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THE STATIONARY STATE OF MAGNETIC FIELD NEAR THE SUN

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ABSTRACT: *In this study, the structure of coronal magnetic field has modeled both analytically and numerically. The coronal magnetic field has been studied inside the active region. The analytical model of coronal magnetic field structure has been compared with that of the analytical model which has been done using NASA's CCMC modeling center software. They showed a good agreement except the analytical mode predicts very elongated closed field lines that are not observed in nature. Both models have been showed that coronal magnetic field on the equatorial region of the sun are closed and are open on the poles. In addition the effect of the structure of magnetic field on other physical parameters like velocity of plasma , density of the corona and temperature on the different parts of the sun have been clearly showed. In the attempt of modeling the magnetic field analytically first the expression for stationary state magnetic field of solar corona has been derived by taking an assumption that the temperature of the corona isothermal , but for the numerical model variation in temperatures have been consider.*

KEYWORDS: *Solar Corona, Magnetic Field, Plasma, Magnetic field lines, MHD, Solar maxima, Solar Minima*

INTRODUCTION

The Sun is not an exotic object in the universe [1], rather merely a star amongst many others. It is at the origin of the energy we receive, the very origin of life. The Sun is a nearly perfect spherical ball of hot plasma. Plasmas in space are extremely tenuous gases of ionized particles in which, on average, there is no net charge [2]. The interior part of the sun is optically thick, and that means all electromagnetic radiations escaping from the Sun comes from the photosphere (a thin layer defining the surface of the Sun at a distance of 513380.7 km from its center), or the solar atmosphere (chromosphere and corona). The corona is very dynamic, and it changes from day to day.

Nowadays, it is known that the structure of the corona in the visible light is directly related with the magnetic field of the Sun, and the dynamic behavior of the corona is related to the dynamic behavior of the underlying magnetic field. Many papers have been dedicated to the magnetic field of the Sun and its relation to the Corona. The general objective of this project is to get an expression for stationary state magnetic field of solar corona and its relation to the structures appearing in a quiet Sun. In addition the research also intended to get a numerical and analytical model of the coronal magnetic field.

Solar corona is always expanding. This atmosphere is around ten billion times less dense than earth's atmosphere. The brightness of solar corona is less than by a factor of million from that of the surface of the Sun or photosphere. Since the solar corona is always expanding into space, it has no specific boundaries, but its shape is determined by the magnetic field of sun. During a solar eclipse or with instruments operating in different wavelengths it is possible to see the various structures of the solar corona, like coronal streamers, helmet streamers, solar wind, coronal holes, coronal mass ejections etc.

In their study of an stationary corona, [3] realized that the helmet streamer type of configuration with its associated neutral point and sheet current is of central importance, and they were able to proof that an schematic picture of a typical helmet streamer configuration which is can be predicted by the equations of magneto hydrodynamics. They solved the complete set equations numerically for the first time in an iterative way, for a stationary corona with a dipole magnetic field at the photosphere as boundary conditions.

Parker's Model has become a standard first approximation to describe the solar wind, and it is discussed is most reviews of solar physics. In here we have followed the approach by

Kallenrode [4]. Serge Koutchemy and MosselLivshiths [5] were able to reproduce some of the characteristics of the magnetic field of the corona in the same configuration (stationary and with dipolar boundary conditions) solving the convection-diffusion equation in an analytical way for various Reynolds number. As it is possible to show from their model, open magnetic field lines appear at high latitudes as the Reynolds number grows, and the appear at lower latitudes as the Reynolds number increases. For sufficiently low number, as expected, the field approaches the field of a dipole.

Nowadays, the approach of Pneuman and Koppa has been generalized to include more realistic boundary conditions. In particular, [11], have developed MAS model, that uses real magnetographs of the photosphere as boundary condition. This model is nowadays available at the CCMC at NASA, and in this project I have used the results of some runs of this model.

The main purpose of the research is to give an approximation of these structures of the magnetic field in the simplest situation: a stationary situation that is a good approximation of the corona at solar minima. We will be able to see how open and close lines arise in this simple case, and give an estimate of the latitude at which close and open field lines separate at solar minimum. In the case of the solar maximum, we will show with the aid of a numerical model available at the Community Coordinated Modelling Center at NASA how the structure of the magnetic field changes and other properties of the solar corona change in solar maximum and solar minimum.

I. THE MAGNETIC FIELD OF SOLAR CORONA

The coronal magnetic field has a complex structure, particularly when sunspots and active regions are present. Here I will concentrate on the two main types of coronal magnetic fields structures, associated to open and closed magnetic field lines. These different configurations result in different solar wind and interplanetary magnetic field properties.

As we have pointed out above, the bottom of helmet streamers corresponds to closed magnetic field lines and the coronal holes to open field lines. Due to the Lorentz force acted by magnetic field, charged particles in corona are forced to move essentially following the magnetic field lines and therefore, particles bounded to closed field lines have difficulties to escape. This means that the particles in the regions with closed magnetic field lines cannot escape easily outside the helmet streamer regions, and they oscillate in a closed loop in lower regions of the corona. As we have mentioned, this is the reason why the density in the regions with closed field lines is higher, and these regions look brighter.

