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SOLAR DYNAMO PROBLEM

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Abstract

The origin of solar magnetic field and the flux tube nature of this field on the smallest observed scales are two key problems in solar magnetohydrodynamics. Despite the success of kinematical models based on the turbulent dynamo theory, continuation of thinking on alternative approaches is justified and may be even necessary.

One such approach is based on consideration of energy transfer in magnetogasdynamical production of new magnetic fields near the base of the solar convection zone. It turns out that the field produced by a substantial transfer of energy from the flows will essentially be in the form of strong thin flux sheaths that may break into 'cluster of flux tubes' similar to those observed on the sun. Quantitative similarity requires nonlinear MHD interactions of flows with amplitudes $\sim 10^4$ cm s^{-1} on timescales $\sim 10^3$s. Such interactions may be provided by azimuthal magnetoacoustic waves at the longitudes where they cross one another. The required wave amplitudes can be provided by a small fraction of the outward energy flux which must be blocked near the base of the convection zone. The resulting phenomenological model of the magnetic cycle provides for (i) two varieties of activity with distributions and phases similar to the XBP and sunspot cycle, (ii) poleward migrations of large scale fields, (iii) long lived coronal hole like magnetic structures during decline of the sunspot cycle and (iv) relations between the decline of each cycle and the amplitude of the succeeding cycle. The basic postulate of this model remains to be established from solutions of MHD equations. However if established, it will provide promising alternative to the turbulent dynamo model.

1. Introduction

Solar magnetohydrodynamics can be said to have begun with the discoveries of strong magnetic fields and Evershed flows in sunspots. The present scope of the solar MHD covers various problems concerning the following phenomena (e.g. Priest 1982): (i) sunspots, (ii) quiescent prominences, (iii) transient events like flares, active prominences and coronal transients, (iv) coronal heating and coronal structures, (v) solar wind and interplanetary magnetic field, (vi) solar dynamo and solar activity cycle and (vii) the small scale magnetic flux tubes in the photosphere and chromosphere. The boundary conditions used in modelling of the first five phenomena are often based on an ad-hoc choice of photosphere (or some other surface like the Alfvénic surface) as one of the boundaries. Secondly the often observed inhomogeneities and discontinuities in directions transverse to the field are ignored in most of the models of these phenomena. The progress in the modelling of these phenomena will depend ultimately on the boundary conditions at the "innermost boundaries" of the magnetic structures (i.e. the depths at which the field lines originate) and also upon the physical conditions and processes in the individual flux tubes constituting the magnetic structures.

Thus, the solar dynamo problem and the problem of thin magnetic flux tubes can be considered as two key problems in the solar magnetohydrodynamics.

In this review, I shall briefly discuss the various approaches to the solar dynamo problem and present a somewhat detailed discussion of a new phenomenological approach which will bring out a likely connection between dynamo problem and the problem of thin flux tubes.

2. Behaviour of the Solar Magnetic Field on Different Length Scales and Time Scales

Because of its key role in almost the whole of the solar MHD, a model of the solar dynamo should be ultimately consistent with the behaviour of solar magnetic field as observed (or observationally inferred) on different length scales and time scales. I have listed in Appendix I as many observed properties of the solar magnetic field as known from different observations which are relevant to the present discussion. The purpose of presenting this list is not to suggest any attempt to "explain" all these phenomena with a single theory. It is only to illustrate how vast is the amount of observational information that a solar dynamo theory will have ultimately to deal with.

3. Solar Dynamo Problem as the Solar Cycle Dynamo Problem

Solar magnetic fields would not have posed any dynamo problem if the observed large-scale field could be understood as a manifestation of the remnant of a 'primordial field' which must have been trapped in the sun during its formation. Theoretically, the presence of such a fossil field cannot be ruled out even though the sun must have gone through a fully convective state in the past (Piddington, 1982). However, such a fossil field, if present, seems to be too weak to be detected in the noise of the strong fields associated with the solar cycle whose surface average near polar region does reverse every 11 y or so. Thus, the solar dynamo problem is essentially that of the dynamo which provides the fields that manifest as the solar cycle.

4. Different Approaches to Theoretical Modelling of the Phenomenon

A theoretical model of any phenomenon must ultimately satisfy the following primary and auxiliary criteria:

C_1: Consistency with the basic laws of physics (primary),
C_2: Consistency with the relevant well established observations (primary), and
C_3: Consistency with well established theories of other related phenomena (auxiliary).

