Physics of the Solar Cycle : New Views
K. M. Hiremath

Indian Institute of Astrophysics, Bangalore-560034, India, E-mail : hiremath@iiap.res.in

Abstract

With the recent overwhelming evidences that solar cycle and activity phenomena strongly influence the earth’s environment and climate (Hiremath 2009a and references there in), it is necessary to understand physics of the solar cycle and activity phenomena. Genesis of the solar cycle and activity phenomena—one of the major unsolved problem in solar physics—remains elusive to the solar community. Presently there are two schools of thoughts viz., turbulent dynamo and MHD oscillation mechanisms that explain the solar cycle and activity phenomena. Both the mechanisms are critically examined and fundamental difficulties are presented. By keeping in mind the more advantages of having MHD oscillation mechanism, compared to the turbulent dynamo mechanism, following new ideas on the genesis of the solar cycle and activity phenomena are presented. Inevitability of most likely existence of a combined steady poloidal and toroidal magnetic field structure in the solar interior. Owing to suitable steady poloidal field structure, Alfven wave perturbations of long periods (∼ 22 yrs) that excite in the solar core travel first to the poles in both the hemispheres and later reach the equator. While traveling towards the surface, Alfven wave perturbations along the weak poloidal field structure in turn perturb the embedded strong toroidal field structure producing sunspots, especially in the convective envelope, that travel to the surface due to buoyancy along isorotational contours. With realistic density structure of the solar interior, computation of Alfven wave travel times along different field lines of the poloidal field structure (Hiremath and Gokhale 1995) yields almost similar periods (∼ 22 yr) explaining the constancy of 22 yr period of the odd degree modes obtained from the Spherical Harmonic Fourier analysis of the surface magnetic field. The observed quasi-periodicities of solar activity indices in the range of 1-5 years are explained due to perturbation of the strong toroidal field structure and, variation of very long period solar cycle and activity phenomena such as the Maunder and grand minima is explained to be due to coupling of long period poloidal and toroidal MHD oscillations.
1 Introduction

Since the discovery of sunspots by Galileo, the physics of solar cycle and activity phenomena is not understood completely. There are two schools of thoughts—turbulent dynamo and MHD oscillatory mechanisms—on the genesis of the solar cycle and activity phenomena. Although turbulent dynamo models explain qualitatively many of the observed solar cycle and activity phenomena, there are several difficulties and limitations in their application to the solar cycle (Piddington 1971; 1972; 1973; Cowling 1981; Levy 1992; Vainstein and Cattaneao 1992; Hiremath and Gokhale 1995 and references there in; Hiremath 2001 and references there in). In this talk, I revisit MHD oscillatory theory and show with new ideas that many of the observed solar cycle and activity phenomena can be explained.

In section 2, I briefly summarize the important observations related to solar cycle and activity phenomena. In section 3, both the turbulent dynamo mechanism and MHD oscillatory theory of the solar cycle are critically examined. Salient features of Alfvén theory on the solar cycle are presented in section 4. In section 5, new views on the genesis of the solar cycle and activity phenomena are proposed and important observations of solar cycle and activity phenomena are explained. The conclusions of this study are given in section 6.

2 Summary of the Observations

2.1 Solar 11 Year Cycle and Grand Minima

Variation of occurrence of the sunspots over the surface of the sun with an average periodicity of \( \sim 11 \) years is termed as "sunspot cycle". The length of sunspot cycle also varies between 9 to 12.5 years (Zwan 1981; Hiremath 2008a). Although sunspot activity appears to be fairly regular (Dicke 1978; Hiremath 2006 and references there in), during the period from 1645 to 1715, there was the dearth of sunspots and is called the Maunder minimum type of solar activity. Sun might have witnessed such grand minima of solar activity during its previous evolutionary history.
2.2 Solar 22 Year Magnetic Cycle

Soon after the discovery of strong magnetic fields in sunspots, Hale (1908) discovered that majority of the leading bipolar spots in the northern hemisphere have the same polarity, whereas in the southern hemisphere they are of the opposite polarity. These opposite polarities in both the hemispheres will reverse during the next cycle. Thus the period of the solar magnetic activity cycle is twice as that of a sunspot cycle and this phenomenon is called "22 year solar magnetic cycle".

2.3 Sunspot Butterfly Diagram

The sunspots’ occurrence in a particular latitude belt varies between nearly 40° north-40° south of the equator. During the beginning of a solar cycle, sunspots of a new cycle appear at the higher latitudes. As the cycle progresses, the occurrence of sunspots drift towards the solar equator from the higher latitudes of both the northern and southern hemispheres constituting so called the sunspot butterfly diagram.

2.4 Spherical Harmonic Fourier Analysis of Magnetic Activity

Spherical harmonic Fourier (SHF) analysis (Stenflo and Vogel 1986; Stenflo 1988; Knack and Stenflo 2005) of magnetograms and inferred magnetic field (Gokhale, Javaraiah and Hiremath 1990; Gokhale and Javaraiah 1992) from the sunspots data show that the axisymmetric global oscillations with specific periods (∼ 22 yr and smaller) do contribute predominantly to the evolution of the large-scale photospheric magnetic field. The power spectra of these data show that the odd and even parity modes behave differently. All the odd parity modes have same periodicity of ∼ 22 years and the frequency of even parity modes increases with degree $l$ that is almost similar to the observed helioseismic $p$ mode spectrum.
3 Theoretical Models of the Solar Cycle

In case of the sun, the diffusion time scale of large-scale global magnetic field structure is \( \sim \) few billion years, i.e., greater than the sun’s age itself. Hence the sun is expected to retain some of its primordial magnetic field structure (Hiremath and Gokhale 1995 and references therein) and varies on time scale much larger than the dynamical time scale. Hence it is easy to understand the existence of observed magnetic field structure, if it were found to be steady with time. However, the large-scale field observed at the surface varies in a cyclic manner with time scales of \( \sim \) decades. Thus one has to seek the theoretical framework that not only incorporates the maintenance of magnetic field structure but also its periodic behavior. That means one needs some sort of a dynamo mechanism that maintains electromagnetic field against dissipation at the cost of energy provided by some source-in the interior of the sun.

