Radiation Heat Transfer
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Lecture - 34
Scattering in the atmosphere

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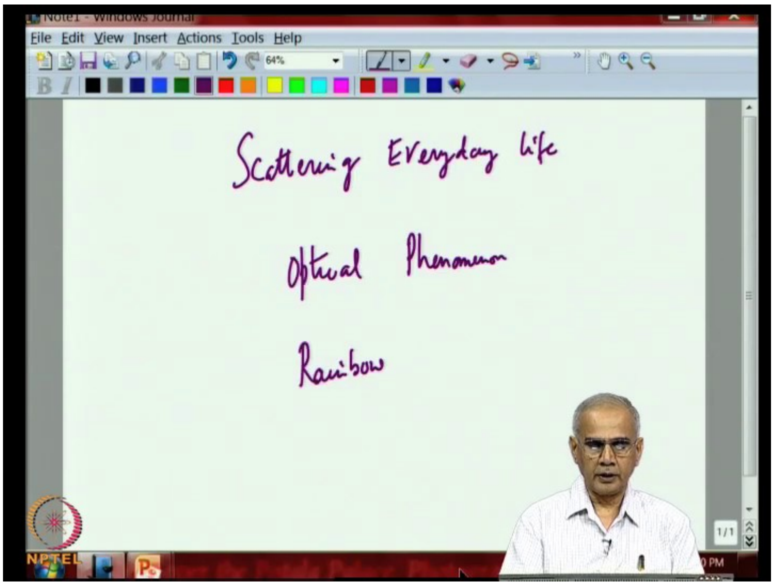

In the last class, we looked at how scattering takes place due to various particles. Today, we look at examples of scattering that we can see in everyday life; that is we go outdoors We see number of phenomena essentially optical, which owe their origin to scattering. The best example of course is Rainbow. All of us have seen rainbows. But have we looked rainbows at their fundamental level and try to understand what factors control the occurrence of primary rainbow, and then the secondary rainbow and even higher level rainbows.

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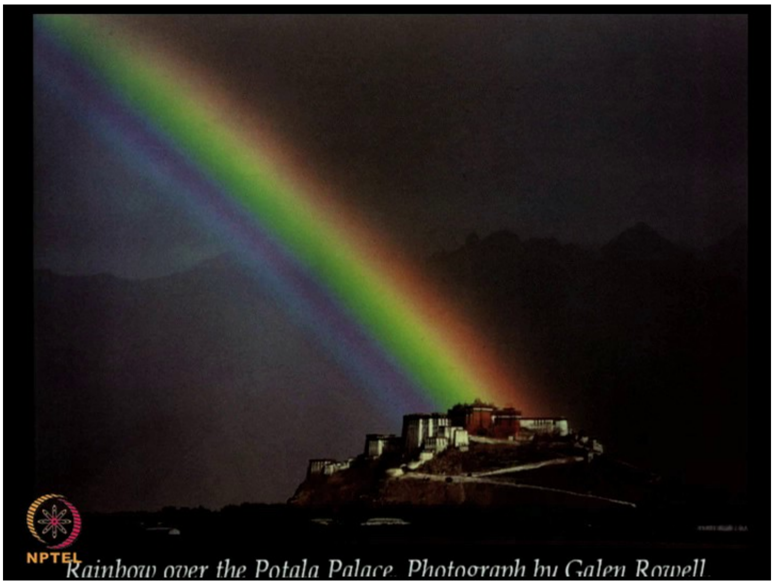

Today, we will try to look at this phenomenon and see whether we can understand them from scattering perspective. The first slide here shows the rainbow over Potala Palace in Tibet; a very impressive picture with very detailed resolution of the various colors.

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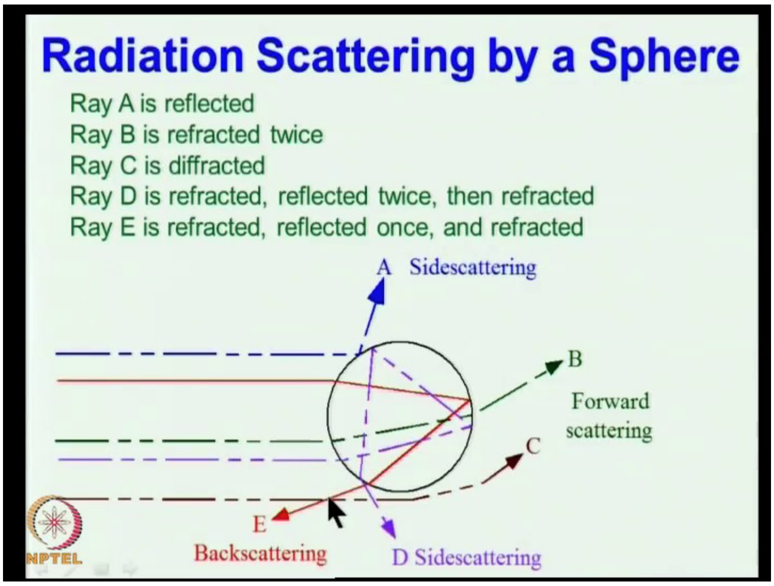

Now, in all this phenomena there is scattering from a sphere. In the last class we saw that scattering has various features in it. The first is reflection; that is like a ray A, there is the difference in refractive index of the liquid drop, water drop and the surrounding air, causes the reflection of this ray A. Then the second one is refraction; that is ray B. It comes here, gets refracted once at this interface, goes inside, gets totally internal reflected, comes back and refracts out. We will see this is an important phenomenon in rainbows. Then we see ray C which is diffracted, which goes close to the rain drop, but does not quite touch it. But, anyway bends on account of diffraction phenomena. The ray D is refracted once, reflected twice and then again refracted. Then ray E is refracted, reflected once and refracted.

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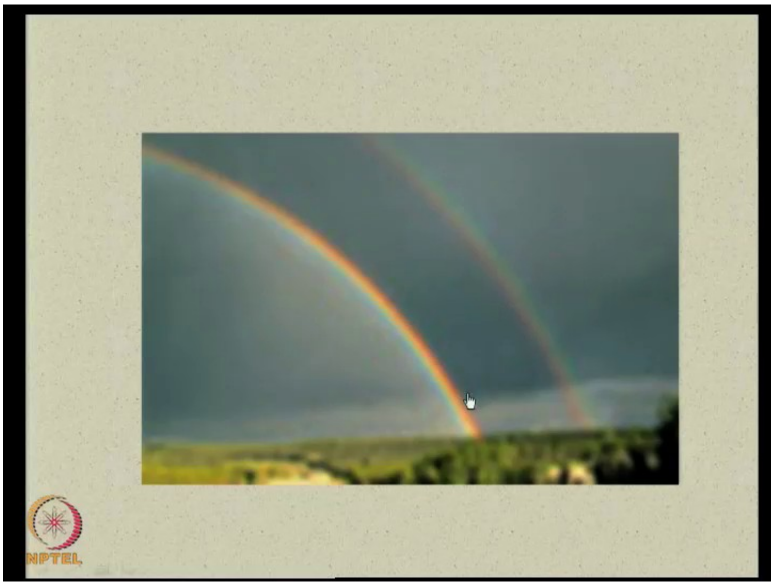

So, all these have some role to play in your rainbow. Now, here is a rainbow; the primary rainbow and the secondary rainbow. This is secondary rainbow; the primary rainbow. We see a clear distance between them which is called Alexander's dark band; that is where the reflection is low.

Also, notice that the color sequence in the two rainbows is not the same. In the first rainbow, the red color occurs on the outside. In the secondary rainbow, the red color occurs on the inside. The question usually you have to answer is whether we can explain these features of the rainbow. The distance between rainbows and the color sequence being reversed; can it be explained through understanding of basic phenomena of scattering?

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Here is another picture here, which shows again the primary and the secondary rainbow. Notice this secondary rainbow is much fainter than the primary. As we go to higher order scattering, higher order reflection, the intensity gets weaker. So, theory says that there are even more rainbows, but most often you would not see them. In many cases, you do not see the secondary. We only see the primary. Secondary is already weak, but there are also tertiary and other rainbows. Here is another picture, where the prime rainbow is very clearly visible and then your dark band and then the secondary rainbow is somewhat subdued. Here, a similar picture is with clear difference with primary and secondary rainbows.

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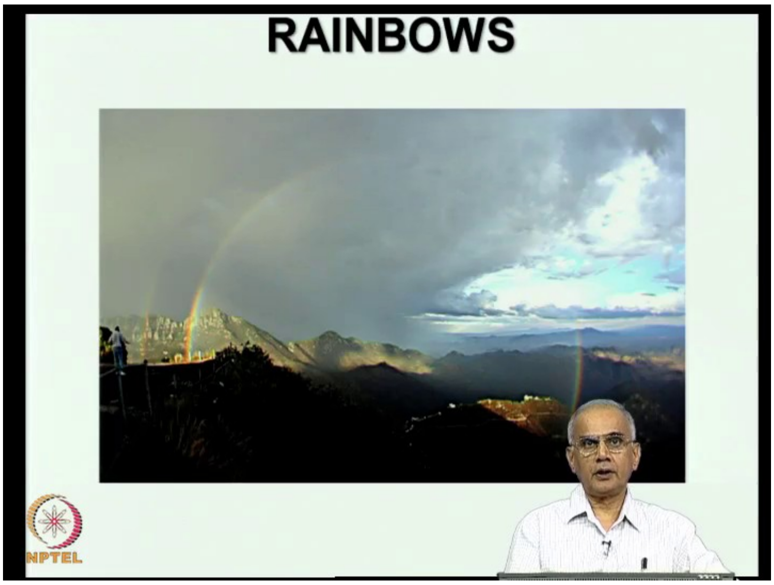

Now, although we may not have seen it very often, you know we can also get completely circular rainbows. That depends on at what distance from the droplets you are. If we are at the right distance, then we will see the entire rainbow; circular one in front o f us.

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It is a picture taken in Hawaii showing the complete circle of rainbow with a secondary rainbow also visible.