Depending upon the initial emphasis on C_1 or C_2, three kinds of alternative approaches are possible.

Physical: (Initial emphasis on C_1) - Zero order model is constructed by solving as many equations representing relevant laws of physics as possible.

Semi-phenomenological: (Mixed initial emphasis) - Zero order model is constructed by solving some simpler sub-set of basic equations and replacing other equations by plausible postulates which provide consistency with some important observations.

Phenomenological: (Initial emphasis on C_2)
- Zero order model is itself a minimal set of plausible and mutually consistent postulates having "provisions for consistency" with as many observations as possible.

5. Successes and Failures of Existing Solar Dynamo Models Based on Such Approaches

The following solar cycle dynamo models have so far been attempted from the above approaches:

Phenomenological:

Babcock's model (1961), Piddington's (1971) model.

Semi-phenomenological:

i) Oscillator models: (e.g. Layzer et al. 1979). In these, the equations of continuity, momentum, magnetic non-divergence are solved whereas the energy equation is ignored.
ii) Turbulent dynamo models: (e.g. Parker, 1963; Stix, 1976; Yoshimura, 1979; Krause and Radler, 1980). In these only the equations of magnetic induction and non-divergence are solved whereas equations for continuity, momentum and energy are replaced by assumptions about the convective flows and turbulence.

Physical:

(Gilman and Miller, 1981). All essential MHD equations are solved, except that effects of turbulence are parametrized.

Naturally, the physical models have the least a-priori 'provision for consistency' with the observed behaviour of the solar magnetic field and plasma motions on different scales. However, the importance of these models lies in showing how difficult it is to satisfy both the criteria, C_1 and C_2, and how far away the present modelling atempts are from the ultimate goal of a satisfactory model. The relaxation of criterion C_1 (ignoring the energy equation) in oscillator models has not yielded commensurate success in satisfying the criterion C_2 (cf. Cowling, 1981). The turbulent dynamo models, which further ignore the momentum equation also, are relatively much more successful. Unfortunately, the turbulent dynamo models are open to several doubts and difficulties (e.g. Piddington, 1981; Cowling, 1981) which are summarized in Appendix II.

In the solar dynamo problem, the phenomenological approach is most suitable since the abundance of observational information might be used to identify and isolate most pertinent physical questions for further investigation. Thus, Babcock's model did provide for qualitative agreement with most of the then known behaviour of the solar magnetic fields on length scales $\lesssim R_\odot$ and timescales ~11y (e.g. the polarity and orientation laws of bipolar regions, migrations of fields and butterfly diagrams). One great drawback of the model, however, was that the evolution of three dimensional topology of its magnetic fields - as required to account for the reversal of the global poloidal field was extremely unsatisfactory. In the framework of its own phenomenology, the magnetic buoyancy invoked to bring the toroidal flux ropes to the surface would more probably remove all the magnetic flux from the sun (e.g. Piddington, 1972).

6. An Alternative Phenomenological Approach

An alternative phenomenological approach which I have developed since last several years (Gokhale, 1977, 1979a,b) is intended to retain the advantages of Babcock's model and to eliminate the difficult situation that the magnetic buoyancy might eventually remove all the magnetic flux from the sun. This difficulty will be remedied if some MHD process keeps producing new magnetic flux in the sun on timescales $\lesssim 11$ y, at an average rate needed to balance the loss due to magnetic buoyancy.

6.1. The Timescale of the Most Efficienct MHD Generation of New Magnetic Flux

Magnetohydrodynamical generation of a new magnetic flux implies transfer of energy from the plasma flow to the electromagnetic field at a rate exceeding the ohmic dissipation.