Presently there are two main schools of thoughts on the modeling of solar cycle: (i) Turbulent dynamo mechanism and, (ii) MHD oscillatory theories.

3.1 Theory of Dynamo Mechanism

These theories are based on the fact that moving conductors generate electric currents due to electromagnetic induction. It is therefore expected that in the sun the flows like rotation and convection could provide dynamo action through electromagnetic induction. However, all the velocity fields cannot maintain the dynamo. For example, according to Cowling’s (1934) theorem, steady axisymmetric magnetic fields cannot be maintained by axisymmetric flows. Thus the dynamos for sun-like stars ought to be either non-axisymmetric or non-stationary (or both).

In this mechanism, the dynamo effect is statistically averaged over the turbulent flows. The velocity \( \mathbf{u} \) and the magnetic field \( \mathbf{B} \) of the plasma are expressed as sums of mean part \( \langle \mathbf{u} \rangle \) and \( \langle \mathbf{B} \rangle \)-large-scale and slowly varying terms) and the fluctuating parts \( \mathbf{u}' \) and \( \mathbf{B}' \)-small scale and rapidly varying terms). With certain assumptions and approximations, the final equation that governs the spatio-temporal variation of the average magnetic field is of the form

\[
\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \text{curl}[\alpha \langle \mathbf{B} \rangle + \langle \mathbf{u} \rangle \times \langle \mathbf{B} \rangle] - \text{curl}[(\eta + \beta)\text{curl} \langle \mathbf{B} \rangle]
\] (1)
where $\alpha$ is helicity and $\beta$ is diffusivity due to turbulence and $\eta$ is electromagnetic diffusion.

Further, the mean field components ($\langle B \rangle$ and $\langle u \rangle$) are written in terms of the poloidal (magnetic field $B_\rho$ and velocity, i.e., meridional flow) and the toroidal (magnetic field $B_\phi$ and the angular velocity i.e., $\Omega$) components leading to two equations containing $\alpha$, $\beta$ and $\eta$ as the free parameters. If one knows the internal rotation $\Omega$ and the meridional velocity, with specifying free parameters, in principle, one can evolve two equations and one can reproduce the solar butterfly diagrams (Hiremath and Lovely 2007 and references there in). These dynamo models are called “kinematic dynamo models”.

Initially, a mechanism for the production of sunspots was proposed by Cowling (1953), who suggested that sunspots are eruptions of submerged toroidal fields produced by the differential rotation acting on a weak poloidal field. Subsequently, Parker (1955) proposed that the poloidal field itself is regenerated by the interaction between cyclonic convection and buoyantly rising toroidal flux elements. Incorporating these ideas, Babcock (1961) phenomenologically modeled the solar cycle. Leighton (1964, 1969) presented a semi-empirical model of the solar cycle and reproduced the well known sunspot butterfly diagram. Recently we have excellent reviews (Charbonneau 2005; Dikpati 2005; Brandenburg and Subramanyam 2005; Solanki, Inhester and Schussler 2006; Hiremath and Lovely 2007 and references there in; Choudhuri 2008) on the solar dynamo mechanism.

3.1.1 Difficulties in the Turbulent Dynamo Models of the Solar Cycle

Though the turbulent dynamo models of the solar cycle reproduced elegantly the properties of the solar cycle and activity phenomena, the models plague with many fundamental difficulties (Hiremath 1994 and references there in; Hiremath 2001 and references there in; Petrovay 2000; Hasan 2008; Venkatakrishnan and Gosain 2008; Choudhuri 2008; Nandy 2009) and few of them are presented in the following.

- The “first order smoothening approximation” used for the derivation of the induction equation is valid only when the fluctuating field is very much smaller than the mean field. This is possible only when (a) the
eddy magnetic Reynolds number $R_m$ is $<<1$, and (b) the correlation time $\tau$, the eddy of length $\lambda$, and the r.m.s velocity $v$ are related as $\tau << \lambda/v$. In reality, neither of these conditions is valid on the sun where $R_m >> 1$ and $\tau \sim \lambda/v$.

- According to Piddington (1971; 1972; 1973): (a) the concept of turbulence of the solar magnetic field is unsound; turbulence may mix magnetic elements but does not destroy large-scale magnetic fields. In fact recent MHD simulations (Brun et al. 2004; Stein and Nordlund 2006; Jouve and Brun 2007; Bushby et al. 2008; Steiner et al. 2008; Miesch and Toomre 2009 and references there in) of the convective envelope substantiate the Piddington’s ideas; (b) the field created by the eddy motions would be mainly turbulent field, unlike the field that is actually observed; (c) the field created during successive cycles would rise successively to higher levels and the whole field would eventually leave the sun.

- Except the previous study of Brandenburg (1988) that possibly explains the diagnostic power spectrum of the even degree modes of the SHF analysis (Stenflo and Vogel 1986) of magnetic field, so far, no dynamo mechanism explains the constant power of 22 years in the odd degree modes whose superposition represents the large-scale solar cycle and activity phenomena (Stenflo 1988; Stenflo and Gudel 1988; Gokhale and Javaraiah 1992).

- The values of parameters $\alpha$, $\beta$ and of the rotational shear are either arbitrarily chosen or estimated crudely from the statistical properties of the observed motions. In order to reproduce sunspot butterfly diagrams, dynamo models require substantial increase of rotational profile from surface to the interior contradicting the rotational profile as inferred by the helioseismology (Hiremath 1994; Hasan 2008).

- Within the framework of kinematic dynamo models, it is impossible to address the question of limiting amplitude of generated magnetic flux owing to linearity of the induction equation.

- One of the fundamental problem in keeping the solar dynamo in the convection zone is buoyant rise of all the flux on time scales very much
smaller than the solar cycle period. This difficulty can be avoided if the dynamo process is operating in a stably stratified region beneath the solar convection zone. However, as pointed out by the previous studies (De Luca and Gilman 1991; Hasan 2008), the process of dynamo mechanism operating beneath the solar convection zone could add some other serious difficulties. For example, how the magnetic flux injected into the convection zone is a question.