In regions where the magnetic field lines are open, particles escape more easily from the gravitation of the Sun because the magnetic fields are lined in outward direction of solar corona, so that the particles have a good opportunity to go far from corona and disappear there. Since many particles are escaping from this region and they are not coming back, the number of particles is small when compared with the area of the regions, and this tells us that the density is lower in this region of Corona.

The solution of MHD equations for the Solar Corona involves the solution of a complicated set of coupled differential equations. The first solution for this problem was presented by [3], where they solved the numerical problem in an iterative way for a stationary isothermal and axially symmetric corona, using a dipole field as a boundary condition at the surface of the Sun. In this chapter, we will adopt a simpler approach, and we will show how some of the features of a high temperature stationary corona can be explained analytically. Although this simple model described is able to predict some of the features of the corona, such as the presence of open field lines and latitude separating open and closed field lines, some other features, such as the current sheet and the actual shape of the helmet streamer are beyond the model.

2.1 Magnetic field lines: axially symmetric fields

The magnetic field equation for dipole is

$$\vec{B}(r,\theta) = \hat{r}\left(\frac{2a\cos\theta}{r^3}\right) + \hat{\theta}\left(\frac{a\sin\theta}{r^3}\right) \qquad 1$$

Where the radial and angular component of the magnetic fields are given as below;

$\overrightarrow{B_r} = \frac{2a\cos\theta}{r^3}, \overrightarrow{B_\theta} = \frac{a\sin\theta}{r^3}$ And $\overrightarrow{B_\varphi} = 0.$

To show the complex structure of solar corona magnetic fields it is useful to represent the field by means of magnetic field lines, that is, lines that are every-where parallel to the magnetic field vector. Dipolar geometry underlies many examples of coronal magnetic fields; so that in this paper it is discussed how to visualize the magnetic field lines. Some mathematical manipulations gives the radius r in the form; $r = r_0 \sin^2\theta$ where r_0 is a constant indicating the distance of the magnetic field line to the center of the dipole in the equatorial plane. By taking x, y plane and start from x = r_0 and y = 0, that corresponds to

$r = r_0$ and $\theta = \frac{\pi}{2}$. Then by using these conditions it is possible to plot the magnetic field lines. Obviously the magnetic field lines for a dipole are closed lines. We notice that the magnetic field lines of a dipole verify that the field ψ is constant along these lines. This statement can be generalized to any axial magnetic field derived from a vector potential of the form given by:

$$\vec{A} = \frac{\psi(r,\theta)}{r sin\theta}\phi$$

2.1.1 A First Approximation to the Magnetic Field of the Solar Corona

The magnetic field of the Sun is transported by solar wind into the interplanetary medium. The Solar wind deforms the magnetic field of the Sun, giving rise to a field which is almost everywhere radial, with open field lines. In a first approximation, the evolution of the magnetic field can be deduced from the induction equation, where the rate of change of magnetic field is expressed as the summation of diffusion term and some other convection term, mathematically;

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{V} \times \vec{B}) + \eta \overrightarrow{\nabla^2}\vec{B} \qquad 2$$

Since the magnetic field is considered as stationary, the left hand side of the equation

$$\frac{\partial \vec{B}}{\partial t} = 0 \rightarrow \vec{\nabla} \times (\vec{V} \times \vec{B}) + \eta \overrightarrow{\nabla^2}\vec{B} = 0 \qquad 3$$

Then to get the magnetic field equation at the solar corona, it is reasonable to assume the solar surface is spherical with radius R, since the Sun is almost a perfect sphere. The flow of plasma in the corona is always in radial direction.

We assume that the velocity is constant and radial: .Then we take the assumption that the magnetic field at the surface of the Sun is a dipolar magnetic field, and that the axial symmetry will not be broken by a radial velocity of the plasma. Calculating the curl of A in spherical coordinates gives the magnetic field B as:

$$\vec{B}(r,\theta,\varphi) = \hat{r}\frac{1}{r^2 sin\theta}\left[\frac{\partial}{\partial\theta}\psi(r,\theta,\varphi)\right] + \hat{\theta}\left(\frac{1}{r sin\theta}\frac{\partial}{\partial r}\psi(r,\theta,\varphi)\right) \qquad 4$$

because $A_r = A_\theta = 0$. This is a general expression for magnetic field of solar corona, but still we don't know the vector field ψ(r, θ, ϕ). This can't tell us to deduce the components of magnetic field are:

$\overrightarrow{B_r} = \frac{1}{r^2 sin\theta}\frac{\partial}{\partial\theta}\psi(r,\theta)\overrightarrow{B_\theta} = \frac{1}{rsin\theta}\frac{\partial}{\partial r}\psi(r,\theta), \overrightarrow{B_\varphi} = 0.$ 5

To determine the stationary state magnetic field for solar corona in this approximation, we have to determine the vector potential first. Bringing the condition for stationary state magnetic field from equation then, we can analyze each terms individually: And the curl of the magnetic field and product of V with B becomes;