For a flow of velocity $\underline{u}$ transverse to a magnetic field of intensity B_0 the timescale τ of such an energy transfer must satisfy

$$[\rho]\,[u^2]\,[\tau]^{-1} \gtrsim [\sigma]\,[u^2]\,[B^2]$$

i.e.

$$[\tau]^{-1} \gtrsim [\sigma]\,[B^2]\,[\rho]^{-1},$$

where square brackets denote the orders of magnitudes of the bracketed quantities, σ is the electrical conductivity and ρ the density at the place of interaction. It is assumed here that there is no external electric field, so that the mean current density is $\sim \sigma u B_0$. The most efficient energy transfer would imply conversion of a substantial fraction of the flow energy and hence the corresponding timescale will be given by

$$[\rho]\,[u^2]\,[\tau]^{-1} \approx [\sigma]\,[u^2]\,[B_0^2]$$

i.e.

$$[\tau] \approx [\sigma]^{-1}\,[B_0]^{-2}\,[\rho] \qquad (1)$$

6.2. Generation of Magnetic Flux Sheaths and the Resulting Clusters of Strong, Thin Flux Tubes

For conditions near the base of the convection zone ($\sigma \approx 10^5$ emu, $B_0 \approx 3$ G and $\rho \approx 10^{-1}$ gm cm^{-3}), *equation (1) implies:*

$$\tau \approx 10^3\,\mathrm{s}$$

For velocities $u \approx 10^4 - 10^5$ cm s^{-1} (comparable to the velocity of solar rotation), the mean field intensity B_* in the resulting electromagnetic structure will be $\approx 10^4 - 10^5$G and the thickness of the structure will be as small as $\approx 10^7$-10^8 cm. The other two dimensions of the structure will be comparable to the corresponding dimensions of the flow, which will be generally $\gg \delta$. Hence, the newly generated structures will consist of electric current sheaths and associated magnetic flux sheaths. If the dimensions H, $\perp$ to both $\underline{u}$ and $\underline{B}_0$ is $\approx 10^{10}$ cm (density scale height near the base of the convection zone), then the total flux in each magnetic flux sheath will be

$$\Phi \approx B_* H \delta \approx 10^{21}\text{-}10^{23}\ \mathrm{Mx}$$

Each such magnetic flux sheath may be expected to 'crumple' sooner or later, into a 'cluster of flux tubes'. The amount of magnetic flux ϕ in an individual flux tube will be

$$\phi \approx B_* \delta^2 \approx 10^{18}\text{-}10^{21}\ \mathrm{Mx}$$

It is quite interesting to note that for $\underline{u} \approx 10^4$ cm s^{-1} the cluster will have a total magnetic flux $\Phi \approx 10^{21}$ Mx, which is comparable to the flux in a typical sunspot group, and each flux tube in the cluster will have a flux $\phi \approx 10^{18}$ Mx which is comparable to the flux in most of the individual flux tubes observed on the photosphere.

6.3. What kind of MHD flows can attain velocities $\approx 10^4$ cm s^{-1} near the base of of the convection zone?

From energy flux considerations alone, velocities $\sim 10^4$ cm s^{-1} cannot be ruled out for convective flows near the base of the convection zone. However, the corresponding mass flux will imply too high velocities ($\sim 10^7$ cm s^{-1}) near the surface, which are never observed. Hence, convective flows may not have velocities $\sim 10^4$ cm s^{-1} near the base of the convection zone, unless their mass circulation is somehow closed much below the observable layers, which is rather unlikely.

Let us, therefore, consider oscillatory flows like those associated with waves. Out of the three types of waves with $\underline{U} \perp \underline{B}_0$, the slow and Alfvén modes are too slow to yield energy transfer on timescales $\sim 10^3$ s. On the other hand, the fast (i.e. magnetoacoustic modes with wavelength $\sim R_\odot$ do have timescales $\sim 10^3$ s. Among such modes the radially propagating modes cannot have amplitude $\sim 10^4$ cm s^{-1} near the base of the convection zone, since the corresponding radial energy flux would be four orders of magnitudes larger than the total energy flux at the surface. Since the background field is poloidal, the only remaining kind of magnetoacoustic mode $\underline{U} \perp \underline{B}_0$ are the azimuthal ones, and there seems no reason why these cannot attain amplitudes $\sim 10^4$ cm s^{-1}.

6.4. Mechanism for Energizing the Magneto-acoustic Modes Near the Base of the Convection Zone

Near the base of the convection zone, there will be a layer of finite thickness where the temperature gradient is superadiabatic but the superadiabaticity is below the critical value required for large-scale convective instability. In such a layer, the minute fraction of the outward energy flux which cannot be carried further either by radiation or by convection will be "blocked". This blocked flux must go in energizing various waves including the azimuthal magnetoacoustic waves.

