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Rainbow Formation in the Venusian Atmosphere

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Abstract

The possibility of rainbow formation in the Venusian atmosphere is discussed. The Venusian clouds contain liquid droplets of aqueous solution of sulfuric acid of 75% concentration by weight having a mean refractive index of 1.437. From the theory of rainbow formation, we find that the primary and secondary bows on Venus would be formed at angles of 29.1^{o} and 74.9^{o} respectively from the anti-solar point. Thus the primary Venusian bow would be much smaller and lower in the horizon than the primary terrestrial bow while the secondary Venusian bow would be much larger and higher up in the sky as compared with its terrestrial counterpart. The intensity of a bow depends upon the intensity of sunlight and droplet size. From the estimated diameters of the droplets in the lower Venusian clouds and the distances of the two planets from the Sun, it is estimated that the Venusian bow would be only one-third as bright as the terrestrial bow. However, since the Venusian clouds are much stabler, one would expect the Venusian bows to be much more persistent.

1. INTRODUCTION

Rainbows are among the most beautiful sights in nature which had engaged the minds of poets, writers and scientists alike. Descartes and Newton were amongst the first to analyze rainbows scientifically [1]. Detailed analysis of rainbow formation are readily found in the literature (e.g., [2, 3]). More recently, Tan and King demonstrated how the local time at a place can be estimated from a full rainbow [4]. This paper discusses the possibility of rainbow formation on a planet other than ours in the solar system. Upon examination, it is found that our neighboring planet Venus offers the best chance for rainbow formation in its atmosphere. First, we outline the theory of rainbow formation in the terrestrial atmosphere. The theory is then applied to the Venusian atmosphere to investigate the possibility of rainbow formation there.

2. RAINBOW FORMATION IN THE TERRESTRIAL ATMOSPHERE

Rainbows are formed when droplets of water in a cloud are large enough to allow sunlight to enter and exit them via one or more internal reflections. This allows the sunlight to be dispersed into colors of different wavelengths. Droplets in which one internal reflection takes place form the brightest rainbow called the ***primary rainbow***. Droplets in which two internal reflections take place form the fainter ***secondary rainbow***. The primary and secondary bows are seen on the opposite side of the Sun, with the most favorable times being the early morning and late evening hours. The primary bow is formed at an angle of 41.5^o from the anti-solar point [4], whereas the secondary bow is formed at an angle of 52^o from the anti-solar point, the angular separation of the two being 10.5^o. Thus the fainter secondary bow is larger and higher in the sky than the brighter primary bow. In the primary rainbow, red appear on the top and violet appears on the bottom; whereas in the secondary rainbow, the order is reversed. Figure 1 (from [5]) shows a clear bright picture of the double rainbow. The ***tertiary*** and ***quaternary bows***, besides being progressively fainter, form on the same side of the Sun and are therefore impossible for one to see.

Fig. 1. A double rainbow.