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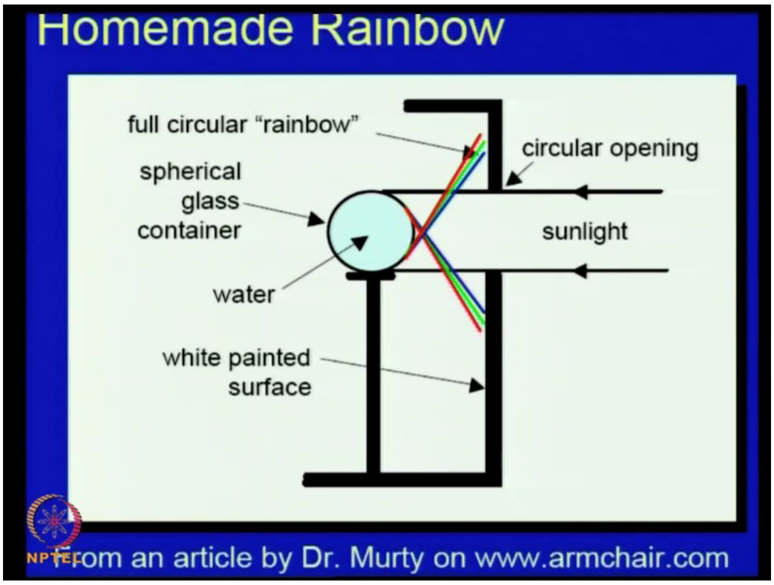

As a matter of fact, the best way to understand a rainbow is either through computer simulations or in the laboratory. In Dr. Murty's website www.armchair.com, he shows how we can setup a simple experiment in your house to observe rainbows. All we need is a spherical glass container, which admits sunlight from outside in. On reflection on the wall we can get many kinds of rainbows.

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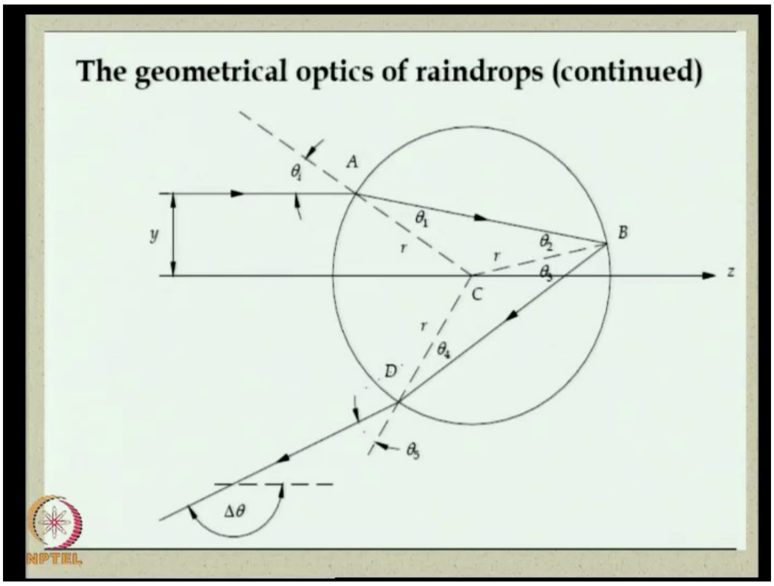

The simple geometric optics of the rainbow says that the ray coming in has to bend. Depending on this angle, it can get totally internal reflected and then reflect out. For us to see the rainbow, the sun has to be behind us and angles at B such that, the ray on reflection under goes total internal reflection until it goes out of this side. If the angles are not right, it may just reflect out. So the angles are very important in this observation of the rainbows.

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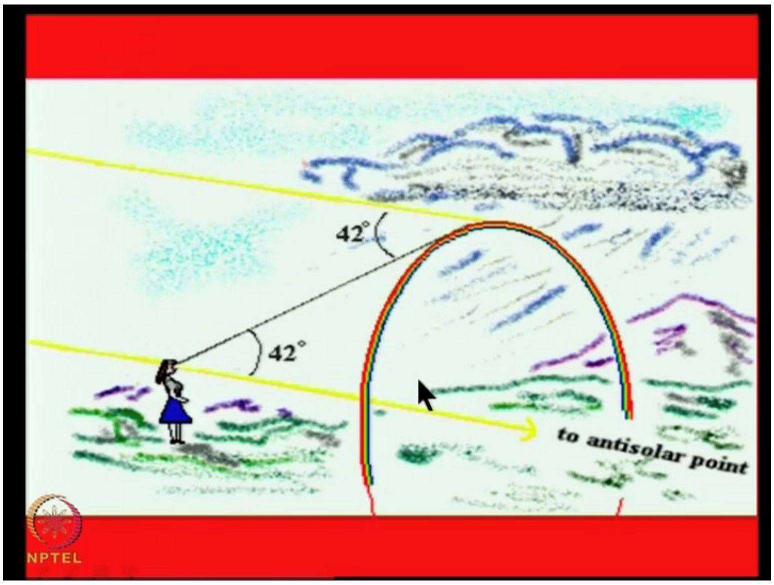

The best way to see is that the human observer has to make an angle of 42 degrees with the sunset coming towards the droplets.

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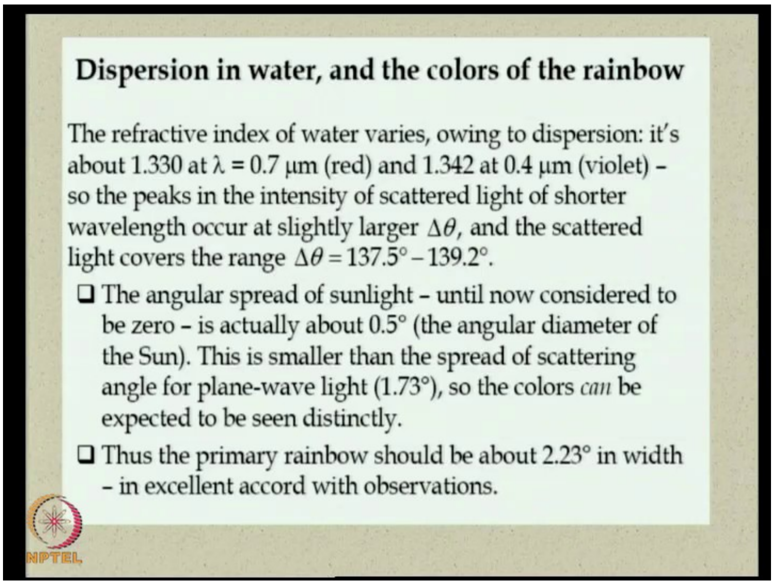

The rainbow occurs not only to the occurrence of refraction and total internal reflection, it is also is due to dispersion. Dispersion is a phenomenon which occurs because the refractive index of water varies with wavelength. For example, the refractive index of water at the red wavelength is 1.330, while at the violet wavelength it is 1.342. Difference of 0.01 has enough impact to create the rainbow.

The angular spread of sunlight is about 0.5 degree. The sun is now exactly and perfectly parallel. And this is smaller than the spread of scattering for plane-wave light which was here; 1.73. The colors can be expected to be seen distinctly. Although it is not quite parallel, it is sufficiently parallel for you to be able to see clearly the rainbow. According to this, the primary rainbow should have width of 2.23 degrees, which is very close to observation.

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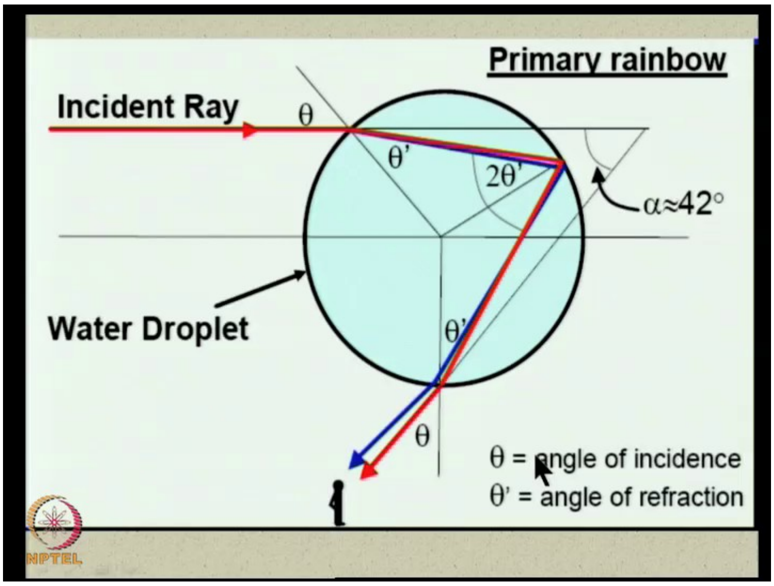

Now, this is a clearer picture of the primary rainbow phenomena. We can see that the red and blue light of the sunlight come here. And after refraction, reflection and refraction because of the slight difference in the refractive index, the ray, the blue and violet and the red rays, come out at slightly different angles. This is the angle; that 42 degree is that we saw in the other picture. If we look at the ray parallel here and after refraction, internal reflection and other refraction, the angle is 42 degrees. That angle is slightly different for the violet and the red in the VIBGYOR spectrum.

