Modeling Temperature profile of Sun at Microwave and Radio frequencies

Abstract

I present here the detail procedure of how we analysed the solar coronal electron distribution and obtained the temperature profile of sun. The radiation has been analyzed at frequencies lying in 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 point. The trajectory of rays in such an environment has been found out and by radiative heat transfer theory, we obtained the brightness temperature of sun and thus the complete temperature profile of sun.

Structure of Solar Atmosphere

Above the photosphere, the temperature first falls to about 4,300 K, but then rises through the chromosphere, and then in particular through the transition region, to reach the temperature of the corona which is between 1 and 2 million K. This is illustrated in Fig. 4 below. Note that the thickness of the transition region is only a few hundred km, yet through it the temperature rises from about 10,000 K to in excess of a million K.

The solar atmosphere above the photosphere is highly non-uniform. It consists of a plasma, mostly electrons and protons, with a small percentage of ionised helium and at least partially ionised heavier ions. Its electrical conductivity is very high (it can even taken to be infinity) and it is shaped by the structure of the magnetic fields in the atmosphere.

Sun

he 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.

There is one interesting thing about corona: The surface of the sun is almost 10,000 degrees Fahrenheit. That’s really hot. But the sun’s corona is over 200 times hotter—millions of degrees Fahrenheit. That’s like the actual flame of a fire being 200 times colder than the air around that fire. Why would the area around a hot burning mass be hotter than something that is actually closer to the source of heat? And if the corona is so hot, then why doesn’t it heat up the sun’s surface to a similar temperature?

Light from the corona comes from three primary sources, from the same volume of space.

- The K-corona (K for kontinuierlich, "continuous" in German) is created by sunlight scattering off free electrons; Doppler broadening of the reflected photospheric absorption lines spreads them so greatly as to completely obscure them, giving the spectral appearance of a continuum with no absorption lines.

- The F-corona (F for Fraunhofer) is created by sunlight bouncing off dust particles, and is observable because its light contains the Fraunhofer absorption lines that are seen in raw sunlight; the F-corona extends to very high elongation angles from the Sun, where it is called the zodiacal light.
- The E-corona (E for emission) is due to spectral emission lines produced by ions that are present in the coronal plasma; it may be observed in broad or forbidden or hot spectral emission lines and is the main source of information about the corona's composition.

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.

- **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 Hα 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.

After having given a brief idea of Corona and its properties, now we will get to more details about the electron density profile and the propagation of rays through the corona.

In the normal background corona, we will adopt the conventional Bambauch-Allen model for the radial distribution of electron density. The model is based on photometry of white light of the corona and zodiac light.

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

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

$$n^2 = 1 - \frac{N e^2}{\epsilon_0 m (\omega^2 + \nu^2)}$$

In terms of rho(photospheric radius) and taking 'w' >> 'v', we have :

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

The path of the rays can be calculated using snell's laws. Note two things here.

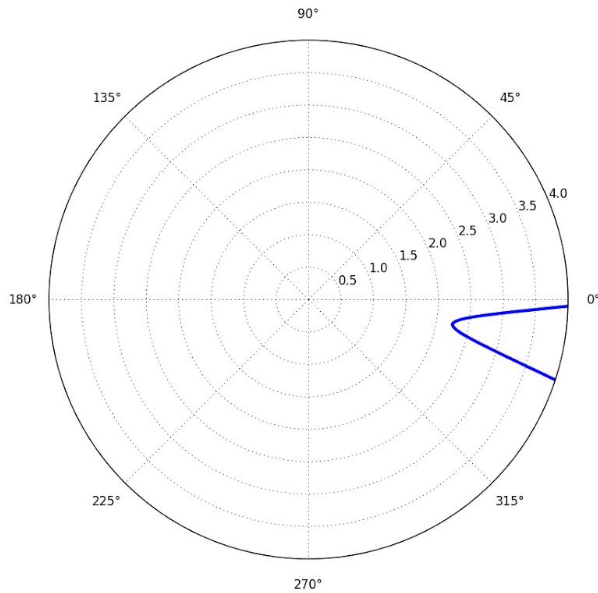
- All the rays lie in the plane containing the center of Sun.
- For all points in the solar atmosphere,

$$n \rho \sin i = a$$

Where, 'a' is a constant for a particular ray. 'i' is the angle of incidence of the ray on the surface of constant refractive index.

Note : Physically, the constant "a" represents the distance between the equator(of sun) and the ray at infinity. The surface of constant refractive index here is spherical in shape.

For any ray like the one shown below, the following equation holds good.