$\vec{\nabla} \times \vec{B} = -\phi\left(\frac{1}{rsin\theta}\frac{\partial^2}{\partial r^2}\psi(r,\theta)\right) + \left(\frac{1}{r^3}\frac{\partial}{\partial\theta}\left[\frac{1}{sin\theta}\frac{\partial}{\partial\theta}\psi(r,\theta)\right]\right).$ 6

$\vec{V} \times \vec{B} = -\phi\frac{v}{rsin\theta}\frac{\partial}{\partial r}\psi(r,\theta).$ 7

Thus we can transform our equation to:

$$\vec{V} \times \vec{B} = -\phi\frac{v}{rsin\theta}\frac{\partial}{\partial r}\psi(r,\theta)$$

$0 = -\phi\left(\frac{v}{rsin\theta}\frac{\partial}{\partial r}\psi(r,\theta)\right) - \phi\eta\left(\frac{1}{rsin\theta}\frac{\partial^2}{\partial r^2}\psi(r,\theta)\right) + \left(\frac{1}{r^3}\frac{\partial}{\partial\theta}\left[\frac{1}{sin\theta}\frac{\partial}{\partial\theta}\psi(r,\theta)\right]\right)$ 8

This is a differential equation for the field ψ(r, θ).

Solving this equation enables us to determine the vector field A(r, θ) and the magnetic field as well. This equation is a second order separable equation which can be solved by using separation of variables. Suppose the solution ψ(r,θ) is in the form: $\psi(r,\theta,\varphi) = \psi_r\psi_\theta$. The angular and the radial term of the proposed solution must verify;

$\psi_\theta = [asin^2\theta r]_{r=R} = \frac{asin^2\theta}{R}, \psi_r = \frac{1}{R_n+2}\left(R_n + 2\frac{R}{r}\right).$ 9

Where $R_n$is the magnetic Reynolds number $R_n = \frac{vR}{\eta}$. Thus the combined solution would be:

$\psi(r,\theta) = \frac{asin^2\theta}{R(R_n+2)}\left(R_n + 2\frac{R}{r}\right).$ 10

As we have shown above, the magnetic field lines are given by ψ constant.

II. Result and Discussion

3.1 Analytical Model of Magnetic Field of Solar Corona

Writing equation 10 as a constant $\frac{asin^2\theta_0}{R}$ the magnetic field lines can be written as;

$\frac{sin^2\theta_0}{sin^2\theta} = \frac{1}{(R_n+2)}\left(R_n + 2\frac{R}{r}\right)$ 11

So that equation represents a line which crosses the surface of the Sun at (R,θ_0). If the angle verifies:

$$sin^2\theta_0 > \frac{R_n}{R_n+2},$$

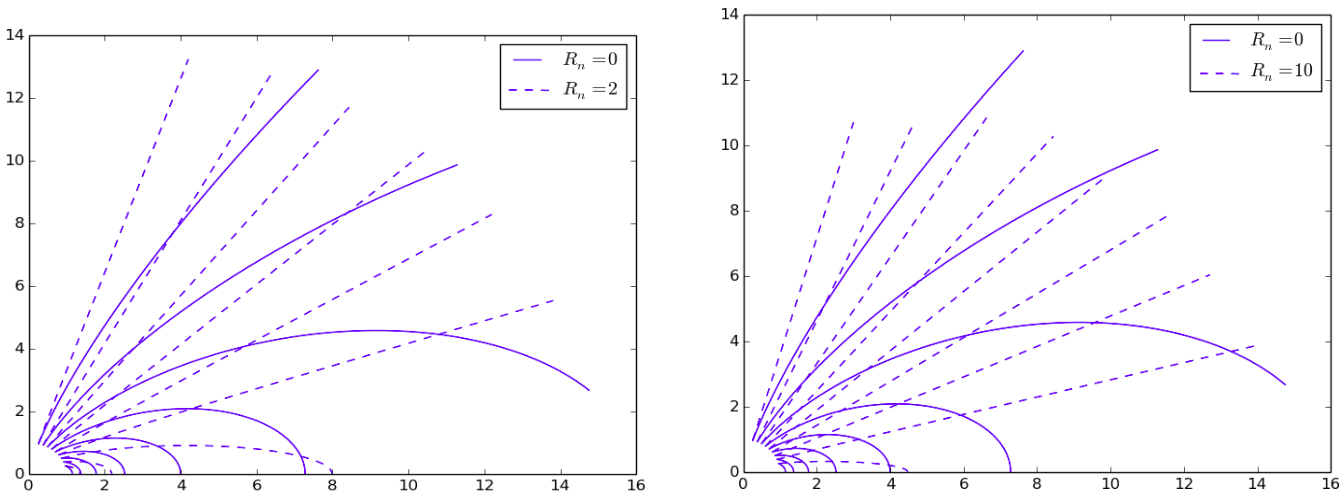
the distance of the field line to the center cannot reach infinity, which physically tells us that the magnetic field lines are closed, and the possible values of the angle θ are in the range from θ_0 to π/2 But if the angle verifies;

$$sin^2\theta_0 < \frac{R_n}{R_n+2},$$

the magnetic field lines will reach r → ∞, and will therefore be open field lines going to infinity. The angle θ_l separating these two families will be given by:

$$sin^2\theta_l = \frac{R_n}{R_n+2}, \theta_l = arcsin\left(\sqrt{\frac{R_n+2}{R_n}}\right). \qquad 12$$

