Analysis of Solar Magnetic Field Using the Dynamo Model

Ahmed Abdul-Razzaq Selman*   and   Samar Abd Alkarem Thabit

Abstract – In this paper we study solar magnetic field using solar dynamo model, utilizing the two main components, the toroidal and poloidal magnetic fields. Surya code was used for calculating the flux transport dynamo and toroidal magnetic field. The results showed that solar magnetic field was increasing as the distance increased from the center of the sun. That is, at R =5.05 the peaks of the main field value declined to 50% of its maximum value between latitude 1.49-1.67 degrees. Also, the poloidal source term effect appears at the maximum latitude and solar radius because it's the same part of the toroidal part rising due to buoyancy.

Keywords: Dynamo model, Solar magnetic field, Surya code, Poloidal and Toroidal components.

————————————— ◆ —————————————

1 INTRODUCTION

The sun shows significant magnetic field, with general strength varying between 1 to 2 G over most area of its surface. Such field is concentrated at densities between 10 to 10^3 G in active regions of the solar surface. The solar weak field may extended by the solar wind, filling the entire solar system to distance of 30 AU or more [1]. There is the theoretical possibility that same astrophysical objects may have large dynamo number generating fields in high modes. The effect of boundaries is diminished and is profitable to consider the fields in terms of four basic waves from boundaries are worked out. Parker made calculations to illustrate same of the behavior at large dynamo numbers to aid in observational recognition [2]. Parker and others [3,4] were able to develop a theory for the origin of the magnetic fields seen in the galactic disk, proving that magnetic field is a property of stars and galaxies as well.

Quantitative and qualitative studies of the solar magnetic field have been made since Parker, and the subject is still developing. About a decade ago, Choudhuri, Dikpati, Nandy and Chatterjee [5,6] developed a useful numerical code, Surya, for solving the flux transport dynamo problem. It is a Fortran code aimed at solving the two-dimensional kinematic dynamo problem in a spherical shell in the presence of a meridional circulation [7].

In this paper we utilized Surya to calculate the solar magnetic field as it varies with latitude and radius. Few Matlab codes were also written to assist in extracting data from Surya output files.

2 PHYSICAL MODEL

The solar dynamo mechanism was thought to involve two basic processes: generation of a toroidal field by shearing a preexisting poloidal field by differential rotation (the ω-effect) and the regeneration: of a poloidal field from a toroidal field by helical turbulence (the α-effect), which displaces and twists the toroidal flux tubes. From new studies of kinematic dynamos with meridional circulation, it is now clear that the solar dynamo mechanism involves not only the above two processes but also an important third process, the advective transport of the magnetic flux by meridional circulation as in a conveyor belt have established a scaling law between the dynamo cycle period and the meridional flow speed. They have shown that the dynamo cycle period is governed primarily by the meridional circulation rather than the combination of differential rotation and the α-effect as in older models; the mean field kinematic flux-transport dynamos have been the leading candidate to explain the generation and evolution of large-scale magnetic fields on the Sun [5].

A flux transport dynamo combines three basic processes: (i) the strong toroidal field B is produced by the stretching of the poloidal field by differential rotation Ω in the tachocline. (ii) the toroidal field generated in the tachocline rises due to magnetic buoyancy to produce sunspots (active regions) and the decay of tilted bipolar sunspots produces the poloidal field A by the Babcock–Leighton mechanism. (iii) the meridional circulation advects the poloidal field first to high latitudes and then down to the tachocline at the base of the convection zone [6]. From the mean field electrodynamics the dynamo equation is [8],

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times (\boldsymbol{U} \times \boldsymbol{B}) + \boldsymbol{\nabla} \times (\alpha \boldsymbol{B}) + \eta t\, \Delta \boldsymbol{B} \dots \dots \dots \dots .1$$

Under the assumption of axisymmetric and using spherical polar coordinates (r, □ □) [5], the magnetic field and flow field can be written as [8]

$$\boldsymbol{B} = B(r,\theta)\hat{e}_\varphi + \boldsymbol{\nabla} \times \big[A(r,\theta)\hat{e}_\varphi\big] \dots \dots \dots \dots \dots \dots \dots \dots \dots .2.a$$

$$\boldsymbol{U} = v(r,\theta) + rsin\theta\Omega(r,\theta)\hat{e}_\varphi \dots \dots \dots \dots \dots \dots \dots \dots \dots ..2.b$$

