Modeling Temperature Profile of Solar Corona at Microwave and Radiowave Frequencies

Pranav Sankhe *EE Dept. IIT Bombay*, Prof R.K.Shevgaonkar *EE Dept. IIT Bombay*

***Abstract*—The electromagnetic waves in solar corona follow strange trajectories owing to the unique distribution of electrons in the corona. The complexity of the distribution poses a challenge to model the apparent brightness temperature of the corona. Explained below is an attempt to analyze the solar coronal electron distribution and obtain the temperature profile of sun. The radiation has been analyzed at frequencies lying in the microwave and radiowave bands. The electron density profile of corona is such that the refractive index is less than one and drops to zero at a particular radial distance from the photosphere. Such a distribution of electrons result into singularity where (Total Internal Reflection)TIR occurs. The trajectories of rays in such an environment have been simulated by using laws of electromagnetic transmission. The temperature distibution of the solar corona has also been found out using laws of radiative heat transfer theory.The results of the simulation have been matched with the verified trajectories of microwave and radio waves.**

***Keywords*—Tempo, EEG, Novelty Curve**

I. Introduction

The Sun of our solar system is a typical star of intermediate size and luminosity. Its radius is about 696000 km, and it rotates with a period that increases with latitude from 25 days at the equator to 36 days at poles. For practical reasons, the period is often taken to be 27 days. Its mass is about 2 x 1030 kg, consisting mainly of hydrogen (90%) and helium (10%).The Sun emits radio waves, X-rays, and energetic particles in addition to visible light. The total energy output, solar constant, is about 3.8 x 1033 ergs sec. In the interior of the Sun, at the centre, nuclear reactions provide the Sun's energy. The energy escapes by first by radiation, through the radiative zone. A set of complex convective cells are set up, which bring the heat, material and magnetic fields to the Sun's surface, the photosphere.

Photosphere
The lowest layer of the sun's atmosphere is the photosphere. It is about 300 miles (500 kilometers) thick. This layer is where the sun's energy is released as light.The photosphere is covered by granulation, which represents the tops of convective cells rising from the interior. The concentration of magnetic fields gives rise to the chromospheric network in the layer above the photosphere, the chromosphere.

Chromosphere
The next layer is the chromosphere. The chromosphere emits a reddish glow as super-heated hydrogen burns off.The temperature rises across the chromosphere from 4,500 degrees Kelvin to about 10,000 degrees Kelvin. But the red rim can only be seen during a total solar eclipse. At other times, light from the chromosphere is usually too weak to be seen against the brighter photosphere.

Corona
The solar corona consists of very tenuous plasma. At times of total eclipse, observations of the corona are possible because radiation from the solar disk is masked by the Moon. What is normally observed is the so-called K-corona.

It has been seen that the structure of the corona is quite varied and complex. Different zones have been immediately classified on the coronal disc. The astronomers usually distinguish several regions, as described below.

The solar transition region is a region of the Sun's atmosphere between the chromosphere and corona. The temperature in the transition region jumps up rapidly to nearly one million kelvin, the temperature of the corona. This phenomenon is called athe temperature catastrophe and is phase transition analogous to boiling water to make steam. Solar physicists refer to the process as evaporation by analogy to the more familiar process with water. Likewise, if the amount of heat being applied to coronal material is slightly reduced, the material very rapidly cools down past the temperature catastrophe to around one hundred thousand kelvin, and is said to have condensed.

Active regions: Active regions are ensembles of loop structures connecting points of opposite magnetic polarity in the photosphere, the so-called coronal loops. They generally distribute in two zones of activity, which are parallel to the solar equator. The average temperature is between two and four million Kelvin, while the density goes from 109 to 1010 particle per cm3.

Large-scale structures: Large-scale structures are very long arcs which can cover over a quarter of the solar disk but contain plasma less dense than in the coronal loops of the active regions. The large-scale structure of the corona changes over the 11-year solar cycle and becomes particularly simple during the minimum period, when the magnetic field of the Sun is almost similar to a dipolar configuration (plus a quadrupolar component).

Filament cavities: Filament cavities are zones which look dark in the X-rays and are above the regions where H filaments are observed in the chromosphere. They were first observed in the two 1970 rocket flights which also detected coronal holes. Filament cavities are cooler clouds of gases (plasma) suspended above the Sun's surface by magnetic forces. The regions of intense magnetic field look dark in images because they are empty of hot plasma.

Professor R.K.Shevgaonkar is a professor at Department of Electrical Engineering, Indian Institute of Technology, Bombay.