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

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

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

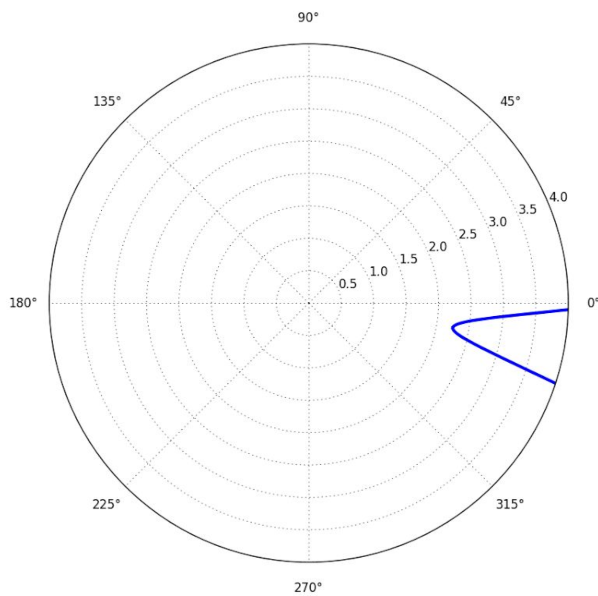
Thus the trajectory of ray can be obtained by solving the above diifferential eqaution.
The value of theta is give by :

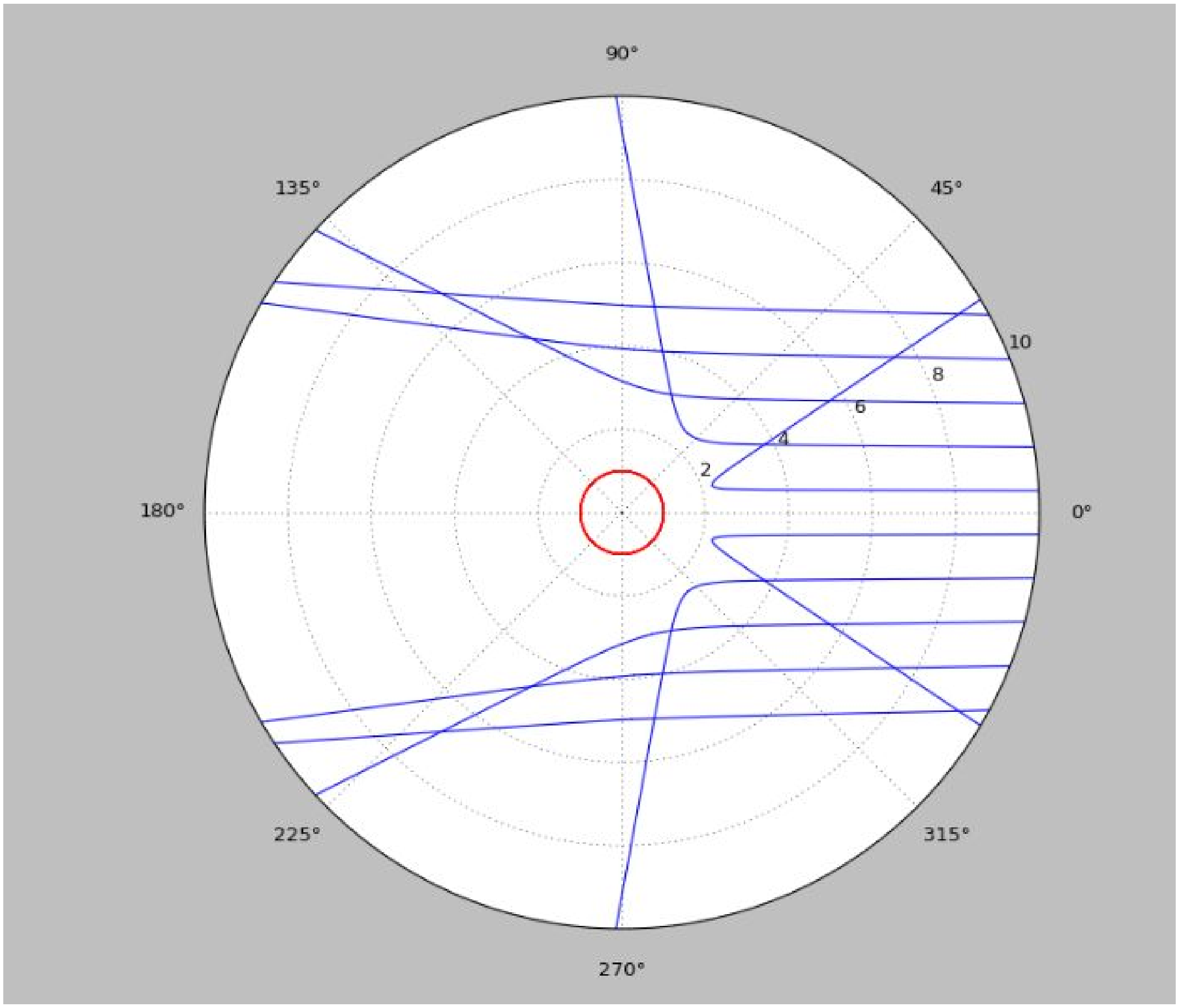
$$\theta_a = a\int_{\rho_a}^{\infty} \frac{d\rho}{\rho\,(n^2\rho^2 - a^2)^{1/2}}$$