In which, B(r,□θ) and A(r,θ) correspond to the toroidal and poloidal components respectively of the magnetic field, v(r,θ) is the velocity of meridional circulation having component in r and θ directions, Ω (r, θ) is angular velocity in the interior of

───────────────────────

- *Ahmed Abdul-Razzaq Selman, Ph.D.; is currently a full-time professor at the College of Science University of Baghdad, Iraq. Email: aaselman@scbaghdad.edu.iq*
- *Samar Abd Alkarem Thabit is currently pursuing masters degree program in science in University of Baghdad, Iraq..*

the sun. With the substitution of equations (2.a) and (2.b) in equation (1), the equations for toroidal and poloidal component for αω dynamo become [9]

$$\frac{\partial A}{\partial t} + \frac{1}{r\sin\theta}(v \cdot \nabla)(r\sin\theta A) = \eta_t\left(\nabla^2 - \frac{1}{r^2\sin^2\theta}\right)A + \alpha B \dots\dots\dots\dots\dots 3$$

$$\frac{\partial B}{\partial t} + \frac{1}{r}\left[\frac{\partial}{\partial r}(rv_r B) + \frac{\partial}{\partial\theta}(v_\theta B)\right] = \eta_t\left(\nabla^2 - \frac{1}{r^2\sin^2\theta}\right)B +$$

$$r\sin\theta\left(B_p \cdot \nabla\right)\Omega + \frac{1}{r}\frac{\partial\eta_t}{\partial r}\frac{\partial}{\partial r}(rB)\dots\dots\dots\dots\dots 4$$

Where: $B_p = \nabla \times (A\hat{e}_\phi)$.

3 RESULT AND DISCUSSION

3.1 Flux transport dynamo

The next figure represents the relationship between (r sinθ ψ) and the angle θ in radian, first at small solar radius R=3.8769 the relation is straight line on 0, that case continues even when the solar radius increase to R=4.0605. When the solar radius increase to R=4.2929 the straight line begins changing his behavior will see small bumps when θ=0.2 and 1.3 rad. Whenever the solar radius increase the bumps will be clear to form top and bottom. The next figures shows the continuous increasing of the same behavior of the top and bottom with the solar radius increasing. When the solar radius R=5.4674 the value of (r sinθ ψ) becomes in maximum value in the top more than 0.08 at θ=1 rad. and minimum value in bottom more than -0.08 at θ=2.18 rad., and look to have the sin wave behavior. That continues to R=5.6999. When the solar radius increase R=6.0669 the value of the field decreased, continues in decreasing until the solar radius reach to maximum value R=6.96. Contour of the same relation and the same solar radius are shown below. (To save space only two figures are listed, corresponding the first and last figures).
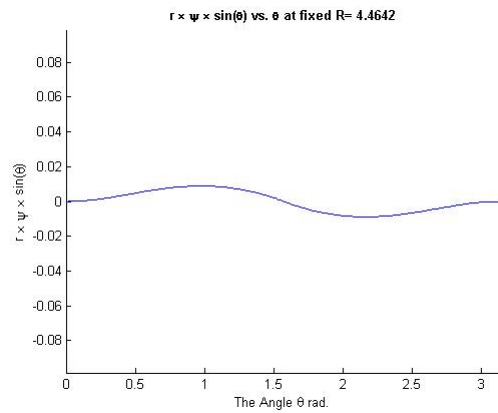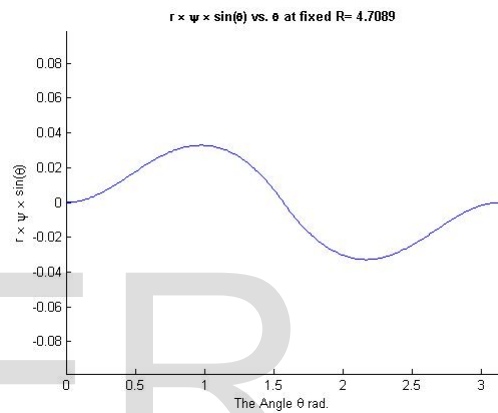

Figure 1- Flux transport dynamo when R=4.4642.
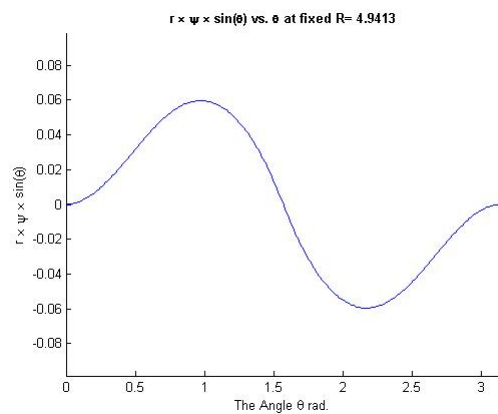

Figure 2. Flux transport dynamo when R=4.7089.