- In order to reproduce proper solar butterfly diagrams (Hathaway et al. 2004) and predict future solar cycles, the flux transport dynamo models (Nandy and Choudhuri 2002; Dikpati and Gilman 2006; Choudhuri, Chatterjee and Jiang 2007) require the meridional circulation that needs to penetrate below base of the convective envelope. However, recent studies (Gilman and Miesch 2004; Svanda, Kosovichev and Zhao 2007; Hiremath 2008b) conclude that owing to high density stratification and strong ($\sim 10^4$ G) toroidal magnetic field structure, it is very unlikely that the return flow will reach the surface with a period of solar cycle.

3.2 Theory of MHD Oscillations

In the electrically conducting magnetized plasma, there are three kinds of MHD (magnetohydrodynamic) waves, viz., (i) Alfven wave, (ii) slow MHD wave and, (iii) fast MHD wave.

Since the sun is such a dynamic body that always disturbances in the medium exist. Such disturbances perturb the magnetic field structure leading to generation of Alfven waves. Alfven waves are of two types (Priest 1981), viz., shear Alfven waves due to incompressibility and compressible Alfven waves due to compressibility. The shear Alfven waves are transverse waves that travel along the field lines, where as the compressible Alfven waves consist of both longitudinal and transverse waves. Since the time scales of compressible waves ($\sim 5$ min) due to density perturbations are very much smaller than the solar cycle time scales ($\sim 22$ yrs), the condition of incompressibility applies and shear Alfven waves are best suited for the present study.

Observed periodic behavior of the large-scale magnetic field structure of the sun is viewed as a consequence of MHD (magnetohydrodynamic) oscil-
lations in the presence of a large-scale steady (diffusion time scale ≈ billion years) magnetic field structure. These theories recognize the fact that most of the observed fields at the surface (including those in the polar regions), are in the form of bipolar regions. The MHD oscillations must be azimuthal perturbations of ambient steady poloidal magnetic field structure. The amplification of the toroidal field can results from the azimuthal perturbations of the ambient steady poloidal magnetic field. Any such perturbations of the field lines would eventually lead to MHD waves. The waves travel along the field lines of the steady poloidal field structure and are reflected due to density gradients near the surface. Superposition of these traveling waves lead to stationary or standing oscillations. The strong fields needed for activity result from the constructive interference of these waves.

For an axisymmetric magnetic field structure and in cylindrical geometry, the MHD wave equation (Mestel and Weiss 1987) is given by

\[ \frac{\partial^2 \Omega}{\partial t^2} = \frac{B_p^2}{4\pi \rho} \frac{\partial^2 \Omega}{\partial s^2} \] (2)

where \( \Omega \) is angular velocity, \( B_p \) is poloidal component of the steady magnetic field structure and \( \rho \) is the density of the ambient plasma. In addition we have a similar equation by replacing \( \Omega \) by \( B_\phi \). These two equations imply that the changes in either \( \Omega \) or \( B_\phi \) propagate with the local Alfven speed 

\[ V_A = \frac{B_p}{\sqrt{4\pi \rho}} \] 

determined by the steady poloidal field structure. Since the perturbations are in the azimuthal direction, such a wave equation is called torsional MHD wave equation. In fact, in the following subsection, we use this equation for checking the admissibility of global torsional MHD oscillations in various models of the steady magnetic field structures in the solar interior.

Alfven (1943) and Walen (1949) were the pioneers to propose this theory and latter their ideas were revived by many authors (Layzer et. al., 1955; Plumpton and Ferraro 1955; Piddington 1976; Layzer et. al., 1979, Vandakurov 1990; Hiremath 1994; Hiremath and Gokhale 1995). In the following, first we revisit Alfven’s seminal work on the theory of solar cycle and also present the fundamental difficulties.
4 Alfven’s Theory of Solar Cycle

In his seminal work, Alfven (1943) assumed that: (i) the sun consists of large-scale dipole magnetic field structure in the interior whose magnetic axis coincides with the rotation axis, (ii) a magnetic disturbance somewhere else in the deep interior travels with Alfven speed $V_A$ along the field lines and reach the surface, (iii) excitation of MHD waves is due to turbulence that is created by the differences in the velocity gradients of the isorotational contours and, (iv) coupling between neighboring field lines expected to transfer the oscillations towards all parts of the sun.

For a polytropic density variation, and for the dipole magnetic field structure with a dipole moment $\sim 4.2 \times 10^{33}$ G cm$^3$, Alfven computed the travel times along different field lines and found that $\sim 70$ years for the field lines near the pole, and $\sim 80$ years for the field lines near the equator. Since these periods did not agree with the 22 year period, he concluded that the 22 year period must be the resonance period of some lines of force in the interior. In addition, Alfven’s theory also explained the observed propagation of sunspot zones and opposite polarities of the sunspots.

Alfven computed dependence of the sunspot frequency with respect to latitude and found almost similar results as that of observation. By the theory of standing oscillations along different field lines, Alfven explained the observed fact that during a particular cycle the sunspots in both the hemispheres have opposite polarities. Assuming that the perturbations in the interior are irregular, he made an attempt to explain the long period sunspot activity.