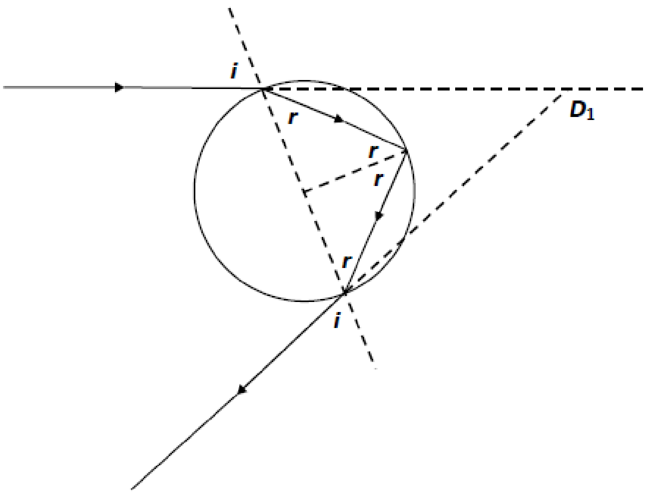

Fig. 2. Path of ray through droplet producing Primary Rainbow

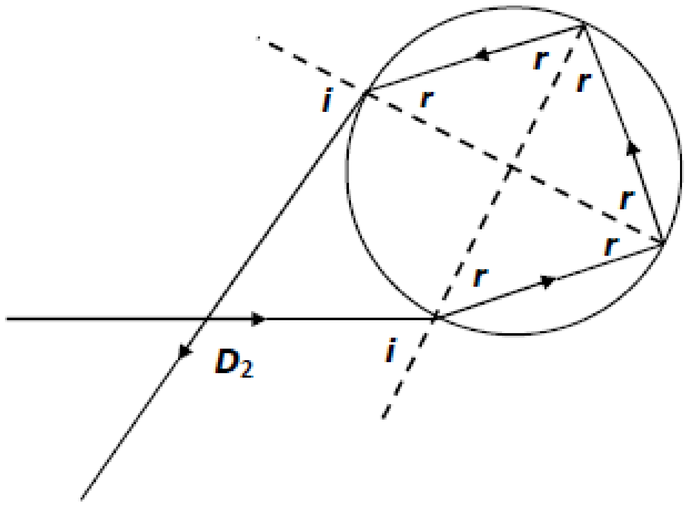

Fig. 3. Path of ray through droplet producing Secondary Rainbow

Figures 2 and 3 are schematic diagrams of visible rays of sunlight through water droplets producing the primary and secondary rainbows, respectively. The angles of incidence and refraction denoted by i and r respectively are related by ***Snell's law of refraction***

$$\sin i = \mu \sin r \tag{1}$$

where μ = 1.337 is the ***refractive index of water for average visible light*** (green). The general theory of the nth order rainbow formation is recapitulated (after [2, 3]) as follows. The deviation of the emergent ray from the incident ray is from geometry:

$$D_n = 2(i - r) + n(\pi - 2r) \tag{2}$$

Converting r into i via Eq. (1) and simplifying, we get:

$$D_n(i) = n\pi + 2i - 2(n-1)\sin^{-1}\left(\frac{\sin i}{\mu}\right) \tag{3}$$

Rainbows are visible at angles where the deviation is minimum. The ***condition of minimum deviation*** is given by the relations:

$$\frac{dD_n(i)}{di} = 0 \quad \text{and} \quad \frac{d^2 D_n(i)}{di^2} > 0 \tag{4}$$

The first condition of Eq. (4) gives:

$$2-2(n+1)\frac{\cos i}{\mu\sqrt{1-\left(\frac{\sin i}{\mu}\right)^2}}=0 \tag{5}$$

Simplifying, we get:

$$i=\cos^{-1}\sqrt{\frac{\mu^2-1}{n(n+2)}} \tag{6}$$

For the primary rainbow, $n = 1$; $i_1 = 59.2^o$; whence from Eq. (3), $D_1 = 41.5^o$. Likewise, for the secondary bow, $n = 2$; $i_2 = 71.7^o$; and $D_2 = 52^o$. These deviations correspond to the average wavelength of visible radiation (green). Since violet light is more refrangible than green and red light less so, their locations in the primary and secondary bows are readily verified. Also, it can be shown that the second condition of minimum deviation in Eq. (4) is met. We would like to further emphasize that since both i_1 and i_2 are greater than the critical angle for refraction from water to air $i_C = 48.4^o$), ***the internal reflections within the raindrops are not total*** [6].

3. RAINBOW FORMATION IN THE VENUSIAN ATMOSPHERE

Amongst all the planets in the solar system, Venus is the closest to the Earth in size, mass and composition. However, it has a far denser atmosphere than ours, consisting of 96.5% carbon dioxide [7]. The atmospheric pressure at the surface is an astounding 93 bar and the temperature is a scorching 740 K, thanks to intense greenhouse effect [7]. The Venusian atmosphere has ***dense clouds consisting of droplets of aqueous solution of sulfuric acid of 75-96% concentration by weight*** [8]. Acid rains occur in the Venusian atmosphere, but they never reaches the surface because of the intense heat.

The ***refractive index of sulfuric acid solution as a function of concentration*** is found in the literature [9]. For an average concentration of 85%, it is extrapolated to be 1.437. Not unlike the clouds in the terrestrial atmosphere, the ***Venusian clouds consist of several layers*** [8]. They reflect about 75% of the incoming solar radiation back into space [7]. The estimated ***droplet sizes of the Venusian clouds are smaller than those of the terrestrial counterparts*** [8]. The various quantities relevant to the Venusian rainbow formation are listed in Table I.

Table I. Comparisons of Terrestrial and Venusian Atmospheres and Clouds

	Terrestrial Atmosphere/Clouds	Venusian Atmosphere/Clouds
Atmospheric Pressure at surface	1 bar	93 bar [7]
Average Temperature at surface	288 K	740 K [7]
Atmospheric Composition	78% N_2; 21% O_2; 1% Ar	96.5% CO_2; 3.5% N_2
Refractive Index of Air	1.000292	1.000450
Atmospheric Clouds	Stratus, 8.2	Upper clouds, 2.0
	Cumulus, 10.8	Middle clouds, 7.0
	Stratocumulus, 15.2	Lower clouds, 8.0
	Nimbostratus, 19.6	Pre-cloud layers, 2.0
Composition of Clouds	H_2O	75-96% H_2SO_4; Rest H_2O [8]
Mean Refractive Index of droplets	1.337	1.437 [9]
Mean distance of Planet from the Sun	149.6 million km	108.2 million km