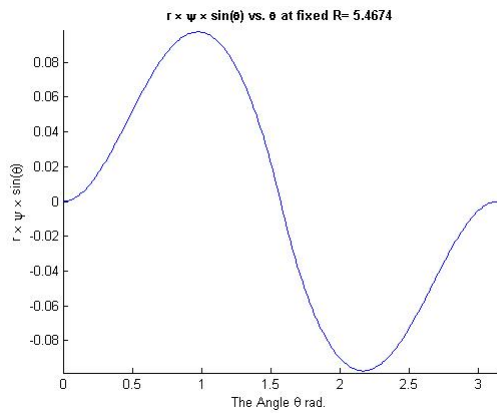Figure 3. Flux transport dynamo when R=4.9413.
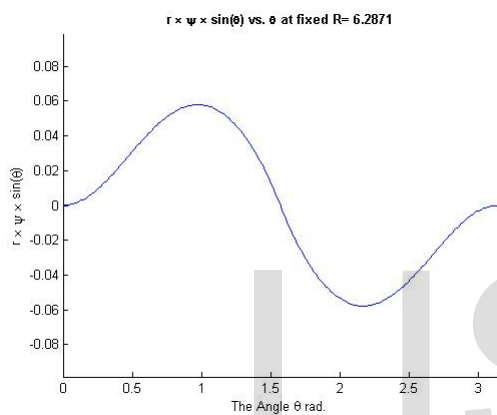
Figure 4. Flux transport dynamo when R=5.4674.

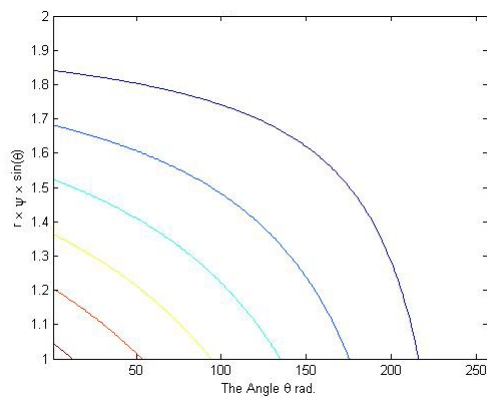Figure 5. Flux transport dynamo when R=6.2871.

Figure 6. Contour for flux transport dynamo when R=4.4642.

3.2 Toroidal Field

The figures explain the toroidal field for the sun from Surya program, from small solar radius to the maximum solar radius R against the angle θ in rad. We start from small solar radius R=3.8769 the shows unstable line beginning in the 0 value for all θ in rad. In this part it was seen that increasing of the solar radius leads to a decrease in the toroidal field, in the small angle the toroidal field increase from 0 and small peak will appear increasing the angle to approximately 1 rad. the toroidal field decreased making a small bottom, after that peak to increase then making a sharp peak at 1.6 rad. With toroidal field value more than 0.2, while the angle is increase the toroidal field have the same old behavior before the sharp peak to the maximum angle, as shown in Figures (9 to 12). When solar radius increase to R=4.3663 the toroidal field completely have different behavior, at small angle (0.42 rad) the toroidal field decreased to -0.82 and this decreased prepared with high and low is not stable, then the toroidal field reach to it maximum value making peak at (1.05 rad.) with toroidal field 1.5. Increasing angle decrease the toroidal field making bottom then increase to form small peak but with two bottoms at (1.45-1.7 rad.).
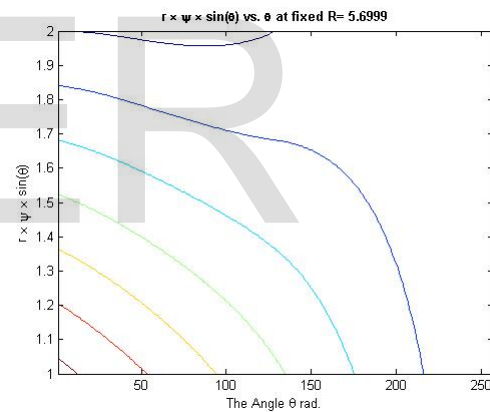