4.1 Difficulties in the Alfven’s theory of Solar cycle

Though Alfven’s theory appears to explain most of the observations of the solar cycle and activity phenomena, following are important difficulties: (i) assumed polytropic density stratification and magnetic dipole field structure that has a singularity near the center are unphysical, (ii) computed period for the one hemisphere is $\sim 40$ years, nearly four times the period of the sunspot cycle; independent of Alfven’s work recently Davila and Chitre (1996) also computed the travel times for the assumed radial field and obtained the travel time of $\sim 300$ years for the fundamental mode, (iii) although origin of sunspots is proposed to be due to superposition of long period oscillations,
more observational and theoretical inferences are needed, (iv) intensity of 
the sun’s apparent dipole field is assumed to be $\sim 10^3$ G contradicting the 
observations ($\sim 1$ G), (v) it is not clear how the random perturbations lead to 
dearth of sunspot activity, similar to Maunder minimum, (vi) if one accepts 
the Alfvén’s model of magnetic field structure in the solar interior, it is 
not possible to reproduce important result (odd degree parity modes have 
constant period of 22 years) from the SHF analysis of the observed surface 
magnetic field (Stenflo and Vogel 1986; Knack and Stenflo 2005) and the field 
inflected from the sunspots (Gokhale, Javaraiah and Hiremath 1990; Gokhale 
and Javaraiah 1992). All the afore mentioned difficulties of Alfvén’s theory 
suggest a suitable geometrical magnetic field structure with proper intensity 
in the solar interior.

5 New Ideas on physics of the Solar Cycle

Firstly, we have to admit that MHD oscillatory theories have the following 
three main difficulties: (i) the lack of observational evidence of magnetic 
field structure of primordial origin, (ii) difficulty in believing that such a 
perturbed poloidal field structure of weak general magnetic field ($\sim 1$ G) can 
produce sunspot activity of strong magnetic field ($\sim 10^3$ G), (iii) owing to 
strong dissipation in the convective envelope, long period ($\sim 22$ years) MHD 
oscillations can not be maintained for the next cycle.

5.1 Existence of a combined Poloidal and Toroidal Magnetic Field Structure in the solar interior

Likely existence of large-scale poloidal magnetic field structure can be 
confirmed from the white light pictures (see the Fig 1 of Ambroz et.al. 2009; 
Pasachoff 2009; see the Fig 3 and 8 of Pasachoff et al. 2009) during total 
solar eclipse around solar minimum. Though direct observational measure- 
ments of such a large-scale weak magnetic field ($\sim 1$ G) are lacking, indirectly, 
from the helioseismic rotational isocontours we (Hiremath 1994; Hiremath 
and Gokhale 1995) proposed a most likely poloidal magnetic field structure 
of primordial origin in the solar interior.

Observations show that strength of the poloidal field is very weak ($\sim 1$ G) 
compared to the strength of rotation, hence the poloidal field must isoro-
tates with the internal rotation of the plasma. This implies that geometrical poloidal field structure must be similar to the geometrical structure of the internal isorotational contours as inferred from the helioseismology. In fact it is true for the rotational isocontours (as inferred from the helioseismology) in the convective envelope where inferred rotational isocontours are reliable. In previous study and by using Chandrasekhar’s MHD equations, we (Hiremath 1994; Hiremath and Gokhale 1995) modeled the steady part of the poloidal field structure and found the diffusion time scale to be \( \sim \) billion years. Gough and McIntyre (1998) also have proposed the inevitability of such a poloidal field structure in the radiative interior. With reasonable assumptions and approximations and, by using MHD equations, we (Hiremath 2001) consistently obtained solution for both internal rotation and toroidal component of the magnetic field structure in the convective envelope. The toroidal field structure in the convective envelope has a quadrupole filed like geometric structure and the field strength varies from \( \sim 10^4 \) G near base of the convection zone to \( \sim 1 \) G near the surface. For the sake of stability (Mestel and Weiss 1987; Spruit 1990; Braithwaite and Spruit 2004), such a combined poloidal and toroidal field structure is necessary in the solar interior.

Hence, the sun may be pervaded by the combination of large-scale steady poloidal and toroidal magnetic field structures (both of which may of primordial origin and diffusion time scales are \( \sim \) billion years). If one accepts the existence of such a combined field structure, the first difficulty in MHD oscillatory theory can be removed.

5.2 Genesis of the Solar Cycle and Activity Phenomena

The second difficulty of the oscillatory model can be removed as follows. Following Alfven (1943), any perturbations near the center travel along and perpendicular to the poloidal field structure and, coupling between neighboring field lines transfer the perturbed energy to all parts of the sun. The interesting property of the shear Alfven waves is that the magnetic and velocity perturbations are perpendicular to the magnetic field lines and travel along the field lines. That means the Alfven waves while traveling along the field lines perturb in turn the neighboring field lines. If one believes that the sun has a magnetic field structure similar to one proposed by Hiremath and
Gokhale (1995), then the field lines that pass through north and south poles (the field line represented by ‘A’ in Fig 1 of Hiremath and Gokhale (1995)) in both the hemispheres experience the Alfvén wave perturbations first and the field lines that are close to the equator (the field line represented by ‘L’ in Fig 1 of Hiremath and Gokhale (1995)) experience the Alfvén wave perturbations later. Thus there is a phase lag of $\pi/2$ radians between the polar and equatorial solar activities. This reasoning that Alfvén wave perturbations reach first poles and then equator is consistent with analysis of the sunspot butterfly diagrams (Pelt et al 2000), the observations of torsional oscillations on the surface (Howard and La Bonte 1980; Komm, Howard and Harvey (1993)), theoretical (Hiremath 1994) and helioseismic inferences (Zhao and Kosovichev (2004); Antia, Basu and Chitre (2008) and, in the atmosphere (Altrock, Howe and Ulrich 2008).

Perturbations of the poloidal field structure in the convective envelope in turn perturbs the embedded toroidal field structure and, superposition of many such azimuthal perturbations attains a critical strength leading to formation of the sunspots and due to buoyancy raise along the isorotational contours and reach the surface. For example, if one accepts the existence of such a steady part of toroidal magnetic field structure with a strength $B_\phi$, then perturbations result in creation of MHD waves whose amplitudes are $\sim \delta B_\phi$. Superposition of many such MHD waves in turn leads to constructive interference and form the sunspots and, erupt towards the surface along the isorotational contours. As for the reversal of polarity, once sunspots are formed, they raise towards the surface in a particular latitude belt due to buoyancy and meridional flow transports the remnant of the flux on the surface towards the poles and change the sign.

