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On The Nature of the Green Vegetation

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Abstract: *The green colour of vegetation has been termed as a paradox and it has explained in terms of the characteristics of the atmospheric absorption against the background of solar irradiance and solar blackbody distribution profile. The green colour is attributed to an absorption holes and analogy of the has been drawn with the spatial holes in the laser theory.*

Keywords: *Green of Vegetation*

1. INTRODUCTION

On a clear day with an unpolluted environment the sky appears blue. The reason for this is that the light from the sun which passes through the atmosphere is scattered according to the Rayleigh law [1] which shows that the scattering is a function of λ^{-4}. In 1871 Lord Rayleigh used dimensional analysis to derive a formula for the intensity of scattering by particles that are small compared to the wavelength of the incident light. The intensity of the scattered light is given by

$$I = I_o \frac{8\pi^4 \alpha^2 N}{\lambda^4 R^2}(1+\cos^2\theta) \text{......... ...(1)}$$

Here I is the intensity, α is the polarizability, λ is the wavelength, N is the number of scattering molecules and R is the universal gas constant. It is also assumed that the atmosphere is an ideal gas so that scattering by N molecules is N times the scattering by one. Rayleigh's formula was subsequently improved for atmospheric scattering using various correction factors by physicists like King, Pendorf and Chandrasekhar, but the main form has remained the same and is still used today [2]. It is worthwhile to note that the majority of gas molecules in the atmosphere, specifically the dipoles N_2 and O_2 are indeed much smaller than the wavelength of visible light. This is the reason why Rayleigh scattering occurs at every point in a clear atmosphere directing energy toward a viewer from all direction. Since the scattering is a function of λ^{-4} the scattering is greater at shorter wavelengths or the violent/blue end of the spectrum. This effect has been observed earlier by John Tyndall in 1859 who examined the passing of light through a clear liquid containing small particles in suspension. At this point it may be emphasized that particles of the same size can also scatter but they are not needed. What is needed is that there is a dark background (or the black universe) to see the scattering and that the atmosphere is optically thin. If the thickness of the atmosphere would be more and identical in composition the colour of the sky would have been different. This is experimentally demonstrated by the fact that sunsets are red. If the sun is very close or below the horizon the light at grazing incidence travels through a great thickness of air than when overhead. More of the blue light is then scattered out of the beam but cannot reach the observer due to the low position of the sun. Therefore there will be relatively more red light present in the beams which reach the observer. An alternate to Rayleighs theory was developed by Einstein [3] in 1910, in his work related to Critical Opalescence, based on the work of Smoluch owski. Critical Opalescence is the strong scattering that takes place in a system where the liquid and gas phase have the same density and liquid drops of the same size as the wavelength of visible light is formed. Einstein expanded on this to derive an equation for scattering without directly assuming that matter in the atmosphere is discreatly distributed. Instead he took the matter to be continuous, but characterized by a refractive index that is a function of the position. The equation he worked out for a homogeneous ideal gas is given by

$$\frac{J_o}{J} = \frac{R_oT_o}{N}\frac{(\varepsilon-1)^2}{P}\frac{(2\pi)^4}{\lambda}\frac{\theta}{(4\pi D)^2}Cos^2\psi....(2)$$

Which also shows the $1/\lambda^4$ wavelength dependency.

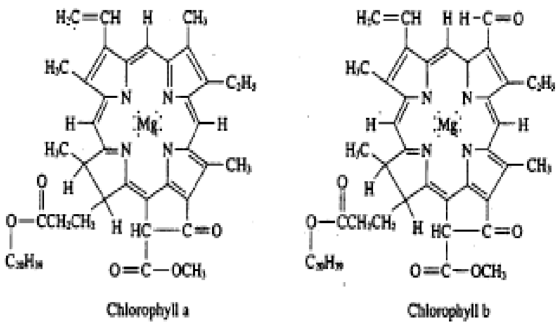
1.1. Mie Scattering

A more general scattering theory is the Mie Debye or Mie scattering of electromagnetic radiation. It was published by Gustav Mie [4] in 1908 and describes the scattering of electromagnetic radiation by spherical or homogeneous particles. Rayleigh scattering is in fact a limiting case of Mie theory for particles much smaller than the wavelength.