This is the python script which simulates the sun's atmosphere and plots the trajectory of the rays. Click here for the code

Here are the simualtion results :

For ray which made a distance of 0.5 solar radii from the equator.

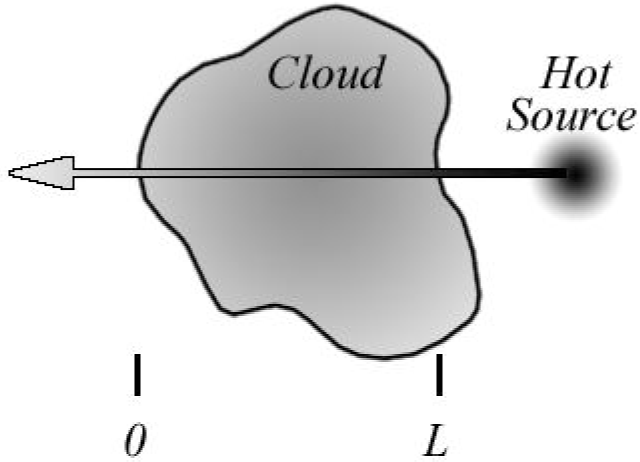




Now after having calculated the paths of individual rays, we will be using the some radiative transfer theory and these paths to get a temperature profile of the sun.

Radiative Transfer

Consider a cool cloud with a hot source of radiation behind it. The radiation will enter the cloud with intensity Io, but will be absorbed on passing through the cloud.



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

$$I = I_o \exp\left(- \int_0^L k_n \, dl\right).$$

Note that the integration is taken along the line of sight from the observer. In the case where the absorption is constant, of course, kn 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 basically measures how many e-foldings of intensity reduction the cloud's thickness represents.

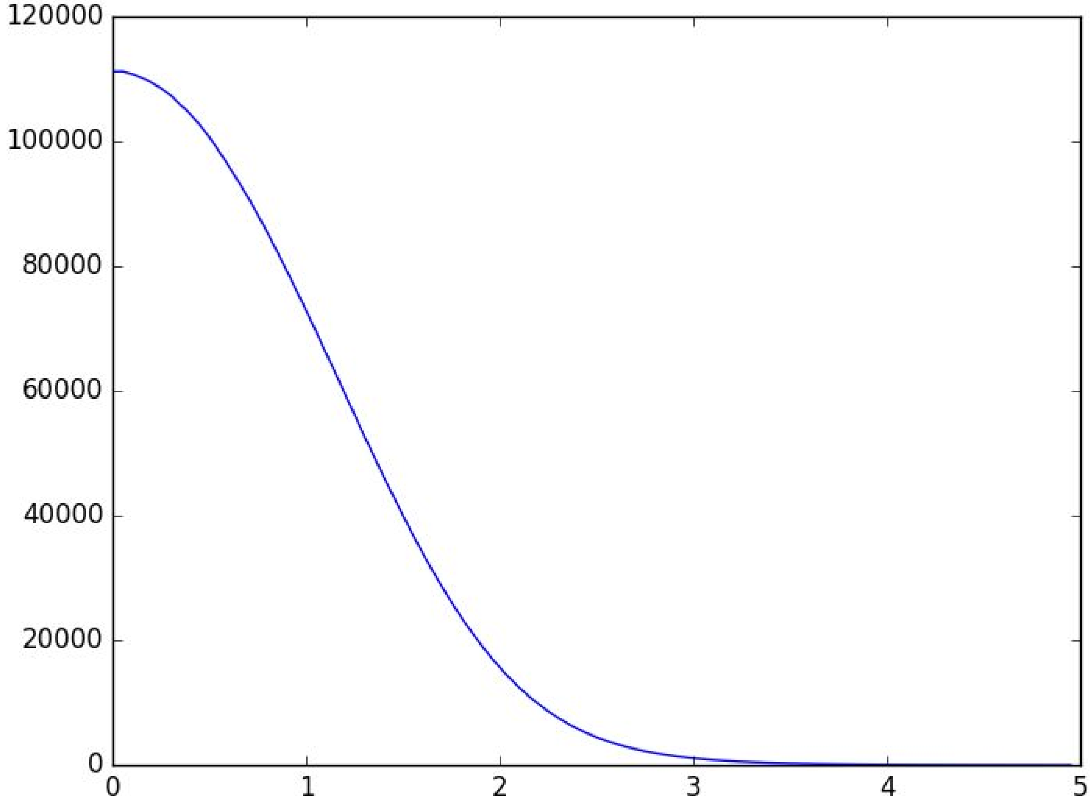
To obtain a relation between the observed temperature, source temperature and the cloud temperature, we use the Rayleigh-Jeans approximation. We obtain the following:

Tobs = Tcloud*exp(-tau)* + *Te*()-exp(-tau))

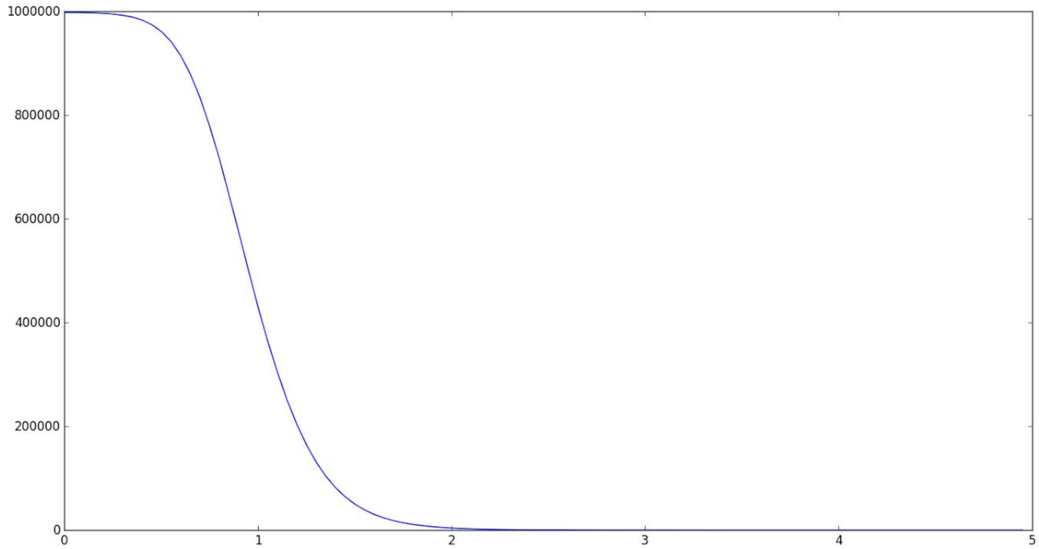
Quite intuitive, isn't it?

To obtain the temperature profile, you need to plugin this equation in the code. And you get this results :