When the magnetic Reynolds number is large this limiting angle is close to $\frac{\pi}{2}$and most lines are open. In the limit of very small Reynolds angle, we recover the magnetic field lines of a dipole. The following model shows the structure of magnetic field lines



(a) (b)

Figure 1: (a) Model of magnetic field lines for R_n= 0 and R_n= 2, (b) Dipolar magnetic field lines for R_n= 0 and R_n = 10

These simple models showed by figure 1: (a) and (b) describes in a correct way the open field lines, but it predicts very elongated closed field lines that are not observed in nature. This is mainly due to the fact that we have ignored the effect of the magnetic field in the deduction of the solar wind, and we have considered a motion that is independent of the magnetic field (in this model, the velocity of the plasma is constant and radial everywhere). A more complete solution in the next session shows that near the magnetic equator the velocity of the plasma gets a non-radial component that changes significantly the shape of the closed field lines, giving rise to the characteristic shape of a helmet streamer. In fact, above a certain height, magnetic field lines corresponding to radial fields of opposite sign get so closed together that a sheet current develops. The shape of current sheet really depends on magnetic field on the Sun and it changes during the solar cycle.

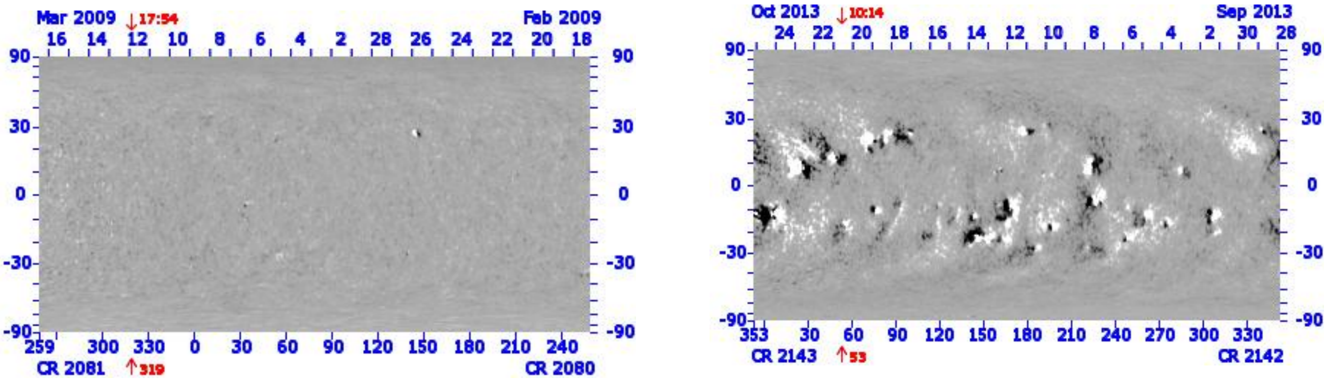
3.2 Numerical Models of Solar Corona

The solar coronal magnetic field, the cause of the most spectacular phenomena in the heliosphere, plays a crucial role in determining the structure of the solar corona, such as the shapes, positions, and sizes of the coronal streamers and the coronal holes [7]. In this section a more complete physical model of magnetic fields of the corona have been discussed and assumes that solar wind velocity is constant, ignoring the effect of magnetic forces in the evolution of the plasma in the corona. In order to improve the approximation the complete MHD equations must be solved and this can only be done in a numerical way. For this purpose I have chosen the National Aeronautics and Space Administration (NASA)'s Community Coordinate Modeling center (CCMC).

In this modeling centre there are five coronal models. Among these models for this project we have chosen the MHD around a Sphere (MAS) model. Because, these model is a full MHD which calculates the coronal temperature, density, velocity in addition to magnetic field [8].

3.2.1 Synoptic maps of the magnetic field at the surface of the Sun

Observations of the Sun at a given moment allow us to measure the magnetic field at the surface with using Zeeman Effect. Since not all the Sun is visible at a given time, so-called synoptic maps are constructed for each Carrington rotation (a full rotation of the Sun) These synoptic maps are available from different solar observatories, and can be used as boundary conditions for more realistic models of the evolution of the solar corona. In a synoptic map, the differences between the Sun at solar minimum and solar maximum are apparent. The magnetic field at the surface of the Sun is very regular at solar minimum, and presents characteristic regions of high intensity, corresponding to Sun spots or active regions during solar maximum. Since in this chapter we will describe the magnetic field of the corona in two Carrington rotations, CR2081 (March 2009), corresponding to solar minimum, and CR2143 (October 2013), corresponding to solar maximum.



