idea that *twisting* magnetic flux tubes concentrates them is heavily disputed.

We have given above the essence of the arguments presented in favor, as well as the criticisms, of dynamo theories. Some of those who do not believe in dynamo theories advocate an explanation of the solar activity cycle based on a steady primordial field. A necessary condition for the validity of this idea is that turbulent diffusion and the resulting reconnection of field lines (at small scales) in the convection zone must be so slow that the primordial field has not been destroyed in the lifetime of the Sun. Also, the observed reversals of the polar fields near the maxima of the last two cycles, if real, are in contradiction to the existence of the primordial field.

It is commonly accepted that the amplification of the toroidal magnetic field is achieved by the differential rotation of the Sun's convection zone. Theories of differential rotation and dynamo theories are therefore closely linked. This bond puts severe constraints on both theories. It is, therefore, of great importance to establish firmly that the dynamo operates, indeed, in the solar convection zone and thus demonstrate that differential rotation is not a surface phenomenon but is significant over the entire convection zone. If this is the case, theories of differential rotation find it, at present, difficult to account for the observed latitudinal variations in the angular velocity without significant variations in the energy flux.

Can the dynamo be located *below* the convection zone? In this case the shear necessary to amplify the toroidal magnetic field would exist as a primordial feature;

the torque exerted by the solar wind would uniformly slow down the convective shell (because of its large viscosity) and leave a rapidly spinning core. This idea encounters serious difficulties: for example, an alternating field cannot penetrate into a region of high conductivity such as the radiative core (the penetration depth is only a few hundred kilometers if the diffusivity is determined by turbulence generated by the Goldreich-Schubert-Fricke instability). Furthermore, the dynamo would tend to choke itself off by the action of Lorentz forces. Finally, questions arise concerning the energy available since the energy for the dynamo must come from the rapidly rotating core and it is not clear that this energy is sufficient to have run the dynamo since the formation of the Sun. An important overshooting of convective motions therefore seems necessary, if the dynamo is to be located in the radiative region. However, everything considered, the most plausible region for the operation of the solar dynamo appears to be the convection zone.

As mentioned in (c), differential rotation theories favor angular velocity decreasing with depth while most dynamo models require the opposite. It is not clear that a real contradiction exists because the approximations used in both the differential rotation and the dynamo models are not well justified for the Sun. In this context, the comparison of the observed and theoretically predicted phase relations between the radial and azimuthal components of the mean field could put an important constraint on how the angular velocity must vary with depth.

Increased efforts to observe velocities on global scales on the Sun should provide useful guidance in the development of more advanced circulation models. Among the important effects which should be studied are (a) variations in the rotation rate with time, (b) structure of additional global-scale velocity anomalies to see if they represent convection, (c) comparisons of velocities measured simultaneously by doppler and tracer techniques, (d) differences in velocity between low and high latitudes, (e) persistence of velocity patterns from one rotation to the next, (f) correlations between velocity fluctuations in northern and southern hemispheres, (g) comparisons of velocity anomalies and time variations with brightness changes, (h) separation of east–west from north–south velocities, so that transport properties can be calculated, (i) solar cycle length variations in velocities, to see whether the magnetic fields are strong enough to react back upon the flow which induced them.