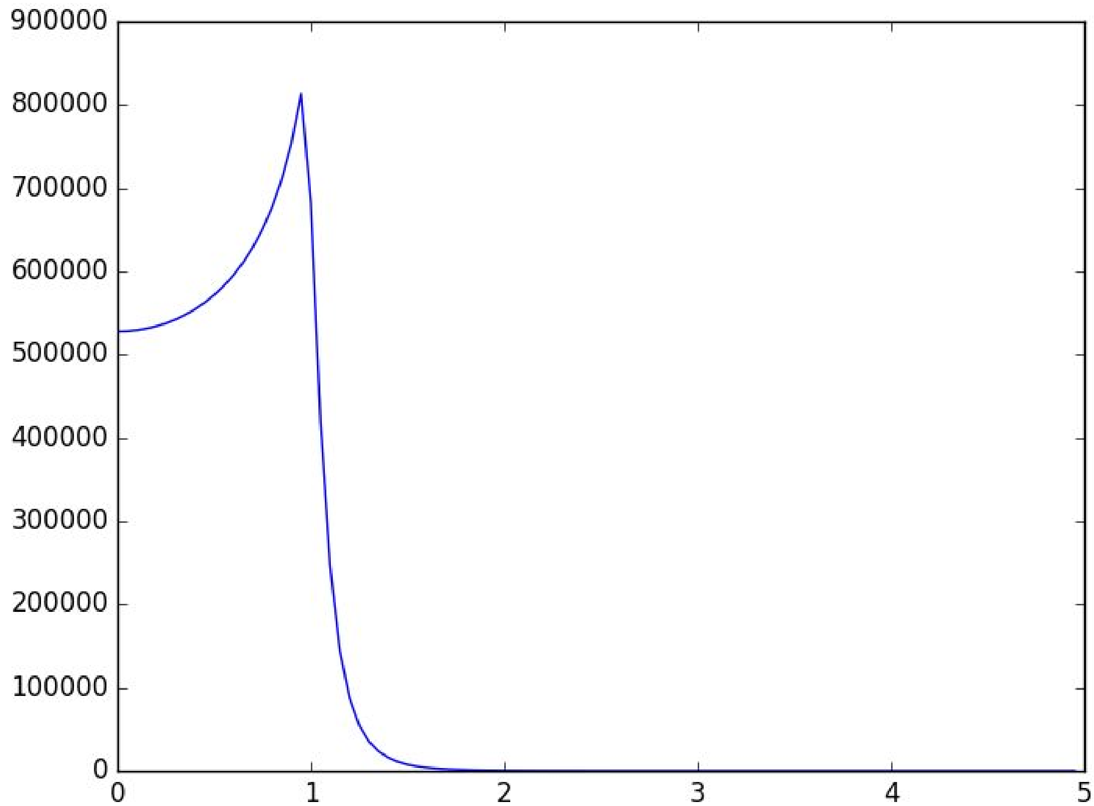
At Frequency = 18 Megacycle per second. (18*10^(6) hertz):



At Frequency = 100 Megacycle per second. (100*10^(6) hertz):



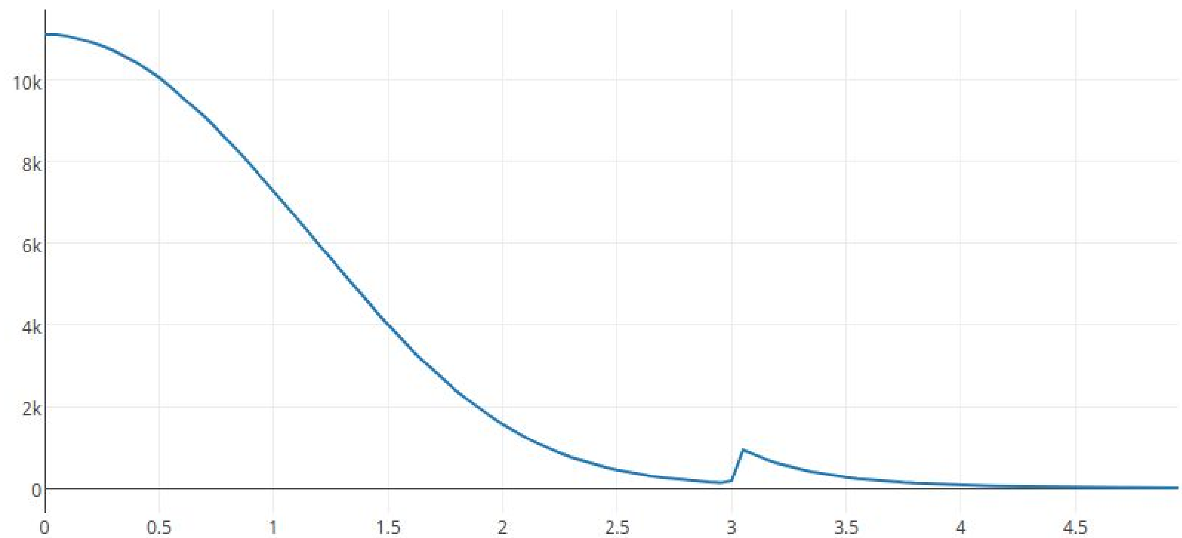
At Frequency = 400 Megacycle per second. (400*10^(6) hertz):



You must have observed that we took a radially symmetric profile of electron density. But actually the sun has many disturbances in it's bizarre atmosphere. One of them are called coronal cones. These are conical shaped regions which have their apex at the core of sun and they extend upto the outer atmosphere. These conical regions have less electron density in them as the material ejects out from this cones and results into solar flares.

Here's the result when you take into account this coronal holes in the electron density model of solar atmosphere.

Simulation with cone angle = 1 radian and Frequency = 18 Megacycles per second.



What you see is that these regions appear darker than the surrounding area by the virtue of low electron density at the given frequency.