6.5. Amount of Energy Required for Wave Amplification Upto 10^4 cm s^{-1}

For building up wave amplitudes $\approx 10^4$ cm s^{-1} the required average value of the blocked energy flux will be only $\sim 10^8$ erg cm^{-2} s^{-1} i.e. only $\approx$ 0.1 - 1% of the total radial energy flux (also comparable to the mean value of the non-radiative flux deposited above the photosphere).

6.6. Locations of Interactions

Conservation of angular momentum requires that the azimuthal MHD modes be generated in pairs of oppositely propagating waves which keep on repeatedly crossing each other at a finite number of longitudes, where the steepest gradients of velocity and magnetic fields would develop. Therefore, it is in the neighbourhood of such longitudes that the non-linear interactions satisfying equation (1) may be localized.

6.7. A Tentative Postulate

On the basis of the foregoing discussion we arrive at the following tentative phenomenological postulate:

Near the base of the convection zone a minute fraction of the outgoing energy generates and amplifies oppositely propagating azimuthal magnetoacoustic waves and these waves produce strong, then, electric current sheaths and magnetic flux sheaths through nonlinear interactions near the meridians where they cross one another. The foregoing postulate remains to be verified by detailed magnetogasdynamical calculations. However, let us assume its validity for the present and proceed to see how one could develop from it a phenomenological model with provisions for agreement with several important observed characteristics of the solar cycle.

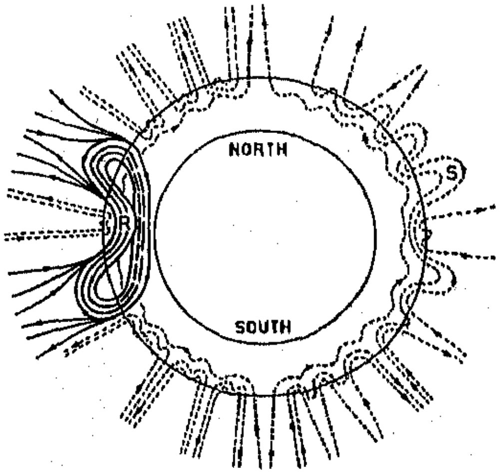

Fig.1. A schematic diagram of the phenomenological model. Thick lines represent one of the several newly created magnetic "flux rolls". Thin lines represent the background magnetic field "S". This background field (S) and the front portions (R) of the newly created "flux rolls" emerge above the photosphere providing two varieties of activity with similar polarities but differing in phase, surface distribution and magnetic flux per active region. Meanwhile the back portions of the flux rolls, represented by dashed lines, diffuse over all latitudes and longitudes to provide the reversed background field for the next cycle.

For convenience of illustration only one newly created flux roll is shown, and no attempt is made to show effects of differential rotation.

6.8. Consequences

6.8.1. Reversal of the Global Field

The newly produced magnetic structures must necessarily be topologically closed. Thus the flux sheaths must be 'flux rolls' and the flux tubes must be 'flux loops'. Therefore, the reversal of the global field on an 11 y time scale can be achieved if: (i) the background field B_0 and the similarly oriented **front** portions of the newly created flux loops rise upto and above the photosphere gradually on a timescale of 11 y and simultaneously; (ii) the **back** portions of these flux loops diffuse in the base layer to provide a background field $\sim(-B_0)$ for the next cycle (Figure 1).

6.8.2. The Two Varieties of Activity

The global field reversal in the above manner would imply that during any 11 y cycle the activity at and above the photosphere will come from segment-by-segment emergence of the following two varieties of flux tubes (segments from both varieties having similar polarities): (1) The thin, frayed flux tubes of the background field which are present at all latitudes and all longitudes and whose current system and field lines are confined to the outer parts of convection zone and the outer space, and (2) The front portions of the newly produced thick clusters of flux tubes which are present predominently in the central latitudes and neighbourhoods of a few preferred longitudes, and whose current system and field lines are closed near the base of the convection zone. The first variety of segments will, in general, emerge earlier than the latter.

Thus, the model of the field reversa automatically provides two varieties of solar activity with the surface distributions and relative phases similar to the x-ray bright point and sunspot related solar activity. Schüssler (1980) presented a model based on a similar modulation of the thickness of flux tubes responsible for the activity without entering into the question of how the magnetic flux tubes are produced. However, in his model thicker flux tubes rise earlier which seems to contradict the fact that each new cycle starts with appearance of the smallest spot groups (e.g. Gokhale and Sivaraman, 1982).