Like the blue of the sky and ocean, the green of the vegetation is another prominent environmental phenomenon of the earth. We are mainly concerned with this phenomenon in this article. It is generally understood that the green of the vegetation from tiny grass to lofty trees is due to chlorophyll. Like the blue of the sky which is completely explained by the scattering theories, the green of the vegetation needs a suitable theory to account for the phenomenon of the green of vegetation. There are presumably many theories and notably that by Sir C.V.Raman [5]. In the present work we give an attempt to some **unexplained** features associated with the green of vegetation. During this a comparative studies with the blue of the sky and red of the sunset have also been made. The role of human vision is emphasized.

2. THE PARADOX OF CHLOROPHYLL

Chlorophyll absorbs strongly at blue-violet and red sector of the spectrum in the visible region, but it absorbs very weakly in the green-yellow and orange sector of the visible spectrum. On the other hand the sun shines strongly in the green-yellow sector of the spectrum and weakly in the blue-violet and red sector of the spectrum. We term it as chlorophyll paradox (for the first time) and try to resolve it as least partially without being influenced by the beliefs and ideas taken from the existing earlier works. Before proceeding to do so let us consider the molecular structures of chlorophyll a and b as shown in Fig 1 (a) (b). The corresponding absorption spectra of chlorophyll a and b are shown in Fig 1c.



(a) Chlorophyll -a (b) Chlorophyll -b

(c)

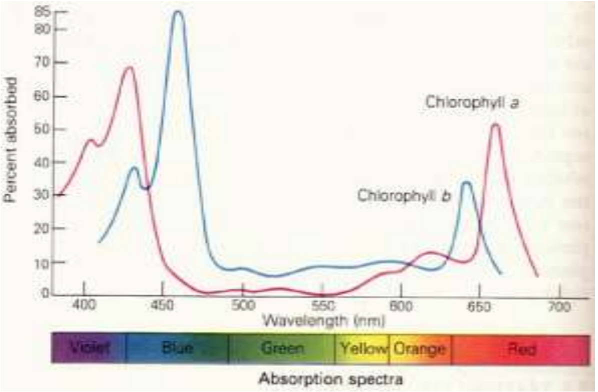


Fig1. *(a) - (b) Structures of chlorophyll a, b and (c) Absorption spectra*

Chlorophyll is a family of photoreceptive molecules widely distributed cyanobacterium that lives in light environments depleted in visible light and enhanced in infrared radiation. Chlorophyll is also present in algae and plants to perform photosynthesis. There are several kinds of chlorophylls, dominant one is chlorophyll-a. Both chlorophyll b (Chl b) discovered in 19th century and Chlorophyll c (Chl c) were considered to be accessory chlorophylls. Chlorophyll d (Chl d) was discovered in red algae (Rhodophyta) more than seventy years ago [6]. Chlorophyll–c was also earlier discovered by the same persons who discovered chlorophyll d [7]. As can be seen from Fig 1, the chlorophyll molecules are largely made of carbon and hydrogen atoms and some nitrogen containing molecules surrounding a magnesium atom. Chlorophyll functions by absorbing light which excites the electrons within the molecule and the process is analogous to the operation of a solar cell. This produces a series of complex reactions. Cynobacteria were the first life forms which use chlorophyll and it is believed that chlorophyll structures in cells that house chlorophyll, originates sort of symbiotic merger of eukaryotic cells around cynobacteria. We observe from Fig 1 that chlorophyll (a, b) is a very poor sorber in the green yellow region. This presumably accounts for the green color of the vegetation.

It is worthwhile to note that the sun emits electromagnetic radiation over a wide range of wavelengths. The distribution of intensity as a function of the wavelength is given by the Planks equation for a black body.

$$I(\lambda)\Delta\lambda = \frac{2\pi hc^2\Delta\lambda}{\lambda^5(e^{hc/\lambda kT}-1)} \ldots\ldots\ldots\ldots\ldots(3)$$

where I (λ) Δ λ is the emitted energy per unit area of black body per unit time within a wavelength interval Δ λ, measured at temperature T, wavelength λ and k the Boltzmann's constant.