(a) (b)

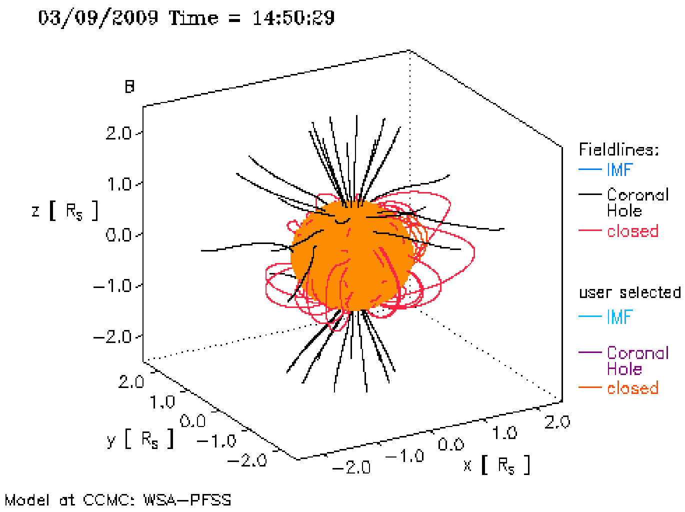
Figure 2: (a) Synoptic map of solar surface during solar minimum, (b) Synoptic map of solar surface during solar maximum.

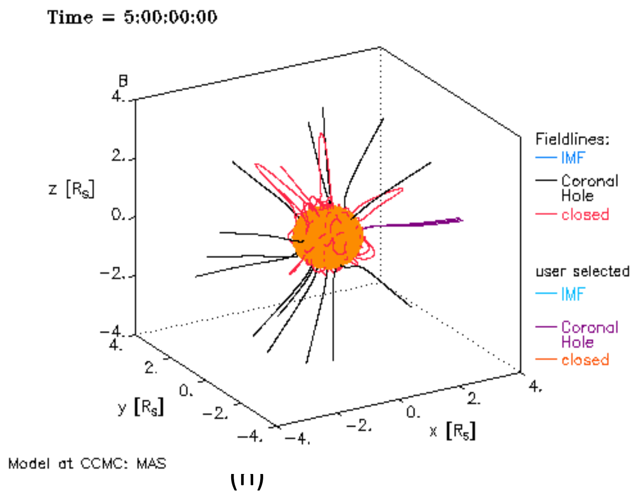
Figure 2 (a) shows the synoptic map of sun at solar minimum, but figure 2 (b) is the map Sun's surface during solar maxima. As it is possible to see from figure 2 (a) the surface of the sun is uniform, that means there is a minimum number of sunspot on the surface of the sun and that is the reason to say the sun is solar minima. But in figure 2 (b) there are a lot of sun spot that is the reason why we said the sun is at solar maximum.

3.2.2 3D Coronal Magnetic Field

The typical solar minimum corona exhibits a well defined streamer belt with coronal holes in the Polar Regions [11]. During the solar maximum, the corona is highly structured and extends far outwards. During the solar minima, only few structures are visible and the corona appears smaller. However, the corona does not have a sharp outer boundary, but instead shows structures which extend into different heights and then fade into the background.

The corona can be seen in visible light during a solar eclipse as a structured, irregular ring of rays around the solar disk. The following two plots show the results of the MAS model retrieved from the Community Coordinate Modeling center (CCMC) in NASA. These models shows the structure of magnetic field lines for the suns outer atmosphere, as predicted for Carrington rotation 2081 (figure 3 (a) and (b)) and Carrington rotation 2143 (Carrington rotation 2143);





(a) (b)

Figure 4: (a) Solar magnetic field model, Model: MAS, Model type: during solar minima, (b) Solar magnetic field model, Model: MAS, Model type: During solar maxima.

The different aspect of the magnetic field at solar minimum and solar maximum is apparent. Figure 3 (a) is a model for magnetic field lines of the Sun at solar minima. We can see in this example that at solar minima case magnetic field lines are well structured, and we retrieve a similar structure to that described in previous sections. For the solar minimum almost all open magnetic fields lines originate at higher latitudes the sun, while closed, but distorted field lines appear in the equatorial region. This clearly indicates that during solar minimum, most coronal holes are at higher solar latitudes, and that helmet streamers concentrate in the equatorial region of the Sun. Looking at figure 3 (b) we see that the structure of the magnetic field at solar maximum is on the contrary very complex. In this case we find closed field lines at higher latitudes, and open field lines originating at equatorial latitudes. This explains the complex aspect of the corona at solar maximum, with helmet streamers appearing at different latitudes, and more importantly, the presence of open field lines (corresponding to coronal holes) at lower equatorial regions which might give rise to the so-called Coronal Interaction Regions (CIRS).

3.2.3 (2 – D) plots of density, temperature, velocity and magnetic fields

The MAS model solves the complete MHD equations for the solar corona, including thermodynamics. As a consequence it predicts not only the structure of the magnetic, but also other properties such as the density and temperature of the plasma at different regions, and the velocity of the solar wind. In this section I will include some 2-dimensional plots of those magnitudes, comparing solar minimum and solar maximum, using the runs described above.