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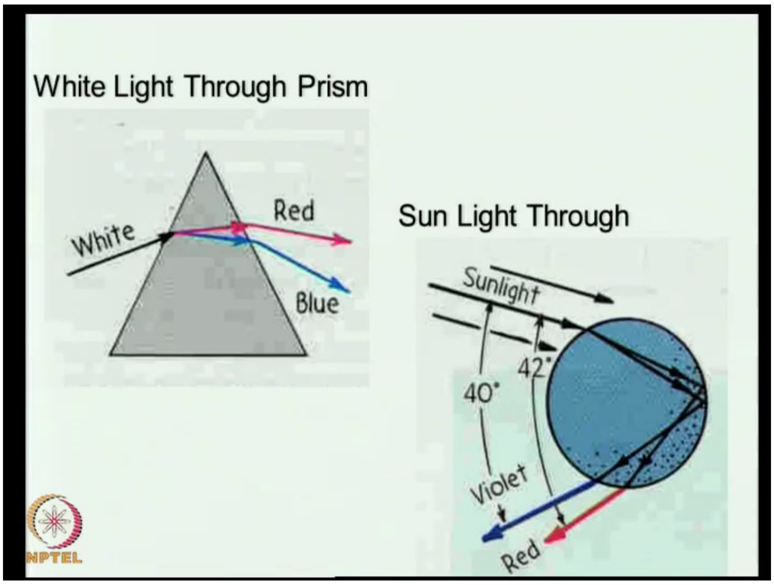

This is similar to what you have observed in the laboratory in your Physics lab; when you sent in white light through prism, red and blue come out because of the difference in refractive index. The same thing is happening here; the red light unable to change in angle of 42 degrees, while the violet light only undergoes change of 40 degrees.

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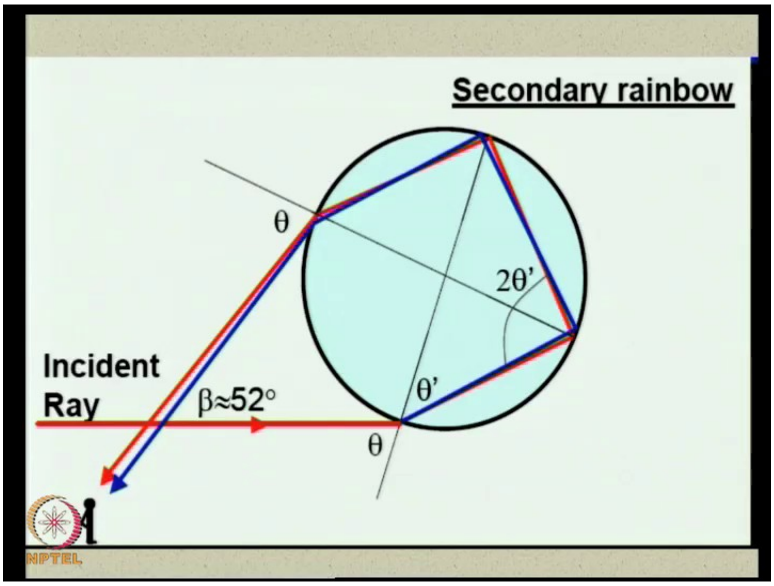

We saw the secondary rainbow in those pictures. What is the secondary rainbow due to. That is, when the rays are incident and after refraction, instead of one reflection, they are in the positions to undergo two reflections; two internal reflections and come out. They come out in different angles. Notice that in contrast to the primary rainbow, where the violet light appears above the red light, and here in the secondary rainbow the violet light comes below the red light. That is why the two rainbows are in inverted sequence.

As we saw in the one rainbow, red was outer and blue was inner. The other one was the other way round. This is because of the way it undergone reflection. In one case, there was only one total internal reflection; while, in other case there were two reflections.

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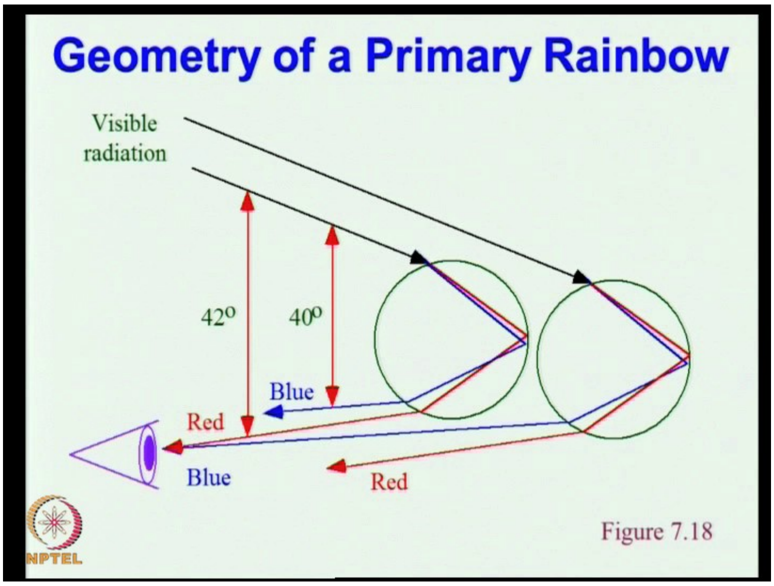

Figure 7.18

This is another picture clearly identifying the geometry of the problem and showing the total bending by 42 degrees for the red light and for the blue or the violet, it is around 40 degrees.

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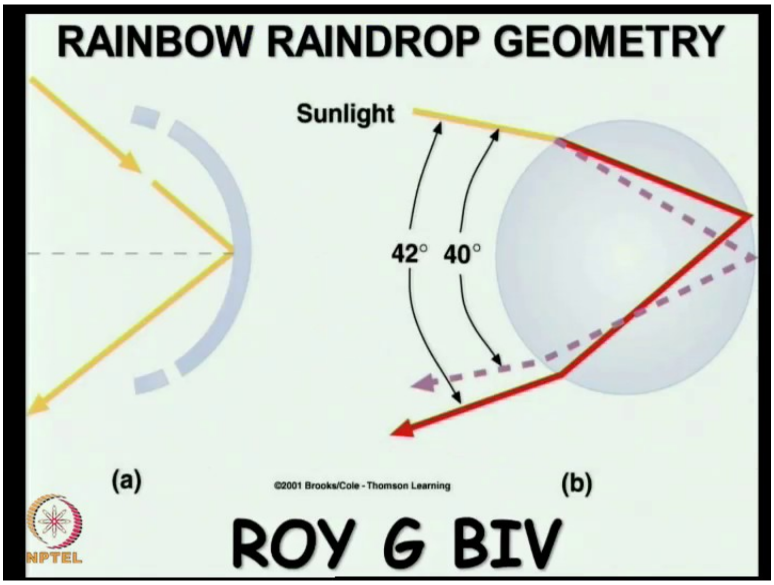

This is essentially saying that, there is no difference between this and the previous one.

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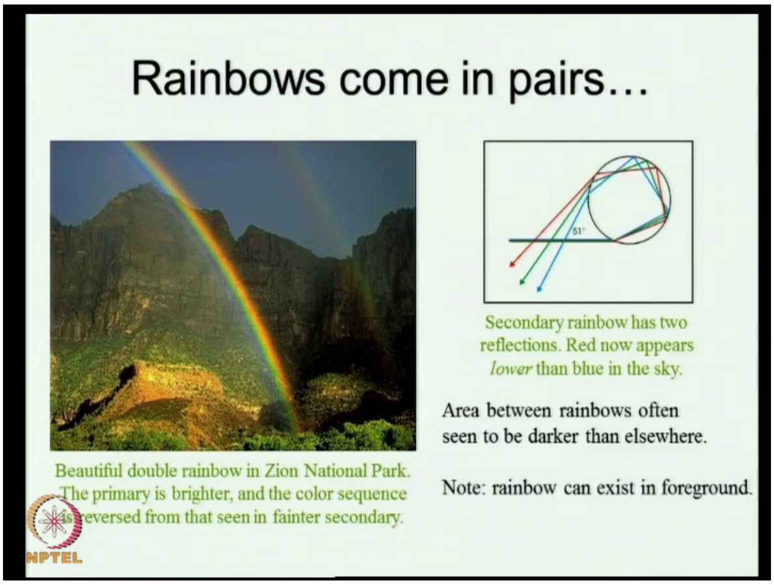

This is again illustration of the two rainbow phenomena and how the change in angle occurs.

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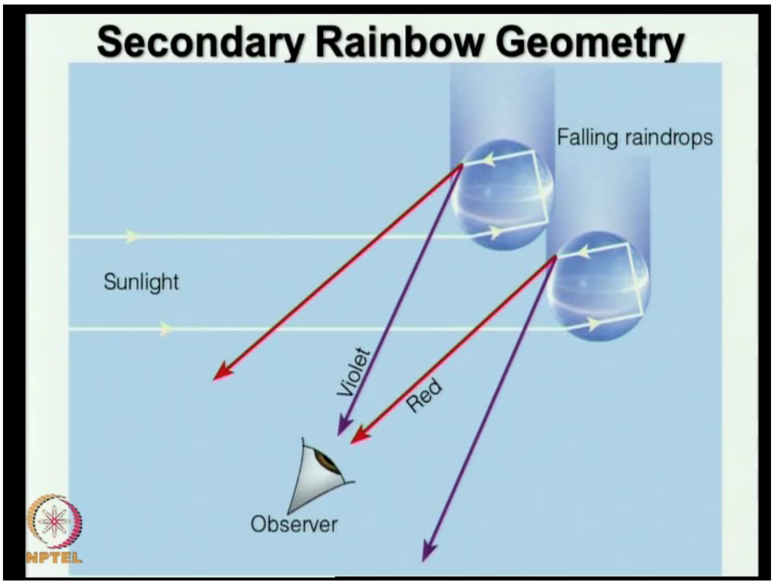

So, here the secondary rainbow geometry is again shown with two refractions and two internal reflections.