We are mainly concerned here with the fact that taking 5800^0 K as the surface temperature of the sun the peak wavelength is about 500 nm. This is the blue-green sector of the visible spectrum or the range of human eye. Thus it is essential to understand the basic facts related to human vision to explain the blue of the sky or the green of the vegetation. This point was in fact raised Sir C.V.Raman several decades ago [5]. Let us consider again the absorption characteristics of chlorophyll as illustrated in Fig 1, for the visible region and compare the characteristic features with the absorption characteristics of the atmosphere species in the region from 200 to 3000 nm as shown in Fig 2. In this curve the energy distribution curve for sun (taken as a black body) at 6000^0 K, Solar irradiance curve outside the atmosphere and solar irradiance curve at sea level are shown. It is interesting to note that the selective absorption processes due to the species 0_3, H_2O and others take place beyond visible region in an oscillating manner. It is reasonable to believe that the absorption characteristics of chlorophyll (a, b) in the visible are also a part the same oscillating pattern as shown in Fig 2. If it is so, what is true for chlorophyll in the visible region is also true for H_2O in the infrared region.

Table1. *Absorption characteristics of the atmosphere in the range 200 – 3000nm. Absorption holes are produced at regular intervals.*

Range (nm)	Species
450 – 700	0_3 chlorophyll
700 – 1000	H_2O O_2
1000 – 1300	H_2O
1300 – 1600	H_2O
1600 – 2200	H_2O
2200 -- 2700	H_2O

Thus the so called chlorophyll paradox is not a paradox at all if we examine the shape of the entire absorption characteristics of the atmosphere against the background of solar irradiance in the wavelength range 200 – 3000 nm. There are six distinct absorption holes as indicated in the following Table 1. These holes are not necessarily at equal distances in terms of wavelengths. We would like to note here that these holes are quite analogous to the spatial holes [8,9], which are burned by the laser filed in the population difference at regular distances inside a laser cavity. Further it may be noted that the spatial holes which are burned by the field intensity for non-moving atoms are seen to wash out for rapidly moving atoms [10].

Both the formulas and calculations with the spatial holes in a laser cavity is outside the scope of the present article. But the question remains whether the model of the atmospheric absorption as considered in Fig 2 is really analogous to the laser cavity exhibiting spatial holes.

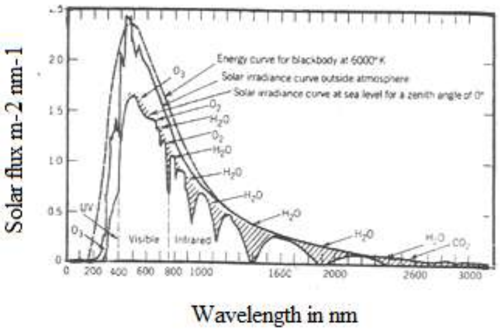


Fig2.*Solar radiation incident at the top of the atmosphere, outside the atmosphere and at sea level. Energy distribution curve for blackbody at 6000^0 K is also shown.*

3. COLOR PERCEPTION AND GREEN OF VEGETATION

In this section we consider the phenomenon of color perception by the human eye. This is indeed required as the visible sector of the spectrum, (whether it is the scattered blue radiation accounting for the blue of the sky or the transmitted green radiation, accounting for the green of the vegetation), is the regime of wavelengths the human eye can see. Thus it is essential to have an idea about the response curves of the human eyes. This is exhibited in Fig 3. Human eye has three types of light receptors located in the retina [11]. They are known as cones which operate only during the period with enough illumination. There are also present in the retina receptors known as rods. These rods are sensitive only during low levels of illumination. It is worthwhile to note here that each cone is sensitive to a broad range in the visible sector of the spectrum. The peak sensitivity of the cones is found at 580 nm (Red), 540 nm (Green) and 450 nm (Blue). The color as perceived by the eye depends on how many photons of particular wavelengths fall within the response curves. As can be seen in Fig 3 the sensitivities overlap which means that if light of any color is intense enough it will be seen as white, because of the fact that all cones will be fully activated.