II. Finding out trajectories of rays

We analysed the propagation of rays through the corona by adopting the conventional Bambauch-Allen model for the radial distribution of electron density in the normal background corona. The model is based on photometry of white light of the corona and zodiac light.

$$N = 1.55 * 10^{14}\rho^{-6}(1 + 1.93\rho^{-10}) electrons/m^3$$

where, N is electron density
ρ is the distance from the sun's center in units of photospheric radius

By adopting this formula we assume spehrical symmetry. The advantage of harboring this model is that we could compare our results with other authors as mentioned and followed by

The refractive index 'n' in a medium consisting 'N' free electrons/cubic meters, each making 'v' collisions/sec, is given by :

$$n^2 = 1 - \frac{Ne^2}{\epsilon_0 m(\omega^2 + v^2)}$$

We ignore w^2 term in the above equation since $\omega^2 << v^2$. Hence in terms of photospheric radius (ρ), we can express the equation of refractive index (n) as,

$$n^2 = 1 - 12400 * f^{-2}\rho^{-6}(1 + 1.93\rho^{-10})$$

Where f is the frequency of the ray

We calculate the path of the rays using the Snell's laws. Tp apply them, we will define our calculation domain,

- All the rays lie in the plane containing the center of Sun.
- For all the points in the solar atmosphere, $n\rho sin(i) = a$

Where,
'a' is a constant and 'i' is the angle of incidence of the ray on the surface of constant refractive index. Intutively speaking, the constant 'a' represents the distance between the equator of sun and the ray at infinity. Also, note that the surface of constant refractive index here is spherical in shape.

We know that in polar co-ordinates, for any curve, we can write :

$$slope = -\frac{rd\theta}{dr}$$

Hence we can write for a curve representing the the equation of a ray considering the centre of the sun as the origin of our polar co-ordinate system, we can write,

$$\frac{\rho d\theta}{d\rho} = -tan(i)$$

Given the above two equations and some elementary trigonometry, this is what we get,

$$\frac{d\theta}{d\rho} = \frac{-a}{\rho(n^2\rho^2 - a^2)^{1/2}}$$

The trajectory of a ray can be obtained by solving the above diifferential eqaution. While the ray propagates through the coronal atmosphere, it reaches to a value of ρ where the denominator of the above equation $[\rho(n^2\rho^2 - a^2)^{1/2}]$ becomes zero and is we increase the ρ further the denominator becomes imaginary. We call this point as the *singularity point* of the ray and this is the point where the ray undergoes *Total Internal Reflection*. Hence we need to change the limits of integration of the equation of θ by taking into account the singularity point.

III. Calculating temperature profile of sun

After calculating the trajectories, we will calculate the temperature(apparent brightneess temperature) of the solar corona. We will be using basic theory of radiative heat transfer. Consider a cool cloud as shown in Fig.4 with a hot source of radiation behind it. The radiation will enter the cloud with intensity I_o, but will be absorbed on passing through the cloud.

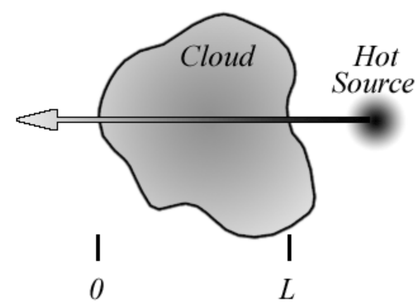


Fig. 1. Cloud

$dI = -k_n I dl$ where I is the intensity entering each volume element. This is a trivial differential equation whose solution is:

$$I = I_0 exp\Big(\int_0^L k_n dl\Big)$$

Note that the integration is taken along the line of sight from the observer. In the case where the absorption is constant, of course, k_n can be brought out of the integral. The integral quantity is a dimensionless quantity called the *optical depth*. The optical depth is a convenient way to refer to the "thickness" of a cloud. It measures how many e-foldings of intensity reduction the cloud's thickness represents.

To obtain a relation between the observed temperature, source temperature and the cloud temperature, we use the Rayleigh-Jeans approximation.

$$T_{obs} = T_{cloud} exp(-\tau) + T_e(1 - exp(-\tau))$$

IV. RESULTS

The solar coronal atmosphere has been simulated using the above equations and the trajectories of the rays and the temperature profile have been plotted. All the simulations have been coded using `Python` packages like `numpy` and `scipy`.

We plot here the trajectories of rays with different 'a' where a denotes the distance between the ray and sun's equator at infinity. We also simulated the results when a beam of radiowave is shone on sun. We make incident a beam of rays spanning from -4.95*solar radii to +4.95*solar radii from the sun's equator. You observe from the figure how the rays which are closer to the equator get deflected more than the rays which are far away. If we connect all the singularity points of the rays, we get the profile of sun as seen in the microwave/radiowave range i.e if we have the capability of looking at the sun in the microwave/radiowave range the sun will appear around 2.24 times than what we see now. (2.24*solar radius is the singualrity point of rays when the frequency is 10 MegaHertz).