6.8.3. The Background Magnetic Flux and the Activity Related Magnetic Flux

Since the magnetoacoustic waves of amplitudes $\sim 10^4$ cm s^{-1} are expected to produce magnetic flux rolls of $\sim 10^{21}$ Mx each, the maintenance of the order of magnitude of the background magnetic flux requires that such a production occurs only once during each ~ 11 y or so, (e.g. in association with some catastrophic transformation of the wave) if the azimuthal wave number of the wave is $\lesssim 10$. In such a case ('catastrophic model') each flux roll will have to emerge in $\sim 10^2 - 10^3$ segments in order to account for the ratio of that order between the activity related flux and the background flux. If the required amplification is provided by the differential rotation as in the Babcock's model, then it will also account for the polarity orientations as in that model.

Alternatively, if the magnetic flux rolls are produced during each wave period ('persistent production model') then the amount in the flux rolls and the rate of their emergence must vary during the 11 y cycle in such a way that the order of magnitude of the background flux is maintained and the number of segments give the right amount of the activity related flux.

These details are yet to be worked out.

6.8.4. Migrations of Large-scale Fields

The emergence of the 'front' portions and the diffusion of the 'back' portions of the newly created fields will lead to poleward migration of the following polarities in the photospheric field along with the neutral lines separating these polarities from the background field (e.g. Howard, 1974; Makarov, et al. 1982; Makarov and Sivaraman, 1983).

6.8.5. Variations of the Sizes and Locations of the Long Lived Coronal Holes and Relations Between the Decline of One Solar Cycle and the Amplitude of the Next Cycle

During the declining years of the sunspot cycle the photospheric intersections of the new magnetic structures will provide deep rooted, monopolar, open field structures at middle latitudes which might account for the occurrence of long lived coronal holes at such latitudes during the declining phase of the solar cycle.

Ultimately, towards the end of the solar cycle, these structures will yield monopolar regions of the reversed polarity near the poles.

6.8.6. The Values of the Period

The period of the solar cycle in such a model will be ultimately determined by the timescale of modulation of the rate of energy trapping near the base of the convection zone. As an illustration it has been shown earlier (Gokhale, 1977) that a value of ~ 11 y can be obtained (for a 'catastrophic model') by assuming a turbulent viscosity $\sim 10^{11.5}$ cm^2 s^{-1}.

6.8.7. Modulation of the Amplitude of the Cycle

Under 'normal' circumstances a relatively steady cycle may be maintained by an approximate balance among the rates of the following processes: (i) production of magnetic flux near the base of the convection zone, (ii) the rise of flux tubes across the convection zone, (iii) migration and diffusion of magnetic flux across the surface and (iv) the removal of magnetic flux by magnetic buoyancy, reconnections and solar wind. Excursions to and from 'abnormal' conditions like Maunder minima might be caused by some non-linear couplings between these processes.

7. Conclusions

I may conclude by saying that the theory of the solar dynamo is far from the final solution of the problem, although the semi-phenomenological turbulent dynamo models and the fully phenomenological new approach described here continue to be the most promising approaches.

The new phenomenology based on the postulated production of thin electromagnetic structures by locally non-linear interactions of magnetogasdynamical modes provides for agreements with many observed features of the solar cycle on timescales $\lesssim 22$ y. However, it cannot be considered as an established model till the basic postulate is verified by mathematical solution of the relevant magnetogasdynamical equations, and the parameters of the solution are shown to vary on timescales > 22 y in a way consistent with the observationally derived behaviour of the solar cycle on such timescales. The dilemma of catastrophic versus continuous production of new field also needs to be resolved.

Appendix I

OBSERVATIONAL CONSTRAINTS

Magnetic Cycle (Timescales $\lesssim 22$ y):

1. Reversal of poloidal ($\sim 10^{23}$Mx) and toroidal fields after about every ~11 y or so.
2. Phase of the reversal: ~ 1-2 y after sunspot maximum.
3. Poleward migrations of 'f' polarities and magnetic neutral lines (filament channels).