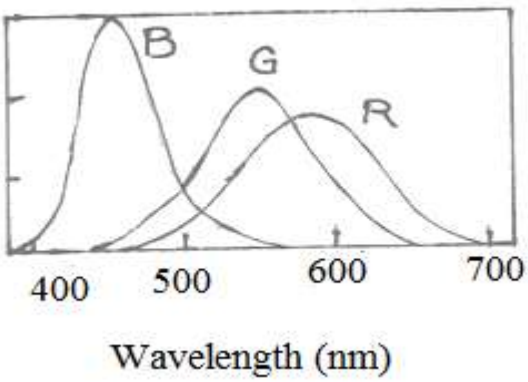


Fig3. *Sensitivity curves of the human eye.*

B denotes blue, G green and R red

In this case the principle of superposition of color is important. The principle of superposition of color indicates that there are more than one way to create a unique combination of wavelengths e.g. to create the green. When looking at the green of the vegetation, the red cones respond primarily to the small amounts of red and less to the orange and yellow green cones have their strongest wavelengths. The response at the scattered or transmitted green and green blue colors and slightly less for yellow. It can be concluded that the sky lights stimulates the blue cones more strongly. By looking at the response curve it can be seen that the sensitivity for the blue light is much higher than that for violet. Thus even though there are more scattered violet radiations than there are blue wavelength the blue is perceived better. What about the green color of vegetations. The familiar examples are the green color (yellow mixed) of the widely spread tea gardens or the green colored rice fields. Similar arguments hold good for explaining the green of the vegetation as well. It is seen that the peak of the response curve for the green lies approximately in the middle of the visible sector of the spectrum. This also means that human eye can perceive the green color of the tea gardens transmitted (or scattered) by the leaves better than any other color under certain environment. To illustrate this idea we consider an experiment where the green color of the tea garden, spread over a distance of 1 kilometer is viewed with the help of a pocket spectroscope fitted with a wavelength scale and the intensity of the green color is visually estimated. A photodiode is connected with a multimode optical fiber to estimate the intensity of the green sector of the spectrum quantitatively. The observation is made from a height of about 4 meter in the first floor of a double storied house. The room is made dark for convenience of observation. It is very instructive to make observations as daytime increases from morning till afternoon. Visual observation clearly indicates that in a clear sunny day the intensity of the green color is at its maximum at noon and the intensities do vary at other occasions. Table 2 includes the results of observations made with the help of a pocket spectroscope and a photodiode. As can be seen from Table 2 intensities are maximum at around midday and they are insignificant in the forenoon and afternoon.

The photodiode readings and visual estimates are identical. Thus the transmitted (or scattered) green color is different from the blue of the sky. The apparent reason of the intensity variation is related to the response curve of the green sector as shown in Fig 3. In this connection we would like to indicate one of the most interesting environmental feature related to the green of the vegetation. This is the so-called blue of the hills. If we look at a hill covered with vegetation from a distance of more than two kilometers, the hill appears blue. The green of the tea gardens located quite close to an observer and the blue of the hills further away is a familiar scene. The explanation was given in a paper by Saikia and coworkers [12]. The blue color of the hills covered with green vegetations is not discussed in any of the early works except in the work describes in reference [12]. This is presumably concerned with the physiology of vision.

Table2. *Intensities of the green color of tea garden at successive stages of the day.*

Time(in hrs)	Intensity	Intensity
6	vw	.000
7	vw	.000
8	vw	.001
9	w	.009
10	ms	.009
11	s	.510
12	vs	.520
13	vs	.400
14	s	.080
15	w	.009
16	w	.005
17	vw	.000
18	vw	.001
19	vw	.000
20	vvw	.000

W=weak, vw=very weak, vvw=very very weak, s=strong, ms=medium strong, vs= very strong etc.

It is however, noteworthy that as one approaches a blue hill from a distance of about 3 kilometer the blue color of the hill fades away and the usual green color of vegetation appears. There is no line of demarcation for this. It depends on various factors like pressure, temperature humidity in the environment and vision etc. Before concluding it is quite interesting at this stage to indicate Ramans observation [5] regarding the green colour of vegetation. Raman used simple spectroscopic techniques to infer the salient features associated with the green of the vegetation. Very interesting results emerged from the comparative study the made of the leaves in different stages of growth. We believe that our work not only supports Raman’s observations but also supplements it.

4. SUMMARY AND CONCLUSIONS

From the discussions above it is essential to make a conclusion and summary of the work. The green color of the vegetation has been termed as a paradox and it has been explained in terms of the characteristics of the atmospheric absorption against the background of solar irradiance and black body distribution profile. The green color is attributed to an absorption hole in the region 450-700 nm. Analogy of the holes has been drawn with the so-called spatial holes in the laser theory. The blue color of the hills is discussed and related to physiology of vision. It is worthwhile to add here that the experiment described in section 3 may be used in the undergraduate curriculum as an activity to demonstrate the visual response of the green of the vegetation such as tea gardens.

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