Due to turbulence in the convective envelope, the amplitude of the Alfvén wave perturbations that travel along the poloidal field (isorotational contours) will be considerably reduced near the surface. That means there is a need of constant forcing for every 22 years near the center. Hence, it is not surprising that the resulting 11 year solar cycle and activity phenomena on the surface can be considered as a forced and damped harmonic oscillator (Hiremath 2006). In this way the third difficulty of theory of MHD oscillations can be removed.
5.2.1 Implications for the combined poloidal and toroidal field structure

Some other consequences of having such a steady toroidal magnetic field structure in the convective envelope are: (a) perturbations to the thermal sound speed in the solar interior that contributes to splitting of the even degree \( p \) modes (Basu 1997; Antia, Chitre and Thompson 2000; Antia 2002); (b) explanation for the recent discovery of ubiquitous horizontal magnetic field structure in the quiet-sun internetwork regions pervading everywhere in the photosphere as detected by Hinode satellite (Jin, Wang and Zhou 2009; Wijn et. al. 2009 and references there in; Tsuneta et. al. 2009; Lites et. al. 2008; Lites et. al. 2009) and ground based telescope (Lites et. al. 1996; Beck and Rezaei 2009); (c) Alfvénic perturbations of the poloidal field structure (Hiremath 1994; Hiremath and Gokhale 1995) should yield the periods around 22 years and of the toroidal field structure should yield the periods around 1-5 years.

5.2.2 Physics of the 1-5 year quasi periodicities

As for the steady toroidal field structure, the periods are computed from the relation \( \tau \sim \frac{L}{V_A} \), where \( \tau \) is the period of oscillations, \( L \) is length scale of the field lines and \( V_A \) is the Alfvén velocity. In case of the toroidal field structure, the length \( L \) is considered to be \( \sim 2\pi r \), where \( r \) is the radius of the ring along the azimuthal direction. For example, at radius of \( 0.1R_\odot \), perturbation of the ring of toroidal field structure with a intensity \( 10^5 G \) (and density of \( \sim 150 \text{ gm/cm}^3 \)) yields the period of \( \sim 5 \) years. If we accept the model (Hiremath 2001) of steady part of toroidal field structure (with a intensity \( \sim 10^4 G \) near base of the convection zone and \( \sim 1 G \) near the surface) in the convective envelope and by taking the typical density values, the period of the oscillations vary from \( \sim 1.3 \) years near base of the convective envelope to \( \sim \) of few months near the surface. These physical inferences imply that as the Alfvén wave perturbations travel along different field lines (or along different isorotaional contours) of poloidal field structure and reach the surface from pole to equator, one would expect periodic phenomena at a particular latitude zone on the surface that is connected with periodic phenomena at a particular radius in the solar interior. To elaborate further, from the above inferences and with the poloidal field structure (between
the field lines zone represented by the symbols A-C of Fig 1 of Hiremath and Gokhale 1995), one would expect near 5 year periodic phenomena, that originate in the beginning of solar cycle and at radius of $0.1 R_\odot$, should occur at the higher latitude zones. Similarly near 1.3 yr periodic phenomena that occur near base of convection zone (between the field lines zone represented by the symbols I-J of Fig 1 of Hiremath and Gokhale 1995) travel along the field lines and reach the surface around solar cycle maximum and in the 20-25 deg latitude (or 70-75 deg colatitude) zone on the surface. To conclude of this subsection, in addition to 11 yr periodicity in both the hemispheres, near 5 and 1.3 yr periodicities should occur during certain phase of the solar cycle. From the observed periodic analysis of different solar activity indices, let us examine in the following whether conclusion of this subsection is right or wrong.

Observations show that near 5 and 1.3 yr periodicities are indeed quasi-periodic and occur at different epochs (or at different latitude zones on the surface) of the solar cycle. For example near 5 quasi-periodicity is detected in the high latitude zones (Vecchio and Carbone 2009 and references there in). Although near 11 yr periodicity is dominant in the analysis of high latitude filaments (Li et. al. 2006), near 5 yr periodicity has a very low spectral power in their analysis.

As for near 1.3 yr periodicity, it is detected in the sunspot data (Krivova and Solanki 2002), in the photospheric mean rotation (Javaraiah and Komm 1999; Javaraiah 2000), in the magnetic fields inferred from H-alpha filaments (Obridko and Shelting 2007), in the large-scale photospheric magnetic fields (Knaack, Stenflo and Berdyugina 2005), in the green coronal emission line (Vechhio and Carbone 2009) and in the occurrence of coronal mass ejections (CME) (Hiremath 2009b). Spherical harmonic Fourier analysis (Stenflo and Vogel 1996; Knaack and Stenflo 2005) of magnetograms taken over 22 years shows the combined powers for the period of 22 years (due to a weak poloidal field $\sim 1$ G (Stenflo 1994)) and 1-5 years (due to a strong toroidal field of strength $\sim 10^4 - 10^5$) respectively. From the helioseismic data, 1.3 yr periodicity is detected near base of the convection zone (Howe, et. al., 2000; Howe 2009). However, using same helioseismic data, Antia and Basu (2000) conclude that there is no 1.3 yr periodicity near base of the convection zone. Further analysis of Basu and Antia (2001) shows somewhat similar period as reported by Howe et al. (2000) but did not consider it to be significant. Interestingly, as expected by this study, analysis of post-2001 data (Toomre et al.,
2003; Howe et al., 2007; , see Figure 32 of Howe 2009) shows the disappearance of 1.3 yr periodicity. Some more such data analysis are required in order to confirm the physical inference of this study that 1.3 yr quasi-periodicity (that occurs around solar maximum) is the result of periodic disturbances near base of the solar convective envelope.

5.3 The Nature of Drivers

In order to maintain the 22 yr oscillations for each solar cycle, either internal or external driver that re-excite the oscillations is necessary. When we say the driver, we mean the unknown perturber that perturbs the magnetic field lines near the center periodically. We don’t know the nature and origin of the drivers.

When we say “internal driver”, we mean the driving mechanism near the solar center due to local perturbations. Since the sun is such a dynamic body that always disturbances in the medium exist. Such disturbances perturb the magnetic field structure leading to generation of Alfvén waves. One such disturbance is the local thermonuclear runways as proposed by Grandpierre and G’bor (2005).