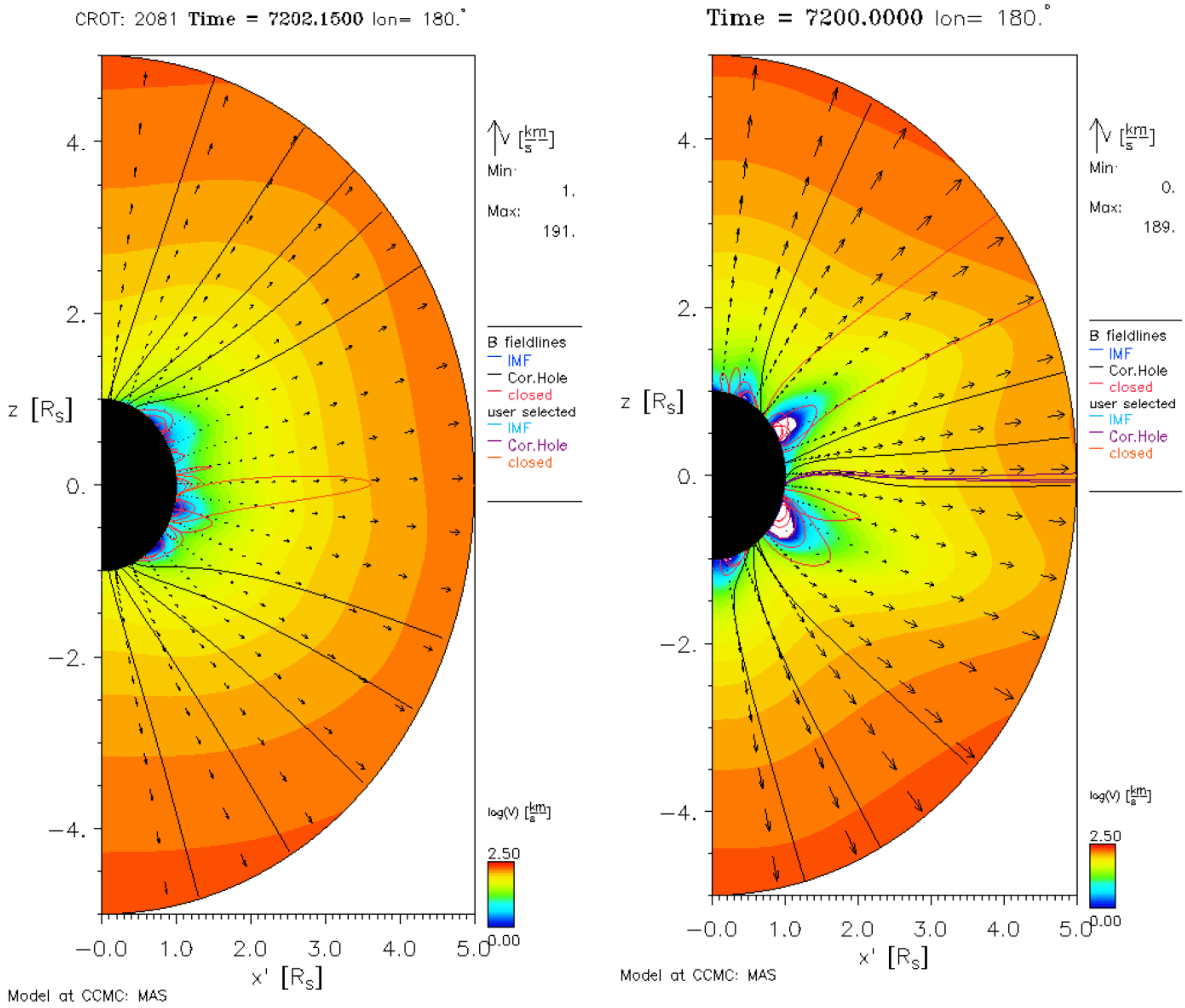
Speed vs. magnetic field vs. velocity plot

In figure 5 (a) and (b) the Continuous lines represent magnetic field lines, open in black and closed in red. Arrows represent velocity of the plasma and color contours its modulus in a logarithmic scale. Figure 5 (a) show the results for CR2081 as an example of solar minimum and figure 8 the results for CR2143 as an example of solar maximum.

As we can see from figure 5 (a) and (b) the solid flow lines which represents the structures of magnetic field line plotted in a meridian plane for solar minimum figure 5 (a) and solar maximum figure 5 (b). We see how the magnetic field at solar minimum resembles our results in section 3.1, with solar Polar Regions as sources of open magnetic field lines and equator as a source of for closed field lines. On the contrary the magnetic field at solar maximum has a much more complicated structure.

In figure 5 (a) and (b), the speed is indicated by a color code, but the direction is also plotted as a vector field representing the velocity of particles. Both in solar minimum and solar maximum, the solar wind velocity is essentially radial at these relatively low distances from the Sun, even if the magnetic field line is much more complicated in the case of the solar maximum.

In both cases it has been seen that the solar wind gets faster as we go farther from the surface, in direct relation with what we have discussed on Parker's solar wind model. Finally it is clear from the plots that in coronal holes (regions corresponding to open field lines, plotted in black), higher velocities are reached at closer distances to the Sun.