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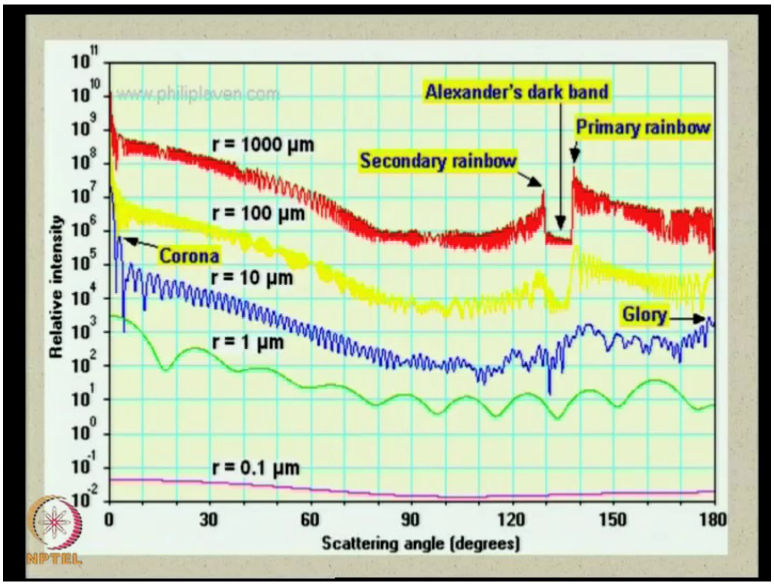

Now, the best way to understand the rainbow phenomena is to look at the intensity of scattered light as the function of scattering angle. In this calculation, done by solving the full electromagnetic equation Maxwell's equations, what is being shown is the scattering intensity in relative terms for liquid droplets, water droplets of various sizes starting from 0.1 micron, 1 micron, 10 micron, 100 micron, 1000 micron.

There is one wonderful website called www dot philipaone dot com, which discuss many optical phenomena in that website. What we see is that when the cloud droplets are very, very small, it is not a cloud, but merely a small droplet. The intensity of scattering is small and is not varying much with angle. As we go to higher and higher radius of the droplets, the intensity goes up almost a million times from 0.1 to 1 we start seeing some variations in the scattered intensity.

As we go to 10 micron you start seeing very large changes. What we see at this scattering angle of zero is called Corona; the high scattering here and high scattering here is called Glory. We will look into this little later. Then we go to hundred microns, this yellow one and finally 1000 micron, which is the most important dimension; because that is where you get actual raindrops. The cloud drops are small in size. They will never actually fall to the ground because their settling velocity based on Stokes law is very, very slow and hence they will never reach the ground as; they only evaporate. Only droplets of the size of 1000 microns are in a position to retain their enough water when they fall to the ground.

We, look at 1000 micron, we can see that the intensity of scattered light is about million times larger than that 1 micron cloud drop. The, cloud drops will not give rainbow, only raindrops will give. We We see clearly the primary, secondary rainbow occurring at angles here, measured with respect to the four directions. That is why we are getting angles like 140, instead of 42; because those 42 degrees you saw in the earlier picture, here we should look at upon angles as180 minus 42; so, 138; that is the primary rainbow. The other one is 150 degrees or 130 degrees. These two rainbows show a sharp increase in intensity. We are able to see them distinctly in the sky because of this; there is more scattering into this angle than any other angle here.

So, locally there are maxima which we are able to see very distinctly. Now, of course other maxima which are not shown in this picture, which refers to tertiary and higher, order rainbows. In between we see the sharp drop in scattering. And that is the dark band; Alexander dark band. We notice that there is a lower size liquid droplet. The liquid droplets must be at least 100 micron above for this feature to emerge. Whenever we see a rainbow in which you see primary and secondary along with the Alexander’s dark band we can be sure that it is raining somewhere because these droplets are large enough to cause rainfall.

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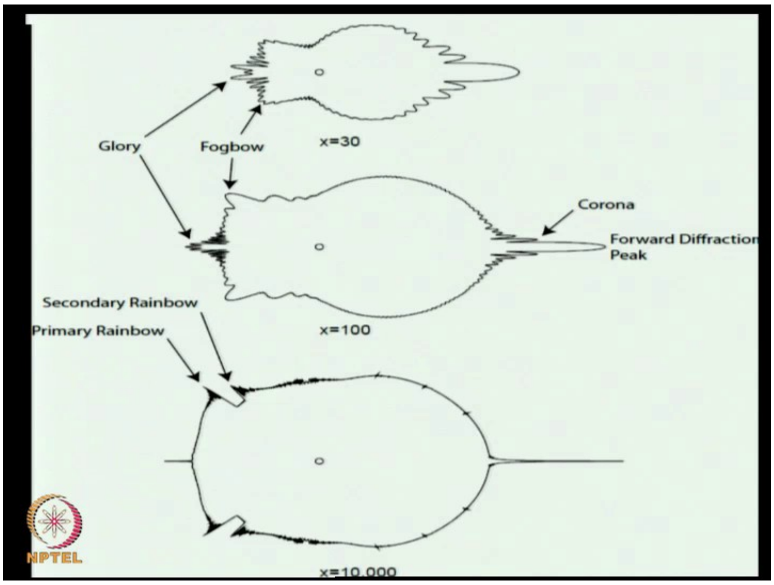

Now, the same thing now is shown in a polar diagram. And this is the size parameter; two pi r by lambda. We can clearly see that there is backward scattering here, forward scattering here; which leads to phenomena such as Corona and Glory. And only when you reach a high value of size parameter around 10000, that is, 1000 micron size particle at a wavelength around 0.7 micron, so we can see that only when the size parameter is around 10000, we see a distinct high scattering around the primary and secondary feature about 42 degrees and 50 degrees from this side; is backward scattering. That is, the sun has to be behind you for you to see the rainbow.

We see that, we are in the position to explain a natural phenomenon such as primary and secondary rainbow as well as the dark band from applying the basic laws of Electromagnetic theory, Maxwell's equation; solve them on computer. Every absorbed feature can be explained by the phenomena of what is called Mie scattering. That is, scattering in which the particle dimensions are of the same order or larger than the wavelength of light. In this case, we are looking at visible wavelength over 0.4 to 0.7 microns, while the size of raindrop is of the order of 1000 microns. We see ratio of the order of 10000 here, which is necessary to get this. If you have only x equal to thirty, you will get Glory and Corona. But, we will not get distinct rainbow structures.

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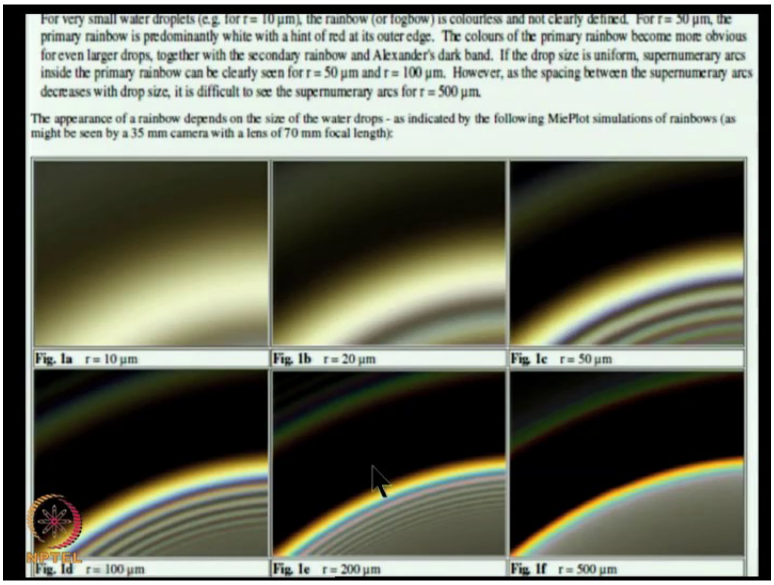

Now, the best way to show this is by computation. Here, we see a clear explanation. We put a 10 micron liquid particle. We would not see any distinct color. We see diffuse scattering, and will become sharper and sharper as the radius of the liquid droplet increases. Then we start seeing the dispersion. Finally, when it comes to about five hundred micron, we see distinct primary rainbow and secondary rainbow. So, all this is from theoretical calculations clearly demonstrating that for very small droplets, the rainbow is colorless. We would not see the rainbow and as it is not well defined.

As the droplets size starts increasing, we start seeing this black region which is really the Alexander dark band. Only when the size reaches 500 micron, we see a clear rainbow structure. This can be simulated by Mie scattering formula very nicely.

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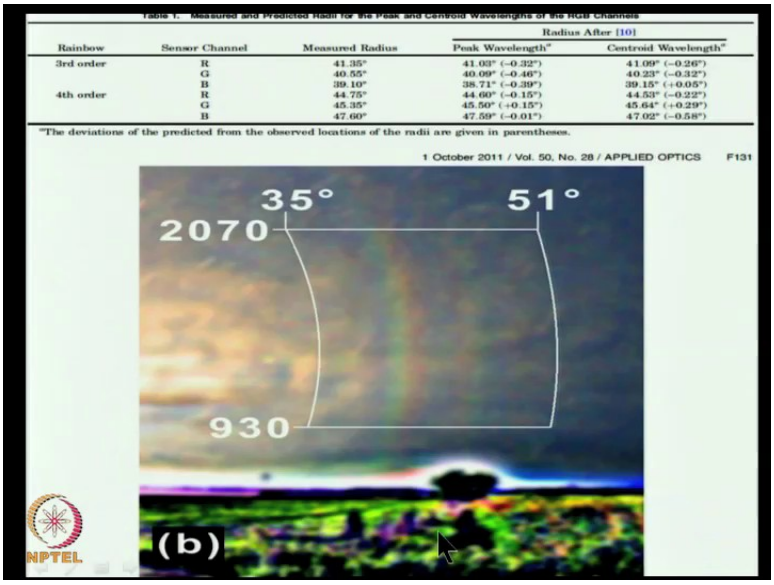

Table 1. Measured and Predicted Radii for the Peak and Centroid Wavelengths of the RGB Channels

Rainbow	Sensor Channel	Measured Radius	Radius After [10] Peak Wavelength[a]	Radius After [10] Centroid Wavelength[a]
3rd order	R	41.35°	41.03° (−0.32°)	41.09° (−0.26°)
	G	40.55°	40.09° (−0.46°)	40.23° (−0.32°)
	B	39.10°	38.71° (−0.39°)	39.15° (+0.05°)
4th order	R	44.75°	44.60° (−0.15°)	44.53° (−0.22°)
	G	45.35°	45.50° (+0.15°)	45.64° (+0.29°)
	B	47.60°	47.59° (−0.01°)	47.02° (−0.58°)

[a]The deviations of the predicted from the observed locations of the radii are given in parentheses.