On the other hand, “external driver” means driving due to combined gravitational forces of the solar system near the solar center or tidal forces due to planets (Javaraiah and Gokhale 1995 and references there in; Wilson, Carter and Waite 2008). According to Zaqarashvili (1997), sun’s motion around the solar system barycenter causes the weak periodic differential rotation that shears the poloidal field periodically leading to 22 year Alfvénic oscillations. However, there are studies (De Jager 2005; De Jager and Versteegh 2005; Shirley 2006) that rule out the external perturbation of driving solar cycle and activity phenomena. Hence, at the present stage, it is very difficult to delineate which driver drives the 22 yr oscillations. However, detection of solar internal gravity ('g') modes (Unno et. al. 1979; Hiremath 1994; Christensen-Dalsgaard 2002; Christensen-Dalsgaard, J., 2003; Garcia et. al. 2008; Jimenez and Garcia 2009 and references there in) will definitely delineate these unknown drivers that excite 22 year oscillations.
5.4 Alfven wave Travel Times

From the SHF analysis of the sun’s magnetic field, it is found that the axisymmetric terms of odd parity modes have nearly the same periodicity (∼ 22 years). This indicates that the Alfven wave travel times may be approximately same along different field lines of a steady magnetic field structure. In order to check the admissibility of such global oscillations, we have computed the Alfven wave travel times \( \tau = (ds/V_A) \) along different field lines (that originate at the center and cut across the surface from pole to the equator), where \( ds \) is the line element of the magnetic field structure and \( V_A \) is the Alfven wave velocity. Alfven wave travel times are computed in the following models by taking into account the real density variation in the sun: (i) the uniform field, (ii) the dipole field, (iii) the combination of uniform and dipole field, (iv) the combination of dipole and hexapole embedded in a uniform field (Gokhale and Hiremath 1993) and, (v) solution of a diffusion equation in an incompressible medium of constant diffusivity (Hiremath and Gokhale 1995).

For the sake of comparison, all the models are assumed to have the same amount of magnetic flux with a nominal value of \( 1.5 \times 10^{22} \) Mx corresponding to a uniform field of ∼ 1 G. It is found that, for all the field lines, the last two models yield the same period of 22 years. It is concluded that, owing to regularity (without singularity) of the magnetic field structure at the center, the last model can be most likely the suitable geometrical magnetic field structure that sustains near 22 years oscillations for all the field lines explaining the constancy of ∼ 22 years of the observed SHF analysis of odd parity modes.

5.5 Coupling of Poloidal and Toroidal MHD oscillations and the Maunder Minimum type of activity

As mentioned in section 2.1, sun might have experienced the dearth of sunspot activity in the past evolutionary history. Yet there is no complete consensus among the solar community whether such grand minima are chaotic or regular. However, in the previous study (Hiremath 2006, end of section 3), it is concluded that Maunder minimum type of activity is not chaotic and must be periodic with a period of ∼ 100 years. Although most of the dynamo mechanisms (Choudhuri 1992; Charbonneau and Dikpati 2000;
Usoskin, Solanki and Kovaltsov 2007; Moss et. al. 2008; Brandenburg and Spiegel 2008) treat the long term variations of the solar cycle and activity phenomena as chaotic, based on the previous studies (Feynman 1983; Price, Prichard and Hogenson 1992; Hiremath 2006 and references there in), we consider such a long term solar cycle and activity phenomena to be periodic.

![Figure 1: The sun’s long period coupled oscillations of the poloidal and toroidal magnetic field structures. The sunspot activity that results from the superposition of toroidal field oscillation modes is represented by blue continuous line and the poloidal field oscillations is represented by the red dotted line.](image)

In the previous study, the observed solar cycle is modeled as a forced and damped harmonic oscillator that consists of sinusoidal and transient parts. It is found that the simultaneous change in magnitude of phase difference ($\sim 2\pi$ radians) between the transient and sinusoidal parts and of very low sunspot activity may be due to the Maunder minimum type of oscillations. This result possibly suggests the following: either a beat phenomenon due to close
frequencies or coupling of long period poloidal and toroidal MHD oscillations. Although beat phenomenon can yield the Maunder minimum type of lull of activity, the constant amplitude of the beat activity can not match varying long term period amplitudes as shown by the observations. On the other hand, as presented below, profile of coupled poloidal and toroidal oscillations is almost similar to the observed long-term variation of the solar activity that constitutes Maunder and other grand minima. Following Fletcher and Rossing (1998), on the theory of mechanical vibrations, analytical solution of the equations governing the coupled oscillations of the poloidal ($B_P$) and toroidal ($B_T$) magnetic field structures in the dissipative medium is derived as follows.

\begin{align*}
B_P &= a_0 \cos(w_0 t) + a_1 \cos((w_2 - w_1)/2) \cos((w_2 + w_1)/2) t) \\
B_T &= a_0 \cos((w_0 + \pi/2) t) + a_1 \sin((w_2 - w_1)/2) \sin((w_2 + w_1)/2) t)
\end{align*}

where $t$ is time variable, $a_0$ and $a_1$ are the amplitudes of the oscillation due to poloidal field and coupled oscillations, $w_0 = 2\pi/T$, $T$ is period due to poloidal field, $w_1 = w_0 \sqrt{1 - (\gamma/w_0)^2}$, $w_2 = w_0 \sqrt{1 + 2(w_c/w_0)^2 - (\gamma/w_0)^2}$, $w_c = 2\pi(\sqrt{V_{AP}^2 \pm V_{AT}^2})/\delta R$ is coupling frequency due to poloidal and toroidal oscillations, $V_{AP}$ and $V_{AT}$ are Alfvén wave velocities due to poloidal and toroidal magnetic field structures and $\delta R$ is distance between the neighboring field lines. The first term in the RHS of equations (3) and (4) is oscillation due to poloidal magnetic field structure and second terms in the RHS of both the equations are coupling of oscillations due to both poloidal and toroidal field structures with a coupling frequency $w_c$.