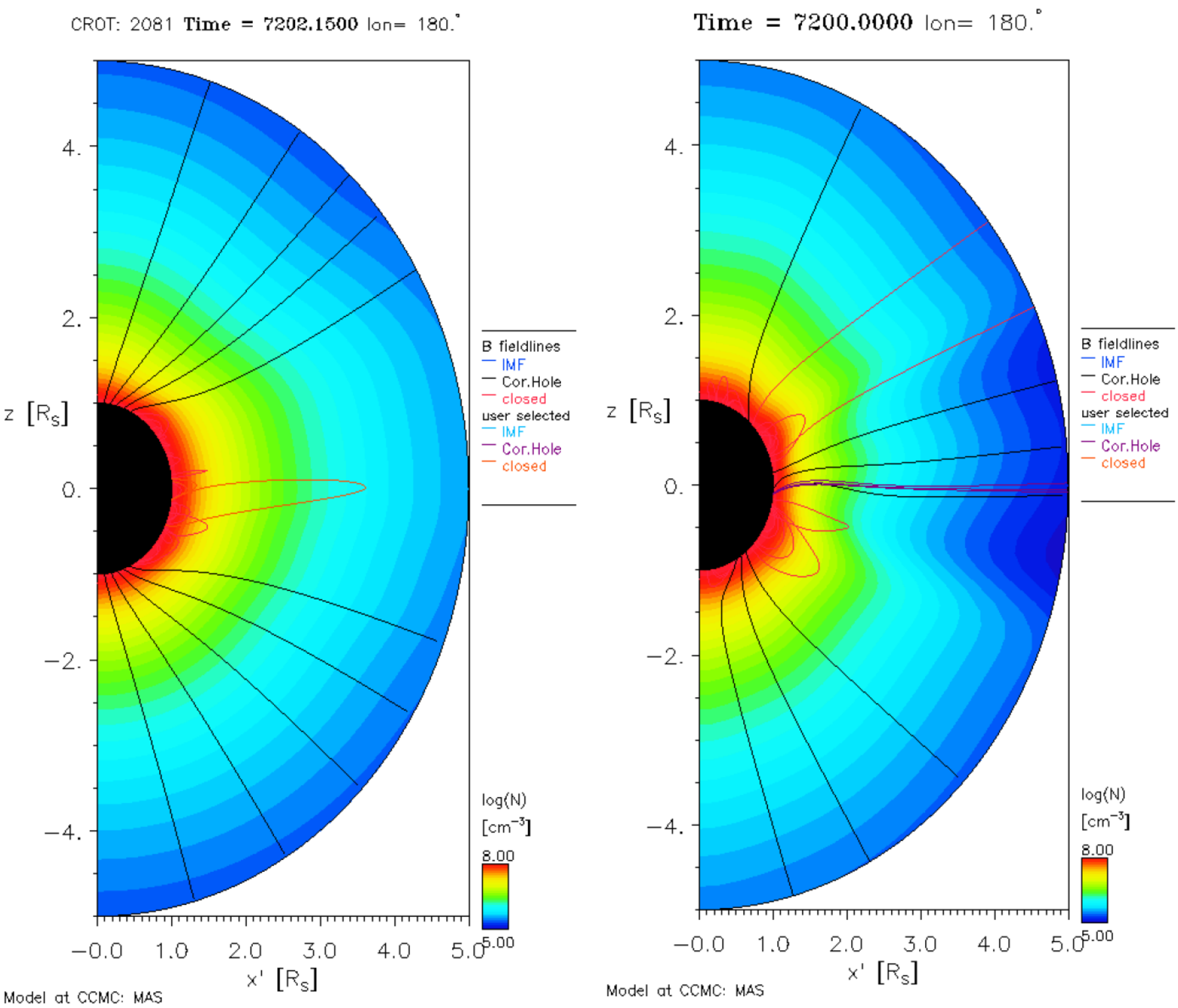


(a) (b)

Figure 5: (a) Simulation of the Solar Corona. Model: MAS, Model type: solar.(a)Solar Minima case (b) Simulation of the Solar Corona. Model: MAS, Model type: Solar maxima case.

Density vs. magnetic field vs. velocity plot

As figure 6 (a) and (b) the continuous lines in figure 6 represent magnetic field lines, open in black and closed in red. Color contours represent the number density in a logarithmic scale. Figure 6 (a) show the results for CR2081 as an example of solar minimum and figure 6 (b) the results for CR2143 as an example of solar maximum.



(a) (b)

Figure 6. (a) Simulation of the Solar Corona. Model: MAS, Model type: Solar Minima case, (b) Simulation of the Solar Corona. Model: MAS, Model type: solar maxima case

On figure 6 (a) and (b) the color code represents the density distribution in solar corona. From this plot we can see that the density of particles in corona is maximum at the equatorial region of the sun which is very near to photosphere and is decreases fast as we move away from the surface of the Sun.