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Now, recently a paper was published in which people were able to identify not only the primary rainbow but also the secondary and tertiary rainbows. This of course is very faint. But, they were able to compare the measured distance of the red, green and blue and so on with the calculated value from Mie scattering. We can see they are pretty accurate.

The theory is able to predict the occurrence of the tertiary and higher order rainbows to within 0.5 degrees, which is quite remarkable. Remember that the kind of theory that are proposed here; in these papers, published in Applied Optics. They are assuming droplets are all of the same size. Now, we would not expect that in a real atmosphere that all the droplets will have same size; there will be distribution of size in the droplets.

But, droplets which are too small, will not give a rainbow. The droplets which are too large would not be there anyway, as they would have fallen out. So, only droplets which are large enough to cause rainbow and which have not yet fallen to the ground are contributing to your scattering but still the results are truly impressive that the theory and the observation in the case of scattering is so well understood.

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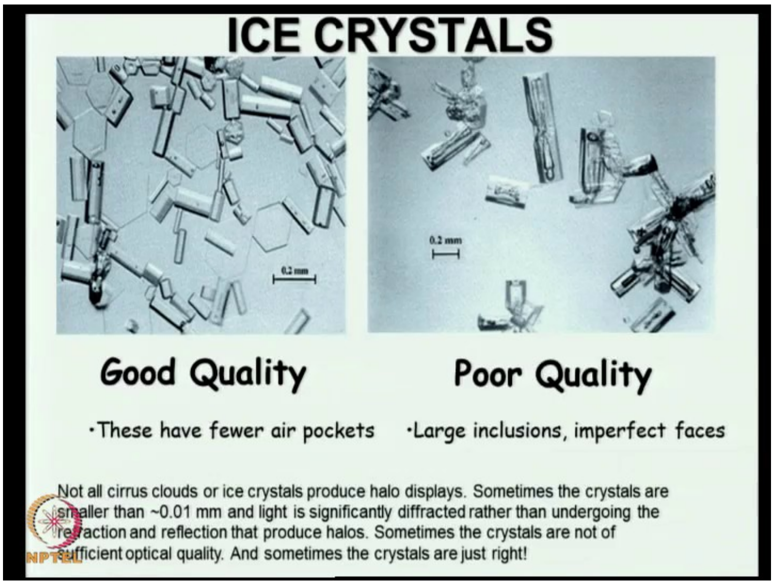

So far, we have looked at liquid droplets. The advantage of liquid droplets is that they are spherical in shape most of the time. Only very large droplets lose their shape and become slightly distorted. But, most of the time because of the surface tension, they maintain their spherical shape. But, when it comes to ice particles which are solid, not liquid, they come in large number of shapes; hexagons and plates.

We can see here various examples of ice crystals of regular shapes; some of them are irregular shape also. These ice particles whose dimensions can be up to 0.2 millimeters will create optical phenomena of a greater variety than the rainbow; because rainbow is produced by spherical particles; water drops. The only parameter which varies there is the radius of the droplet. If the droplet is very small, we do not see rainbow and if it is very large, we can see it. But, droplet radius above 1 millimeter, 2 millimeters are very rare because they fall down.

The rains that cause rainbow are fairly narrow. But, in the case of ice particles you see a huge plates and bullets and all kinds of shapes are there. We should expect that ice crystals will produce scattering phenomena called halos. Hence we see the phenomena. Many of us in India may not have seen these spectacular effects of ice particles because they are not that common in India. But, both in the Arctic and Antarctic, those who have gone for expedition to polar region, they do find huge number of phenomena involving scattering of sun light and even moon light. That is because ice occurs more often in the Antarctic and Artic conditions. These phenomena and others are seen there more often.

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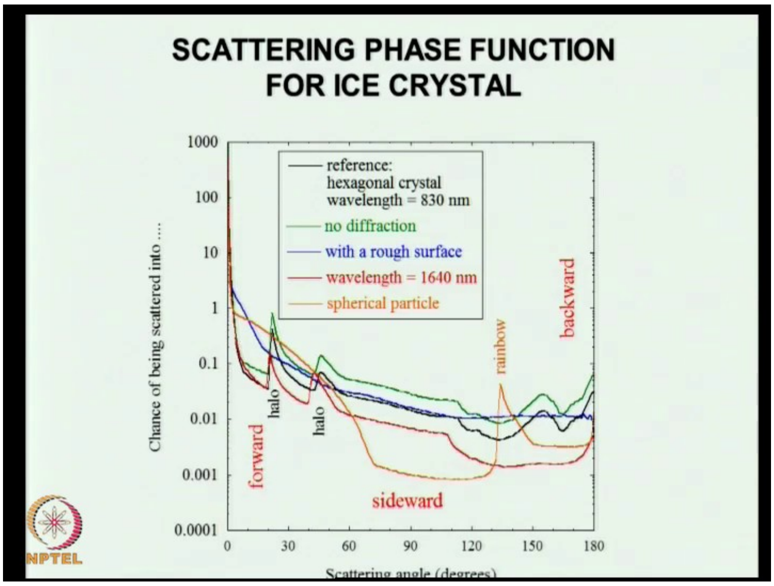

Now, here is a picture of scattering; probably, scattering with scattering angle for a hexagonal crystal at wavelength of 830 nanometer at 0.8 micron. We can see that the variation of scattering intensity with scattering angle has only a few features in the front around to 220 degrees and pretty larger angle here, 44. And of course this is the rainbow thing we saw earlier, which is the spherical particle; this is.

Here we have shown the curves for two different wavelengths. We can see a rough surface will completely remove this peaks. In order for you to see the optical phenomena created by scattering of ice particles, the ice particles have to be smooth and uniform in size, so that effects of different ice particles do not cancel out. This is not commonly observed phenomena.

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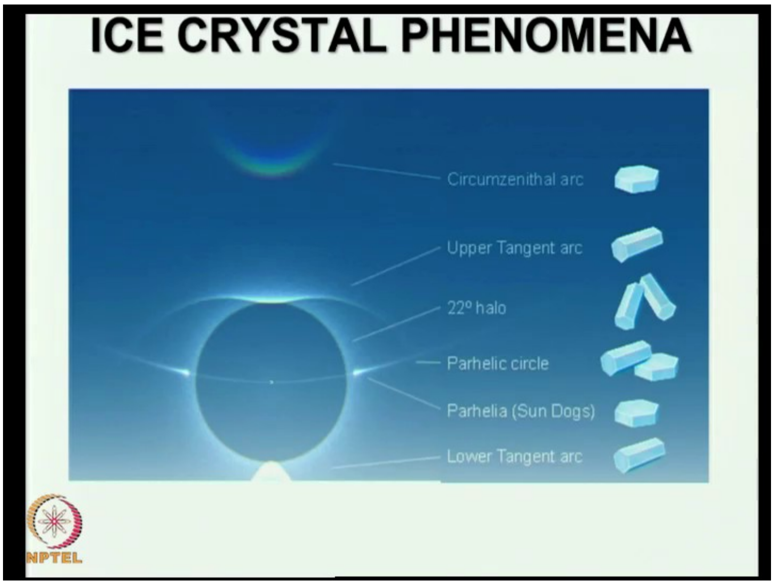

The phenomena that observed a lot have been given a lot of nomenclature, so that people can compare and contrast their discoveries. The one, you see on the top is called the Circumzenithal arc, which you see well above the sun and that is caused by flat ice crystals.

On the other hand one is called Upper Tangent arc; that is caused by solid vertical bullets. And depending upon their orientation, horizontal or vertical, they can cause a 22 degree halo, parhelic circle or parhelic or Sun dogs, which we will see later; and the Lower Tangent arc. So, all this phenomena that are marked here are caused by ice crystals of different shapes and sizes and orientation.

Remember that there is a phenomenon that you see is linked to the existence of ice crystals of a certain shape and orientation. Also remember that these are rare because all the ice crystals which are formed must have similar sizes. If the ice crystals formed have a range of sizes, then the phenomena may not be as distinct and we may not be able to see it so clearly.

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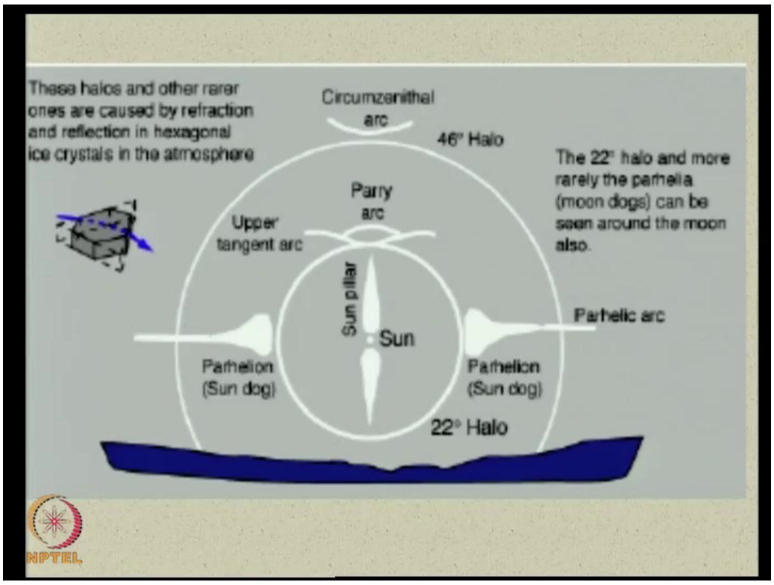

Again the same picture, but now highlighting the role of 22 and 46 degree angle in the picture as well the large vertical structures here called the Sun dog, which appears in the either side of the sun. The one, which is above right above the sun is called Sun pillar. All this phenomena have been analyzed through scattering by particles. Many of them can be explained from first principles.