In order to closely match with the 11 year cycle and the long term variation of the sunspot activity, the fundamental period due to poloidal oscillations must be 22 years (or frequency $\omega_0$ is $\sim 0.286$ rad/yr), the dissipation factor $\gamma$ must be 0.185 and the coupling frequency $\omega_c$ should be 0.11 rad/yr. It is interesting to be noted that theoretical dissipation factor $\gamma$ of 0.185 is almost same as the dissipation factor of 0.186 obtained from the observed solar cycles (Hiremath 2006). The simulation of magnetic energy (square of amplitude of either poloidal or toroidal oscillations with arbitrary and equal amplitudes of $a_0$ and $a_1$) of such coupled oscillations with respect to time span of 500 years (Fig 1) shows that oscillations of the poloidal field with a
fundamental period of 22 yrs excite the toroidal field oscillations such that the toroidal field structure oscillates in consonance with the poloidal field oscillations resulting in coupling of poloidal and toroidal oscillations that reproduce the observed cyclic periodicities of 11 and 100 yrs with a very deep minimum around 350 years when both the strengths of poloidal and toroidal oscillations have very low amplitudes. The paleoclimatic records show that during Maunder minimum although the sunspot activity was practically absent, the 11 year activity due to geomagnetic indices (Cliver, Boriakoff and Boumar 1998) and solar proxy records (Beer, Tobias and Weiss 1998; De Jager 2005; Muscheler et al 2007) was present. As the activity of geomagnetic indices (Feyman 1982; Legrand and Simon 1991; Georgieva and Kirov 2006) and the solar proxy records are considered to be due to solar polar magnetic activity, the simulation of long term solar activity due to poloidal oscillations in Fig 1 shows also normal activity during deep minimum period activity confirming the observations.

6 Conclusions

In this talk, after summarizing the solar observations, two theoretical models, viz., turbulent dynamo and MHD oscillations mechanisms on the genesis of solar cycle and activity phenomena are critically examined. The seminal work of Alfvén on the solar cycle is revisited. The new ideas on the genesis of the solar cycle and activity phenomena and it’s long-term variations are presented.

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7 References

Alfvén H 1943 *Arkiv Math Astr Fys* 29A No 12
Altrock R Howe R and Ulrich R 2008 *ASP Conf Ser* 383 p. 335
P. Ambroz, M. Druckmiller, A. A. Galal and R. H. Hamid, 2009, Sol. Phys., 258, 243
Antia, H. M. & Basu, S., 2000, ApJ, 541, 442
Antia, H. M., Chitre, S. M., & Thompson, M. J. 2000, A&A, 360, 335
Antia, H. M. 2002, Proceedings of IAU Coll. 188, ESA SP-505, p.71
Antia, H. M., Basu, S. and Chitre, S. M., 2008 ApJ 681 680
Babcock H W 1961 ApJ 133 572
Basu, S. 1997, MNRAS, 288, 572
Beck, C. and Rezaei, R., 2009, A&A, 502, 969
Beer J Tobias S Weiss W 1998 Sol Phys 181 237
Braithwaite J and Spruit H C Nature 431 819
Brandenburg A 1988 in Proc of 6th Sov-Fin Astron Meet p. 34
Brandenburg A and Subramaniam K 2005 Phys Rep 417 p.1
Brandenburg A and Speigel I A 2008 Astron Nach 329 351
Brun et. al., ApJ, 614, 1073, 2004
Bushby P J Houghton S M Proctor M R E and Weiss N O 2008 MNRAS 387 698
Charabonneau P and Dikpati M 2000 ApJ 543 1027
Charabonneau P 2005 Living Rev Sol Phys 2
Choudhuri, A. R., 2008, Advances in Space Research, 41, 868
Cliver E W Boriakoff V and Feynman J 1998 Geophys Res Let 25 1035
Choudhuri A R 1992 A&A 253 277
Choudhuri A R Chatterjee P Jiang J 2007 Phys Rev Let 98 131103
Choudhuri A R 2008 Adv in Space Res 41 868
Christensen-Dalsgaard, J., 2002, Int. Journ. Mod. Phys. D, 11, 995-1009
Christensen-Dalsgaard, J., 2003, Lecture Notes on ”Stellar Oscillations”
Cowling T G 1934 MNRAS 94 39
Cowling T G 1953 in The Sun p. 532
Cowling T G 1981 Ann Rev Astron Astrophys 19 115
De Jager C and Versteegh G M 2005 Sol Phys 229 175
Davila J M and Chitre S M 1996 Bull Astron Soc India 24 309
De Jager C 2005 Space Sci Rev 120 197
De Luca E E and Gilman P A 1991 in Solar Interior Atmosphere p. 275
Dicke R H 1978 Nature 276 676
Dikpati M 2005 Advances in Space Res, 35, p.322
Dikpati M and Gilman P A 2006 ApJ, 649, 498
Feynman J 1982 JGR 87 6153
Feynman J 1983 Rev of Geophys and Space Phys 21 338
Fletcher N H and Rossing T D 1998 The Physics of Musical Instruments, second edition, p. 103
Garcia, R. A., et. al., 2008; Astronom Nach, 329, 476
Georgieva K and Kirov B 2006 Sun and Geosphere vol 1, 12
Gilman P A and Miesch M S 2004 ApJ 611 568
Gokhale M H Javaraiah J Hiremath K M 1990 IAU Symp 138 p. 375
Gokhale M H and Javaraiah J 1992 Sol Phys 138 p. 399
Gough D O and McIntyre M E 1998 Nature 394 755
Grandpierre A and Gbor G 2005 Astrophys & Space Sci 298 537
Hale G E 1908 ApJ 28 315
Hasan, S. S., 2008, in Physics of the Sun and its Atmosphere, eds. B.N. Dwivedi and U. Narain, p. 9
Hathaway D H Nandy D Wilson R M and Reichmann E J 2004 ApJ 602 543
Hiremath K M 1994 Ph D Thesis Bangalore University, India
Hiremath K M and Gokhale 1995 ApJ 448 437
Hiremath K M 2001 Bull Astron Soc India 29 169
Hiremath K M 2006 A&A 452 591
Hiremath K M and Lovely M R 2007 ApJ 667 585
Hiremath K M 2008a Astrophys & Space Sci 314 45
Hiremath K M 2008b arXiv:0803.1242 eprint
Hiremath K M 2009a, accepted in Sun and Geosphere, also see the eprint arXiv:0906.3110
Hiremath K M 2009b, arXiv:0909.4376 eprint
Javaraiah J and Gokhale M H 1995 Sol Phys 158 173
Howe, R., Cristensen-Dalsgaard, J., Hill, F., et. al., 2000, Science, 287, 2456
Howe, R., 2009, Living Reviews in Solar Physics, vol. 6, no. 1
Javaraiah, J and Komm, R. W., 1999, Sol. Phys, 184, 41
Javaraiah, J., 2000, Ph. D. Thesis, Study of Sun’s rotation and solar activity, Bangalore University, India
Jimenez, A. and Garcia, R. A., 2009, Accepted for publication in ApJSS
Jin, Chunlan; Wang, Jingxiu and Zhou, Guiping, 2009, ApJ, 697, 693
Jouve and Brun, A&A, 474, 239, 2007
Howard R and La Bonte B J 1980 ApJ 239 L33
Knaack R and Stenflo J O 2005 A&A 438 349
Komm R W Howard R F Harvey J W 1993 Sol Phys 143 19
Krivova, N. A. & Solanki, S. K., 2002, A & A, 394, 70