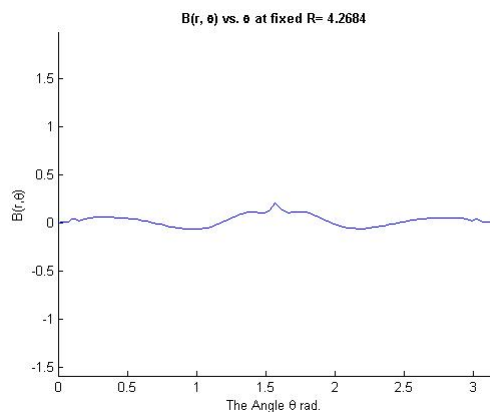Figure 8. Contour for flux transport dynamo when R=5.6999.
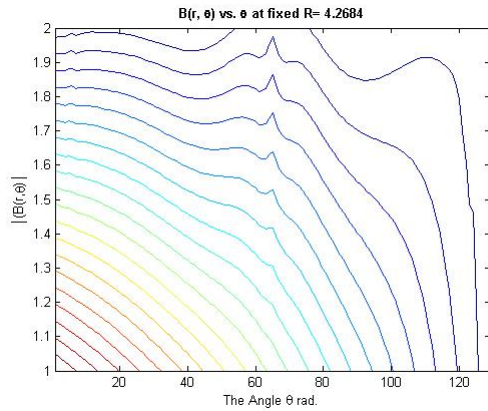

Figure 9. Toroidal magnetic field when R=4.2684.

Figure 10. Contour for toroidal magnetic field when R=4.2684.

Figure 13. Contour for toroidal magnetic field when R=4.2929.

After that peak the toroidal field goes down to make bottom, then it will have the same behavior to the higher latitude, but the second peak will have value less than the first one (less than 1.48) at (2.0862 rad.) and when it goes dawn to (-0.75) at (2.725 rad.) at higher latitude the toroidal field goes back to 0. This behavior is explained for Figures (14-17). The continues increasing in the solar radius R=4.4642 will make the peak value increase to (1.75) at (1.34 rad.) and the second peak (1.74) at (1.805 rad.), and the bottom also decrease to less value (-1.58) at (0.88 rad) while the second bottom (-1.54) at (2.26 rad.),the tow bottom in the mid latitude increase also (-0.78) at angle between (1.47-1.67), in general all the peak and bottom will be close to each other.
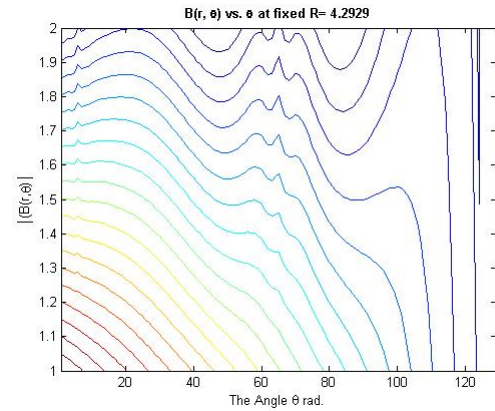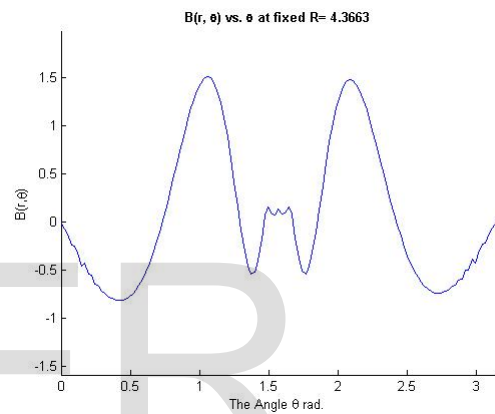