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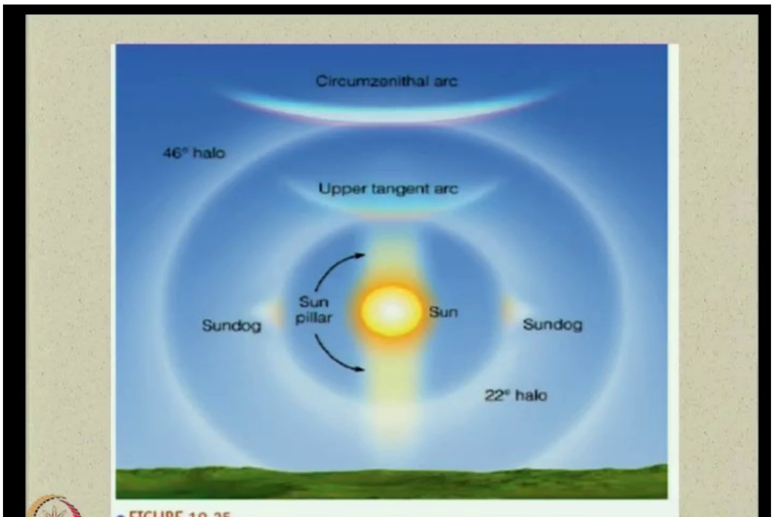

• FIGURE 19.25
Ice crystal phenomena. (A picture of the circumzenithal arc is in Fig. 2 on p. 533.)

Here, another little picture identifying the same thing. Now, we have to remember that we are looking at rare pictures. Remember that the Sun pillar occurs above and below the

Sun, Sun dog appears in the either side of the Sun, then we have the Upper tangent arc and the Circumzenithal arc and the two halos at 22 and 46.

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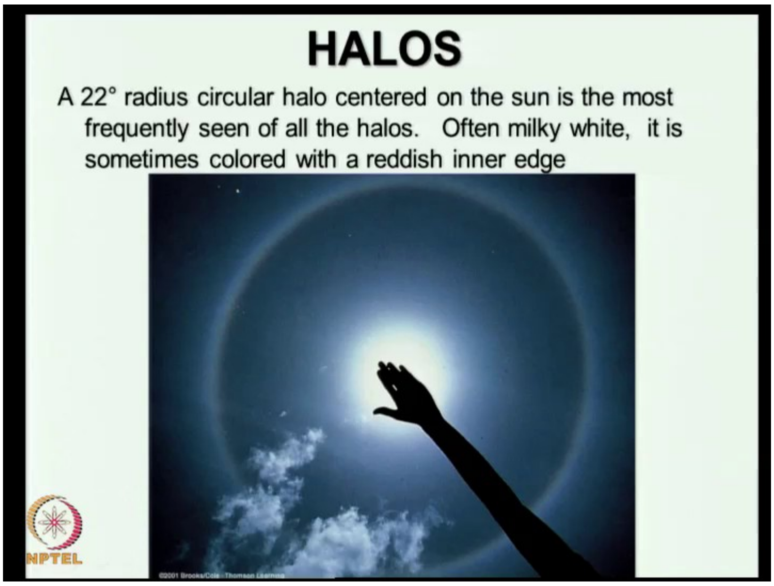

So, halos are at 22 degree radius circular halo centered on the sun and sometime on the moon, often milky white and sometimes colored with a reddish tinge, is the halo that you see around the sun. This is caused by ice crystals.

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This is another picture in spite of the sun being blocked, but the halo is still visible.

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Now, here is the example of a 22 degree halo. Most common phenomena that is observed are due to ice crystals.

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Here is the halo observed where in the building.

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This is caused by the moon. On a full moon night, if the ice crystals in the sky are between you and the moon light, you will see a moon halo. Again, this angle is 22 degrees

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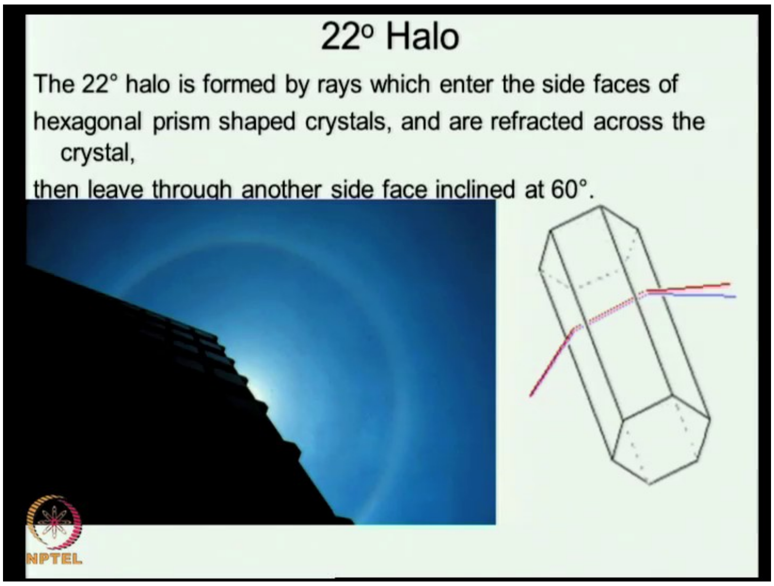

Now, the best way to explain the 22 degree angle of the sun is that the rays of sun or moon enter the side face of the hexagonal prism and are refracted across the crystal and they come out through the other side. So, they enter through one face and go for another face. As in the case of rainbow, there is dispersion. We should see some color, but the color is not very strong. We may not see it so distinctly, but it is there. A careful photograph reveals that there is a rainbow like structure there.

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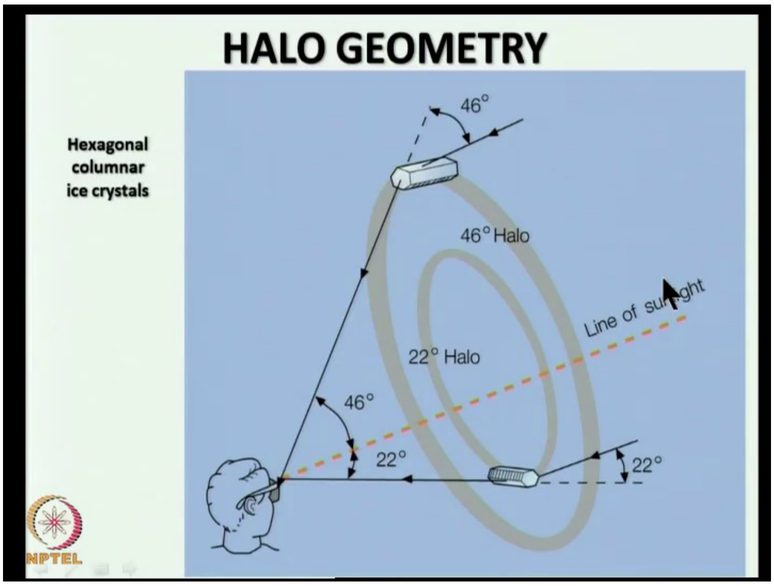

We can see that the difference between the 22 degree halo and the 46 degree halo is essentially with reference to the orientation of the crystal.   In the case of 46 degrees, the ray enters the top of the hexagon and then comes out of this side. So, the geometry here 46 degree halo, while the 22 degree halo we saw is coming from the side of a crystal and hexagonal side. Whether we will see a 22 degree halo or a 46 degree halo will depend upon the orientation of the ice particles falling in the sky. They have to fall because they are heavy. Because they have to fall horizontally or vertically, so whether it is vertical or horizontal will be determined the kind of halo we will see.

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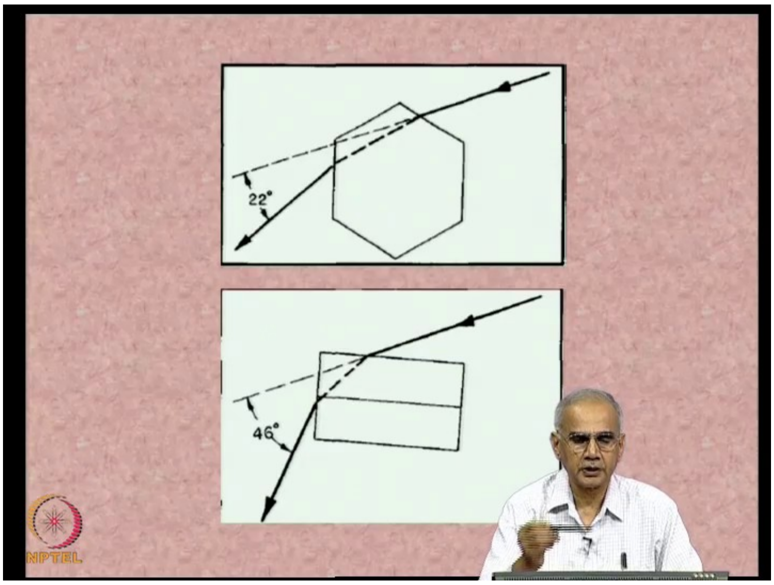

This is explained little more clearly in this picture. In which the 22 halo comes in because the rays enter one side of the hexagonal prism and exit through the other side causing 22 degree diffraction, while the other one enters through the other side, but enters through the edge phase; through the edge phase it enters. Here the angle is 46 degree. So, all these are easy to explain based on the laws of refraction.