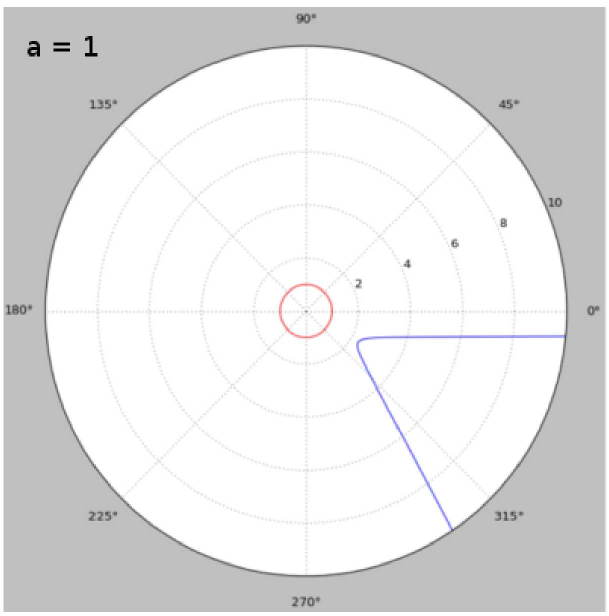


Fig. 2. Trajectory of ray having $a = 1$

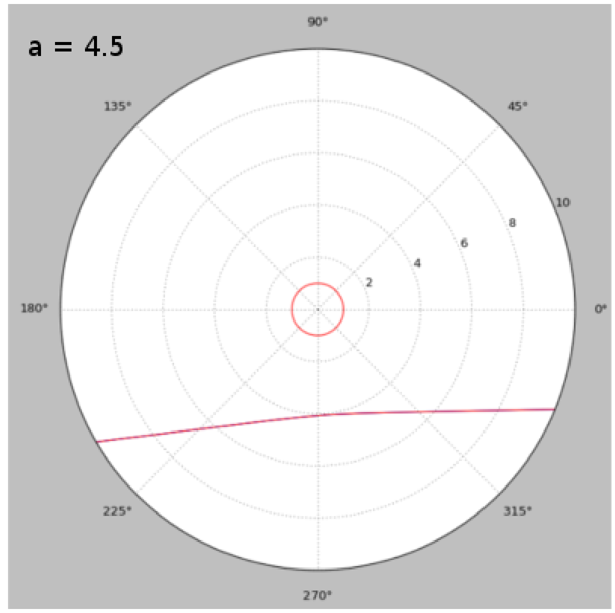


Fig. 3. Trajectory of ray having $a = 4.5$

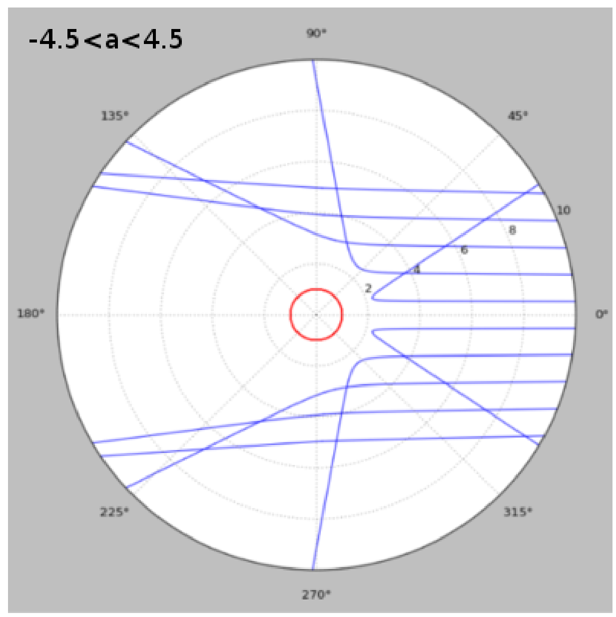
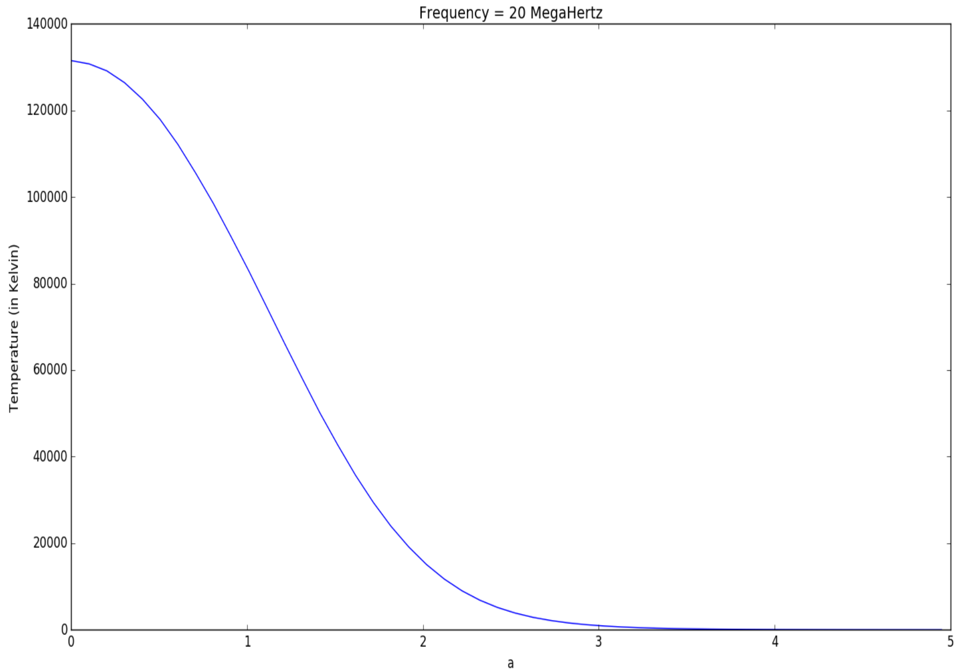
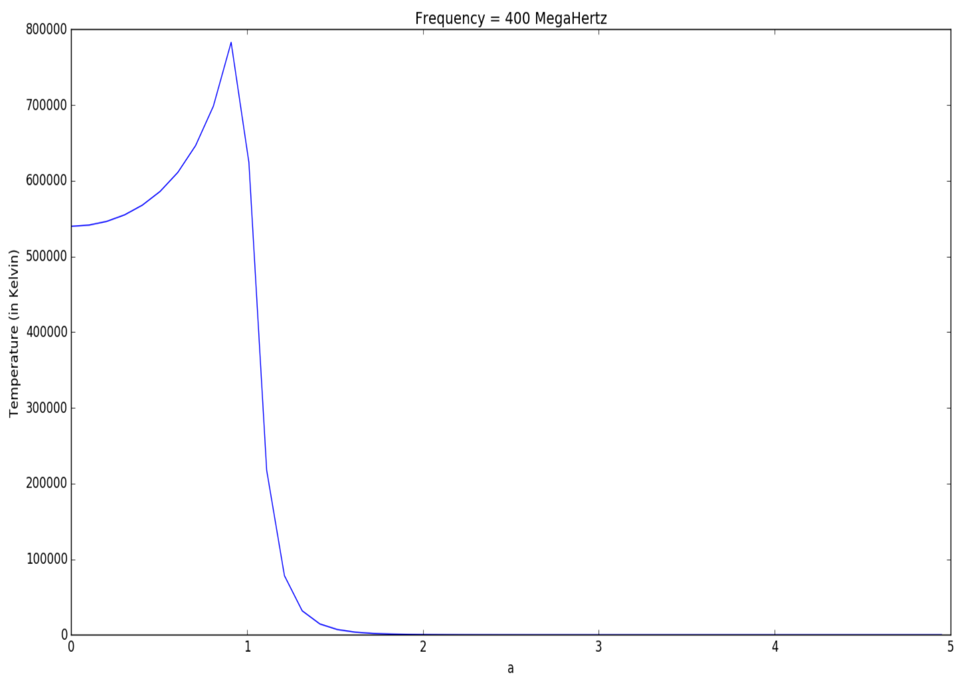


Fig. 4. Trajectory of a beam which has a in the range of -4.5 to +4.5

In order to calculate the temperature profile we need to calculate the optical depth as elaborated in section III. The calculation of the optical depth involves calculating the line intergral along the obtained trajectories of the individual rays. We plot the temperature profiles at different frequencies. The below displayed plots are at frequency 20 MegaHertz and 400 MegaHertz. The decreasing of the brightness temperature is due to the thinning out of electrons as the level of origin rises with decreasing frequency as observed by [1]


Frequency = 20 MegaHertz
Temperature (in Kelvin)
a
140000
120000
100000
80000
60000
40000
20000
0
0
1
2
3
4
5


Frequency = 400 MegaHertz
Temperature (in Kelvin)
a
800000
700000
600000
500000
400000
300000
200000
100000
0
0
1
2
3
4
5