Sunspot Activity Cycle (Timescales $\lesssim 11$ y):

4. Periodicity in sunspot abundance with a period ~ 11 y (Historically the first 'solar cycle phenomenon' discovered).
5. Total flux: $\sim 10^{24} - 10^{25}$Mx.
6. Distribution:
   a) central latitudes ($\lesssim 40°$)
   b) preferred longitudes (?)
   c) butterfly diagrams
7. Properties of the 'unit' of activity (viz. a spotgroup):
   a) polarity laws
   b) orientation laws
   c) typical flux $\sim 10^{21}$ Mx

EAR and XBP Activity Cycle (Timescale $\lesssim 11$ y):

8. Periodicity in Ephimeral Active Regions (EARs) and X-ray Bright Points (XBPs) with periods ~ 11y.
9. Phase:
   a) similar to sunspot cycle for EARs
   b) opposite for XBPs
10. Total Flux:
    $10^{25} - 10^{26}$ Mx
11. Distribution:
    a) all latitudes (pole-to-pole)
    b) no preferred longitudes (except the tendancy to avoid those occupied by spot activity)
12. Properties of the unit of activity (EAR/XBP)
    a) polarity random but often turning to normal for EARs
    b) typical flux $\sim 10^{18} - 10^{19}$Mx

Magnetic field behaviour on smallest and medium scales length scales < R:

13. 'flux tubes' with B ~10[illegible]G; flux $\sim 10^{17} - 10^{18}$Mx.

14. Clustering in active regions (upto $\sim 10^{22}$ Mx; typical 10^{21} Mx)
15. 'Down flows' (?) total mass supply $10^{26.5}$ gms per cycle.

Coronal Behaviour on Timescale

16. Variation of the shape and size of the corona with sunspot cycle.
17. Variation in abundance, location and sizes of coronal holes (e.g. from geomag. data)

Flows and Differential Rotation (length-scale $\lesssim R_0$):

18. Two varieties of differential rotation of magnetic structures.
19. Variation between the two with the phase of the cycle.
20. Torsional oscillations in the photospheric plasma rotation.

Timescale $\lesssim$ 22 y:

21. Relations between $(N)^{th}$ & $(N+1)^{th}$ cycle (e.g. from geomag. data)
22. Rise amplitude relations.

Timescale $\gtrsim$ 22 Y:

23. Modulation on timescales ~ 88 y.
24. Maunder minima and resurrection there from.

Long Term Behaviour:

25. Long time scale stability upto ~ 700 millioniums ago.

Appendix II

TURBULENT DYNAMO MODELS HAVE ACHIEVED AGREEMENT WITH MANY OBSERVATIONS. THEN WHY IS THE DYNAMO PROBLEM STILL UNSOLVED?

1. Agreements with observations are not from a single set of input parameters.
2. First order smoothening approximation requires $|B'| < |\bar{B}|$. But observed thin strong flux tubes imply $|B'| \approx |\bar{B}|$ if the tubes are densely packed (in which case Lorentz-forces cannot be neglected) and $|\bar{B}| > |B'|$ otherwise. Here $\bar{B}$ is the ensemble average and B' is the random part of the field.
3. Another basic assumption $\lambda >> \langle v \rangle \tau$ is not valid for the observed turbulence (Here λ is correlation length, $\langle v \rangle$ is r.m.s. velocity of turbulence, τ is correlation time).
4. No way of removing the small scale fields produced at the boundaries of the eddies.
5. Requires $d\omega/d\tau < 0$. True near top of convection zone. But buoyancy removes the field completely (if at the base of convection zone where $d\omega/d\tau > 0$ for stability, then α effect is < 0). (Here ω is angular velocity of rotation).
6. When the dynamics is introduced, the field either grows indefinitely or contradicts migrations (butterfly diagrams) and the differential rotation (Gilman and Miller, 1981).

TURBULENT DYNAMO THEORY CANNOT BE SAID TO HAVE SOLVED THE DYNAMO PROBLEM. CONTINUATION OF THINKING ON ALTERNATIVE APPROACHES IS JUSTIFIED AND MAY EVEN BE NECESSARY.

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DISCUSSION:

GOPALSWAMY: Knowing the set of observations and the parameters to be introduced, can one do an optimization?

GOKHALE: So far even the set of parameters has not been uniquely identified, and hence the question of the optimization of values does not arise. Turbulent dynamo experts must be working towards the final choice.