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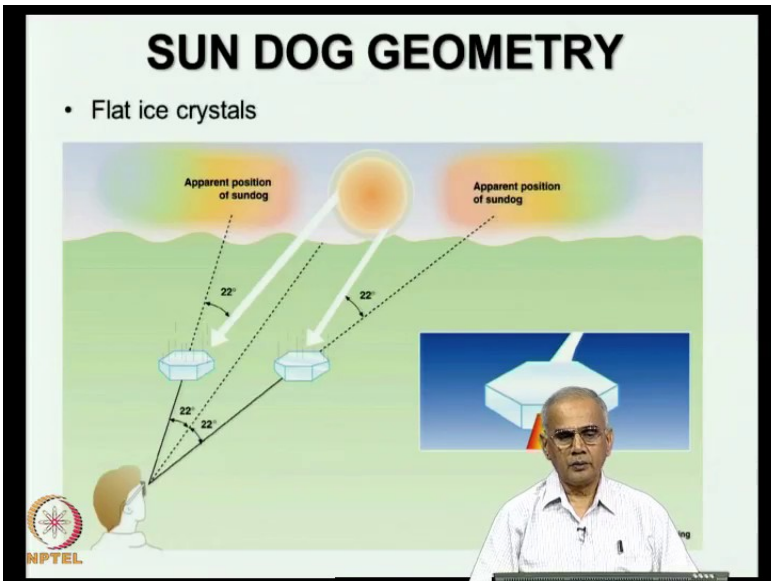

Now, the Sun dog is caused by reflection by flat ice crystals. And it is really the two images of the sun, that our eye assumes based on extrapolation backwards. It sees the

Sun dog appearing on either side of the sun. Actually, it is coming from the edge of the sun, but with refraction it is deflected slightly. So, for the observer; this light coming in and on reflection entering here, we extrapolate backwards and we see it here. And the other one you see it there. That is the Sun dog.

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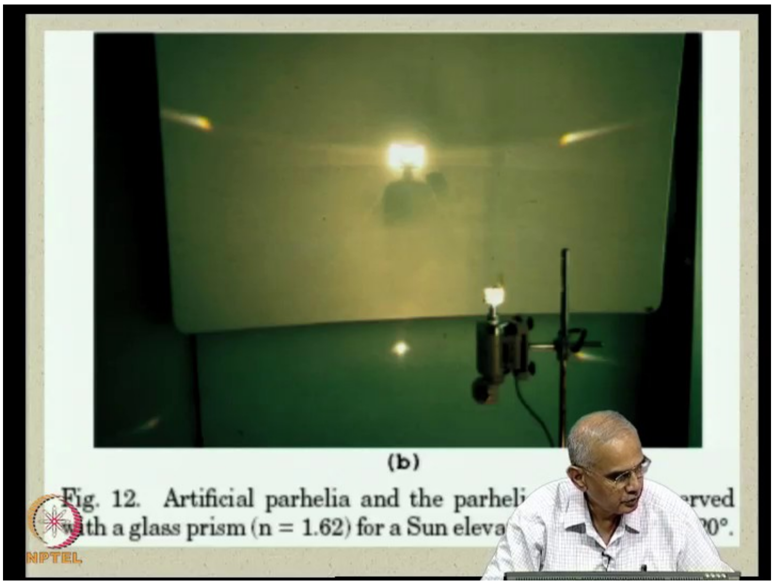

This can also be demonstrated in the laboratory as shown in this laboratory picture. So, many of these phenomena can easily be done at home or at the laboratory because everything can be done through Geometric Optics.

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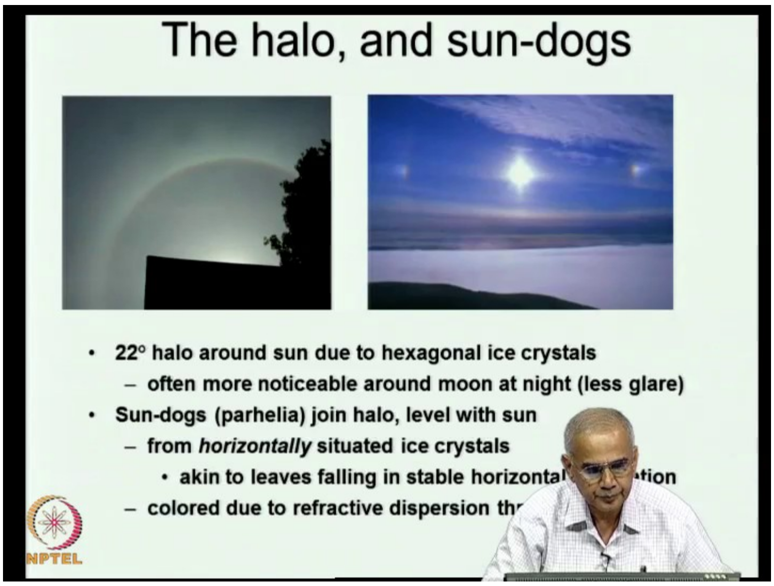

Here pointing out that it is clearly visible on full moon. We you see the halo clearly and here is the Sun dog that is visible.

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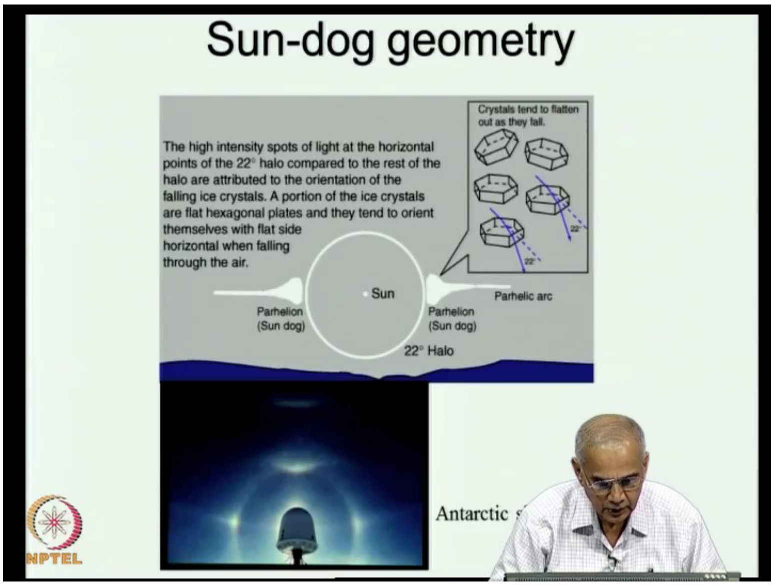

The Sun dog geometry is explained more clearly here. When, we have flat crystal reentering to the top and existing to the side, we will do a 22 degree change in direction. It is caused by the hexagonally flat plates. When the flat plates are falling horizontally in the air, they cause the Sun dog phenomena. In Antarctica this is; This again we can see clearly here look because sun has been blocked deliberately. Here, we see the Sun dog and we see the upper arc that we will discuss. So, all these are visible in Antarctica where ice crystals are plenty throughout the season.

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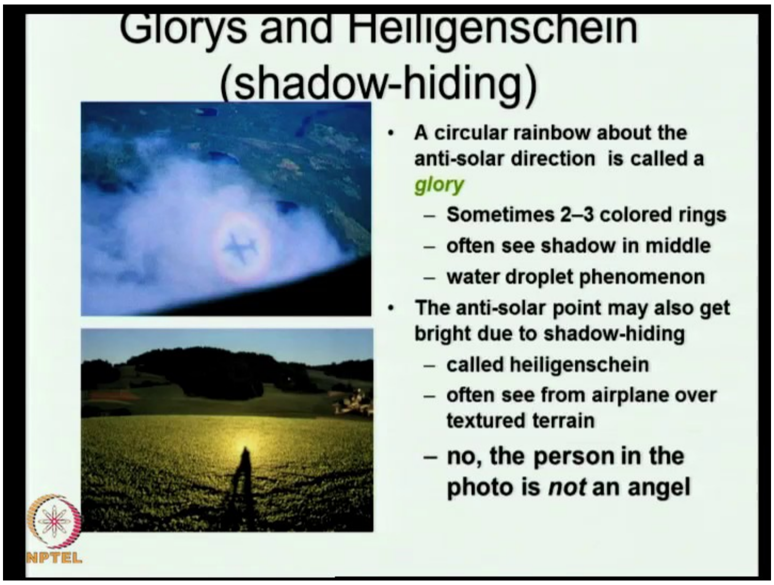

The Glory as you saw is a scattering phenomenon. This is not so common, very often observed from an aircraft.

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Here is very nice picture of the pillar near the sun and the two Sun dogs; clearly visible as well as the upper arc here. This is again pictures in the polar region, where ice crystals are quite common, the atmosphere is quite clean and pristine, and there is no contamination by aerosols. So, this phenomenon is very well observed.

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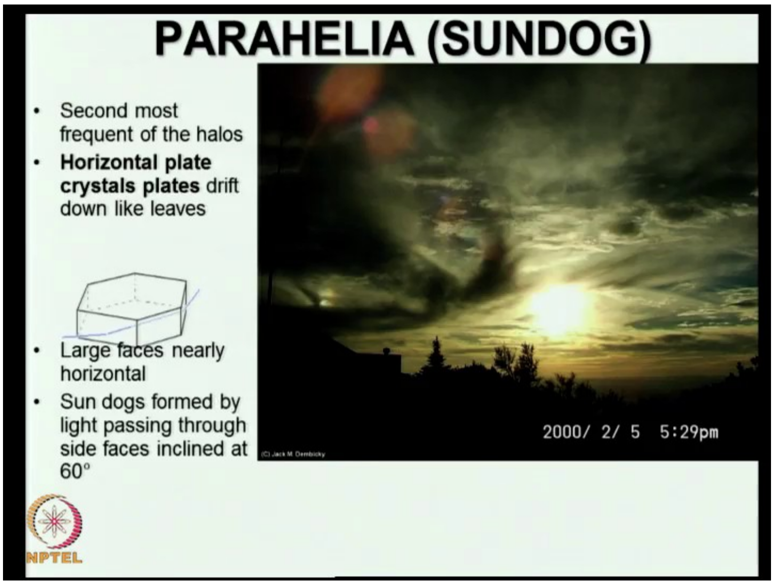

The second most frequent halo is the when horizontal size ice particles fall down and this is a slightly different angle here. It is coming from one side and goes to other side. Previous one came from the top; this is going to the side, so that the side faces inclined at 60 degrees.

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Here is another example of two Sun dogs on either sides of the sun.

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One more picture showing the Sun dogs and Sun pillar here.