The formation of rainbows in the Venusian atmosphere would follow the same principles as those in the terrestrial atmosphere in accordance to the steps outlined in the earlier section. One needs only to change the refractive index μ from 1.337 to 1.437. The results are as follows. For the primary rainbow, $n = 1$; $i_1 = 53.4^o$; and $D_1 = 29.1^o$. Likewise, for the secondary bow, $n = 2$; $i_2 = 68.6^o$; and $D_2 = 74.9^o$. Thus, both the primary and secondary bows are formed on the opposite side of the Sun, and would, in principle, be visible as in the terrestrial atmosphere. The placement of the colors will also be the same. However, ***the primary bow would be situated at 29.1º from the anti-solar point***, and hence be far smaller than the primary terrestrial bow, besides being far lower in the sky (Fig. 4). On the other hand, the ***secondary Venusian bow will be situated much higher up at 74.9º from the anti-solar point*** and therefore far larger than its terrestrial counterpart (Fig. 4). The ***separation between the primary and secondary Venusian bows would be 45.8º***, more than half of a right angle as compared with 10.5^o in the terrestrial atmosphere.

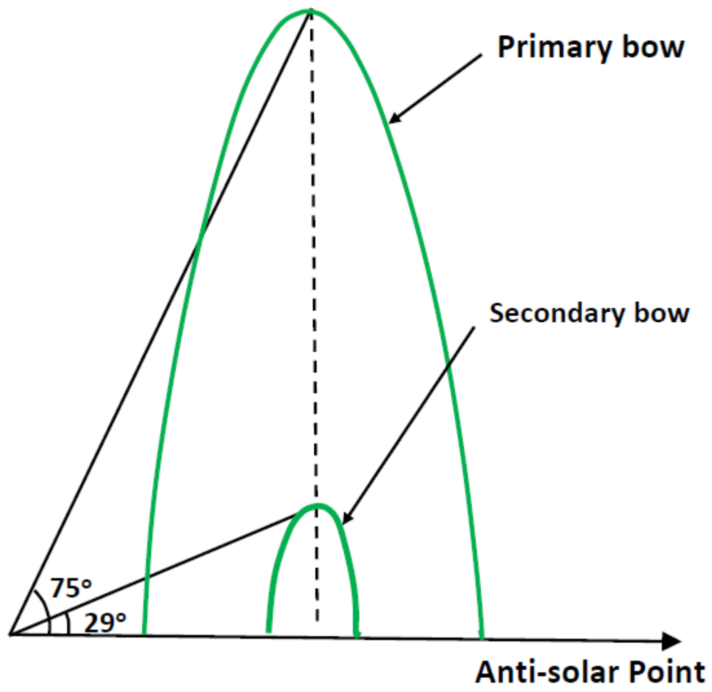

Fig. 4. Configuration of Venusian rainbows

4. INTENSITIES OF THE VENUSIAN RAINBOWS

The ***intensity of a rainbow*** depends mainly upon two factors: (1) the ***intensity of incoming solar radiation*** (often referred to as ***insolation***); and (2) the ***droplet size***. First, the insolation varies ***inversely as the square of the distance of the planet r from the Sun***. Second, for a bow of a certain order, the intensity of the bow is ***proportional to the square of the droplet diameter d*** (or radius, for that matter) [3]. Thus, the intensity of a bow of a certain order I varies in accordance with:

$$I \propto \frac{d^2}{r^2} \tag{7}$$

Denoting the subscripts V and E for Venus and the Earth, respectively, we get:

$$\frac{I_V}{I_E} = \left(\frac{d_V}{d_E}\right)^2 \left(\frac{r_E}{r_V}\right)^2 \tag{8}$$

Upon putting the values on the right hand side of Eq. (8) (from Table I), we get $I_V = .32\ I_E$. Stated in words, the ***Venusian bow would be only one-third as bright as its terrestrial counterpart***. To sum up, the formation of rainbows in the Venusian atmosphere is a real possibility, even though the Venusian bow would not be as bright as its terrestrial counterpart. However, since the Venusian clouds are very stable [8], the ***Venusian bow would be much more persistent***.

5. REMARKS

Even though rainbow formation in the Venusian atmosphere is a theoretical possibility, actual capturing it on photograph is a difficult proposition for the lack of a suitable platform. Even though several Soviet spacecraft had landed on Venus's surface, their instruments did not survive the intense temperature and pressure for long [10]. Moreover, the dense clouds on Venus insure that visible sunlight is reflected and absorbed before reaching the ground [7]. As matters stand, the only possibility of capturing a rainbow on Venus would be from a slowly descending spacecraft when it passes below the middle and/or lower clouds where the droplet sizes are the largest.

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