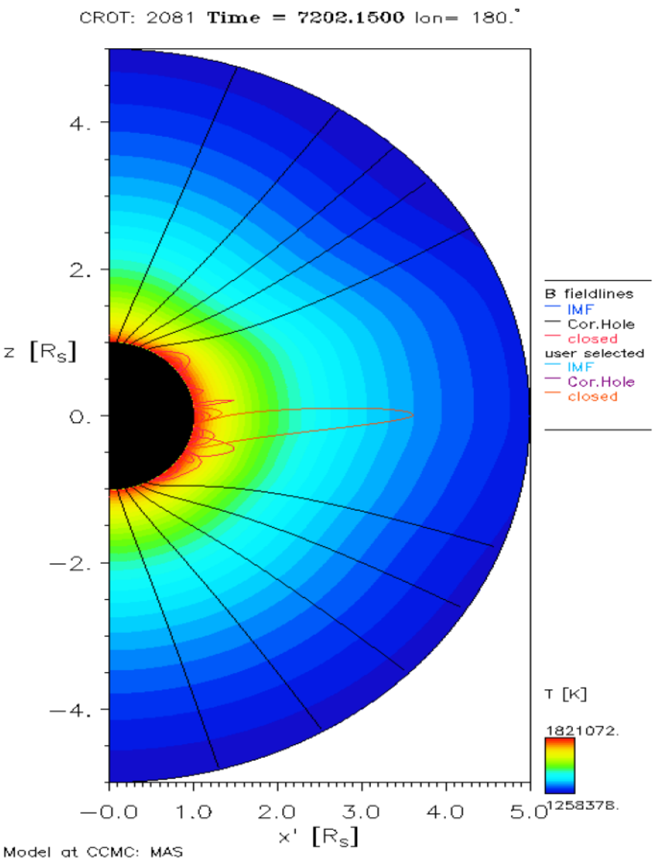
In the image corresponding to solar minimum figure 6 (a) the density of particles in corona decreases in a slower way in the equatorial region, and this is related with the presence of a brighter helmet streamer at those regions; Another way of looking at it is to see that the density of particles at the same radial distance varies as we move from the equator to the poles.

The density at solar poles is lower than that of the solar equator. This statement also clearly fitted with the theory we developed in the analytical session.

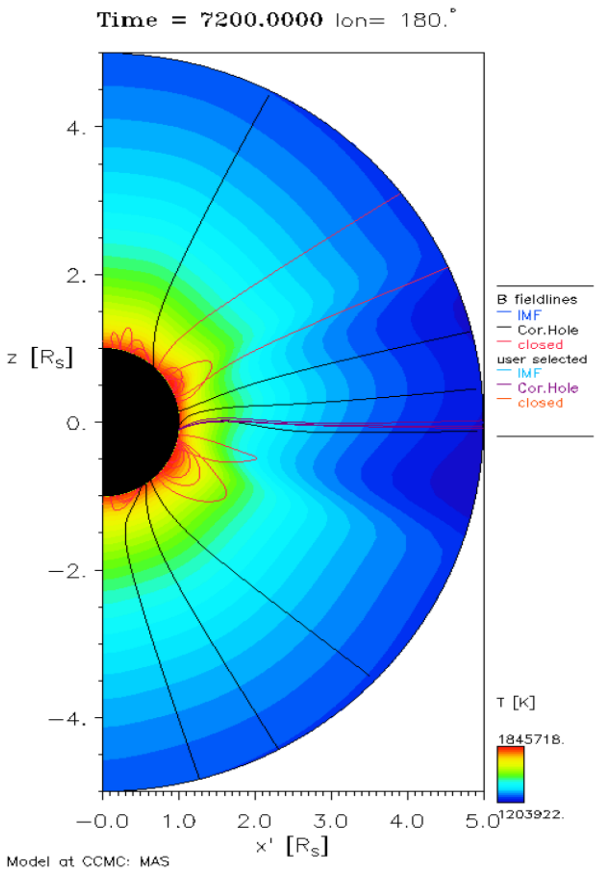
Figure 6 (b) represent a similar diagram for the solar maximum. We see how the density pattern reproduces the presence of open and closed field lines. In the regions with closed field lines, the density remains higher at higher altitudes, and the density is clearly lower in the coronal hole near the equator (which is related to the corresponding open field lines).

Temperature vs. magnetic field vs. velocity plot

As in previous figures, continuous lines represent magnetic field lines, open in black and closed in red. Color contours represent the temperature in a linear scale. Figure 7 (a) show the results for CR2081 as an example of solar minimum and figure 7 (b) the results for CR2143 as an example of solar maximum. The temperature is given by the color code in figure 7 (a) and (b).



(a)



(b)

Figure 7: (a) Simulation of the Solar Corona. Model: MAS, Model type: Solar Minima case, (b) Simulation of the Solar Corona. Model: MAS, Model type: solar maxima case.

The simulations tell us the temperature distribution in solar corona is not radially uniform, but it is possible to conclude the temperature is continuously decreasing radially. This statement is only works for regions out of photosphere.

III. CONCLUSION

The magnetic field of the corona affects the flow of plasma inside it, and the approximation of a radial flow is not consistent. Since the magnetic field lines structures of solar corona are different from surface to surface of the sun, the direction of the forces acted by the magnetic field is also in different direction. Magnetic field around the solar poles are directed radially outward for that matter the particles also move to that direction with high speed but for the case of equatorial regions the magnetic field lines are closed, so that the particle faced a resistive force and results low speed of the particles. The pressure, density and temperatures are other physical parameters vary with latitude in the solar corona, and this can only be modeled numerically. We have used numerical models provided by CCMC to illustrate how density, temperature and wind velocity are affected by the magnetic field. Since in the numerical model we use utilizes the photospheric magnetic field as a boundary condition, in this last section we have also compared the solar minimum with the solar maximum.

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