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Layzer D Krook M and Menzel D H 1955 Proc Roy Soc A223 302
Layzer D Rosner R and Doyle H T 1979 ApJ 229 1126
Legrand J P and Simon P A 1991 Sol Phys 131 187
Leighton R B 1964 ApJ 140 1547
Leighton R B 1969 ApJ 156 1
Levy E H 2002 in The Solar Cycle ASP Conf Ser 27 p. 139
K. J. Li, Q. X. Li, T. W. Su, and P. X. Gao, 2006, Sol Phys, 239, 493
Lites, B. W.; Leka, K. D.; Skumanich, A.; Martinez Pillet, V and Shimizu, T, 1996; ApJ, 460, 1019
Lites, B. W., et. al., 2008, ApJ, 672, 1237
Lites, B. W., et. al., 2009, First Results From Hinode ASP Conference Series, 397, p.17
Mestel L and Weiss N O 1987 MNRAS 226 123
Mark S. Miesch and Juri Toomre, Annual Review of Fluid Mechanics, Vol. 41: 317-345, 2009
Moss D Sokoloff D Usoskin I and Tutubalin V 2008 Sol Phys 250 221
Muscheler R et. al. 2007 Quaternary Science Reviews 26 82
Nandy D and Choudhuri A R 2002 Science 296 167
Nandy, D., arXiv:0906.4748, 2009
Obridko, V. N and Shelting, B. D., 2007, Advan in Space Res, 40, 1006
Pasachoff, J. M., 2009, Nature 459, 789
J. M. Pasachoff1,, V. Ruin, M. Druckmiller, P. Aniol, M. Saniga and M. Minarovjech, 2009, ApJ, 702, 1297
Parker E N 1955 ApJ 122 293
Pelt J Brooks J Pulkkinen P J Tuominen I 2000 A&;A 362 1143
Petrovay K 2000 ESA SP 463 p. 3
Piddington J H 1971 Proc Astron Soc Australia 2 7
Piddington J H 1972 Sol Phys 22 3
Plumpton C and Ferraro V C A 1955 ApJ 121 168
Piddington J H 1973 Astrophys Space Sci 24 259
Price C P Prichard D and Hogenson E A 1992 JGR 97 19113
Priest E R 1981 in Solar magneto-hydrodynamics
Shirley J M 2006 MNRAS 368 280
Solanki S K Inhester B and Schussler M 2006 Rep Prog Phys 69 563
Spruit H C 1990 in Inside the sun 415
Stein R F and Nordlund A 2006 ApJ 642 1246
Steiner O Rezaei R Schaffenberger W and Wedemeyer-Bohn S 2008 *ApJ* 680 85
Stenflo J O and Vogel M 1986 *Nature* 319 285
Stenflo J O 1988 *Astrophys Space Sci* 144 321
Stenflo J O and Gudel M 1988 *A&A* 191 137
Stenflo J O 1994 in *Solar surface magnetism* p. 365
Svanda M Kosovichev A G and Zhao J *ApJ* 670 69
Toomre, J., Christensen-Dalsgaard, J., Hill, F., Howe, R., Komm, R. W., Schou, J. and Thompson, M. J., 2003, in ”Proceedings of SOHO 12 / GONG+ 2002”, ESA SP-517, p. 409
Tsuneta, S., et. al., 2009, *ApJ* 688, 1374
Unno, W., Osaki, Y., Ando, H and Shibahashi, H, 1979, in ”Nonradial oscillations of stars”, University of Tokyo Press
Usoskin I G Solanki S K and Kovaltsov G A *A&A* 471 301
Vainstein S I and Cattaneo F 1992 *ApJ* 393 165
Vandakurov Y V 1990 *IAU Symp* 138 333
Vecchio, A and Carbone, V, A&A, 2009, 502, 981
Venkatakrishnan, P and Gosain, S, 2008, in *Physics of the Sun and its Atmosphere*, eds. B.N. Dwivedi and U. Narain, p. 39
Walén C 1949 in *On the Vibratory Rotation of the Sun*
Wijn, D. A. G.; Stenflo, J. O.; Solanki, S. K. and Tsuneta, S., 2009, *Space Science Rev.* 144, 275
Wilson I R G Carter B D and Waite I A 2008 *Pub Astron Soc Austr* 25 85
Zaqarashvili T V 1997 *ApJ* 487 930
Zhao J and Kosovichev A G 2004 *ApJ* 603 776
Zwaan C 1981 in *The sun as a star* NASA SP-450 p.163