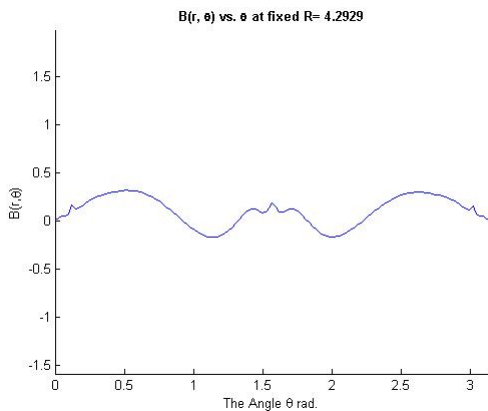Figure 14. Toroidal magnetic field when R=4.3663.
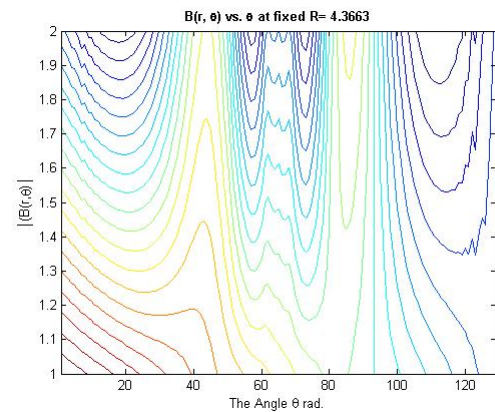

Figure 11. Toroidal magnetic field when R=4.2929.

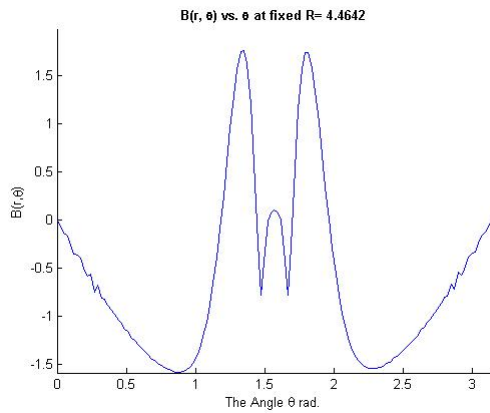Figure 15. Contour for toroidal magnetic field when R=4.3663.
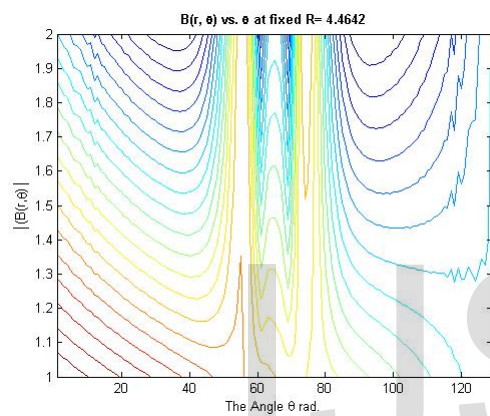
Figure 16. Toroidal magnetic field when R=4.4642.

Figure 17. Contour for toroidal magnetic field when R=4.4642.

CONCLUSIONS

The conclusions thus reached from the results are summarized in the following:

The poloidal source term effect appears at the maximum latitude and solar radius because it's the same part of the toroidal part rising due to buoyancy. The flux transport dynamo which solve by Surya code, the differential rotation will also have the strong shear at the tachocline R=4.7578 and the differential rotation is faster at the equator and slower at the poles. The maximum Poloidal Field happen at the maximum solar radius R=6.9.

References

1.[1] E. N. Parker, (1970), "The origin of the magnetic fields", astrophysical journal Vol.160, p.383.

2.[2] E. N. Parker, (1971), "The generation of magnetic field in astrophysical bodies. V. Behavior at large dynamo numbers", Astrophysical journal Vol.165, pp.139-146.

3.[3] E. N. Parker, (1971), "The generation of magnetic field in astrophysical bodies. II. The galactic field" Astrophysical journal Vol.163, PP.255-278.

4.[4] R. M. Kulsrud, (2010),"Plasma physics for astrophysics", First edition, Chapter 13, Princeton University press, USA.

5.[5] M. Dikpati, and P. A. Gilman, (2001), "Flux-transport dynamos with α-effect from global instability of tachocline differential rotation: A solution for magnetic parity selection in the sun". Astrophysical journal Vol.559, pp.428-442.

6.[6] A. R. Choudhuri, (2005), "The User's Guide to the Solar Dynamo Code SURYA", Indian Institute of Science.

7.[7] A. R. Choudhuri, (2007), "An Elementary Introduction to Solar Dynamo Theory", Department of Physics, Indian Institute of Science.

8.[8] J. Jiang, P. Chatterjee, and A. R. Choudhuri, (2007), "Solar activity forecast with a dynamo model". Monthly Notices of the Royal Astronomical Society Vol.381, pp. 1527–1542.

9.[9] Samar A. Thabit, M.Sc. Thesis, Dept. Astronomy & Space, Uni. Baghdad, 2014.