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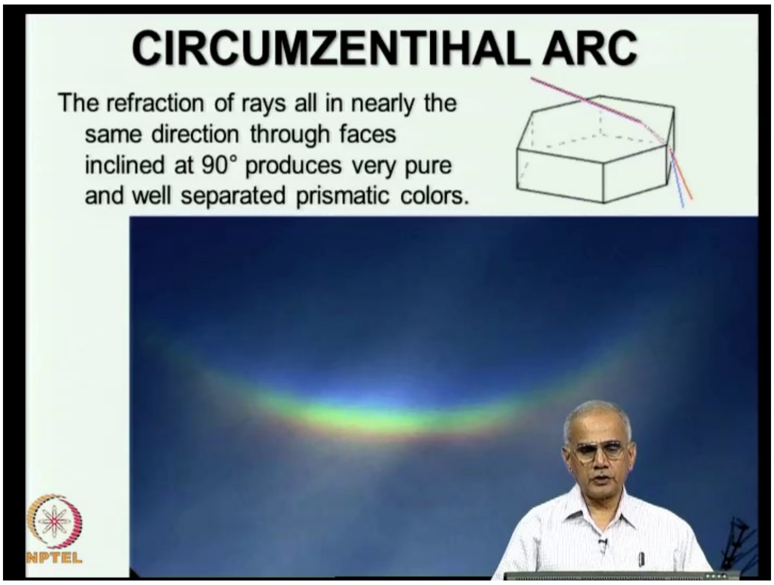

The one we saw on the top is called the Circumzenithal arc is the refraction rays through faces inclined at 90 degrees; these two faces. Produce very pure, well separated, chromatic colors seen here. This is, can be shown to be coming at that angle.

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Here is a Sun pillar reflected on a water body after sunset.

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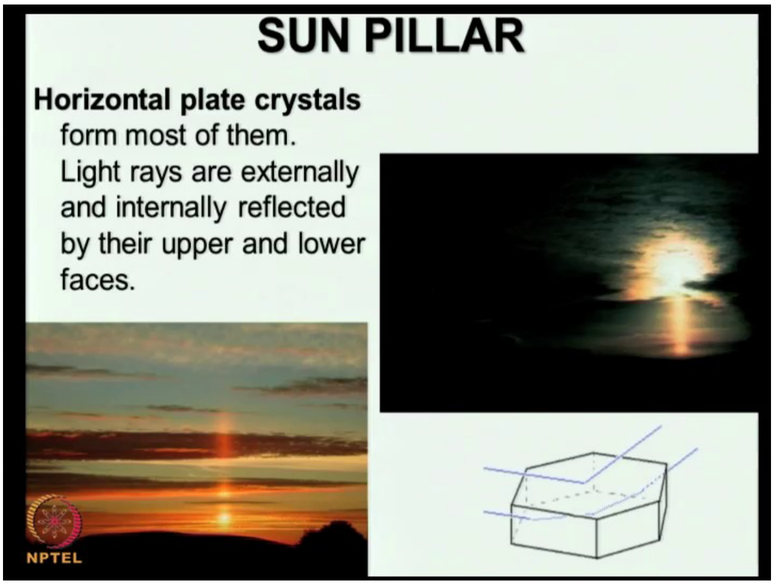

Here we can see the light rays are reflected by their both upper and lower faces. It is coming inside from this side and exiting through the top. It is the both internal reflection and the role of the upper lower surfaces, is what causing this phenomena.

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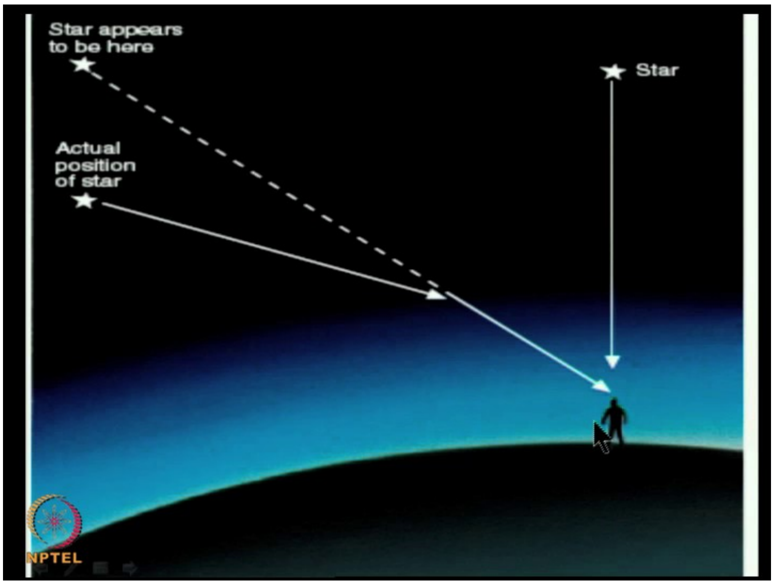

Now, for astronomers all these phenomena are important because whenever, we are looking at the star overhead, there is no problem. But, if we are looking at the star at an angle, then the apparent position of the star is not same as the actual position because the rays of the stars are refracted in the sky. We have to correct for it. These are the things which have been studied by astronomers very closely because they want to know the actual position of star, not the apparent position here.

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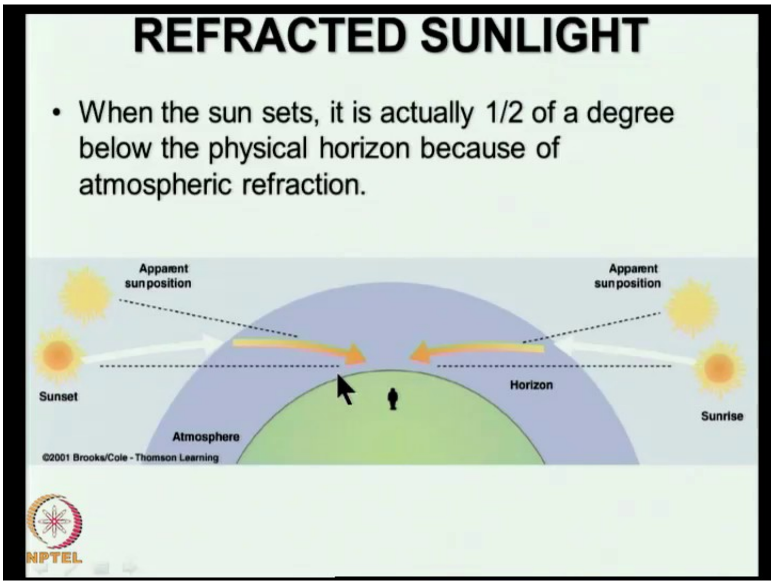

Now, refraction is also very important during sunsets. All of us have watched this. When a sun is setting, the rays of the sun actually bend due to the changes of different index in the atmosphere. So, once more your eye extrapolates backwards. So, even though the sun is set, you see the sun. The sun has set, but because of the bending of rays, you think that the sun has not set. If we want to calculate precisely, the sun setting time to within a few seconds, then we have to account for this refraction.

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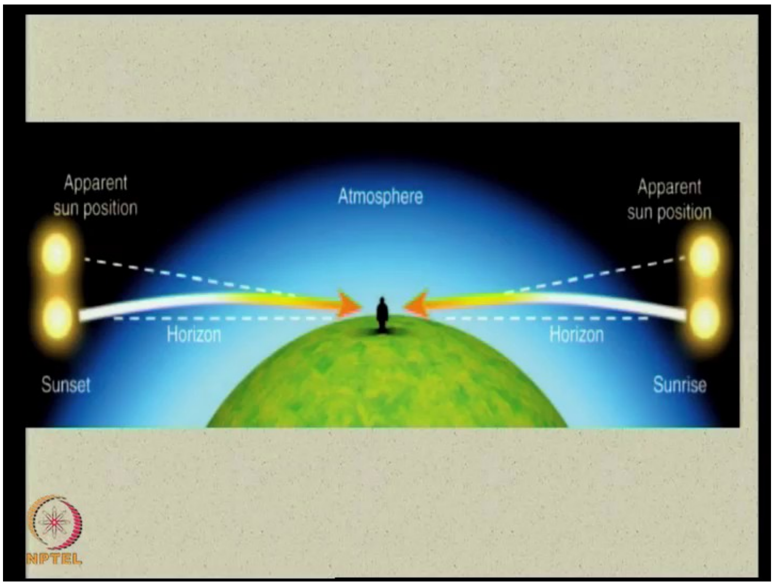

This is another vertex plane.

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Now, when the sun sets, we see some very interesting distortion of the spherical shape of the sun and this is again on account of refraction.

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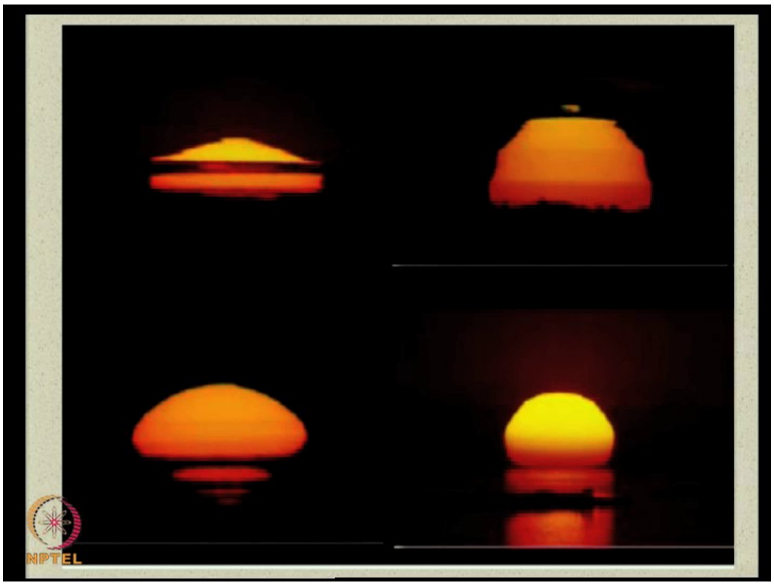

We see a dramatic example of sun setting here and changing the colors and changing the shape of the sunlight.

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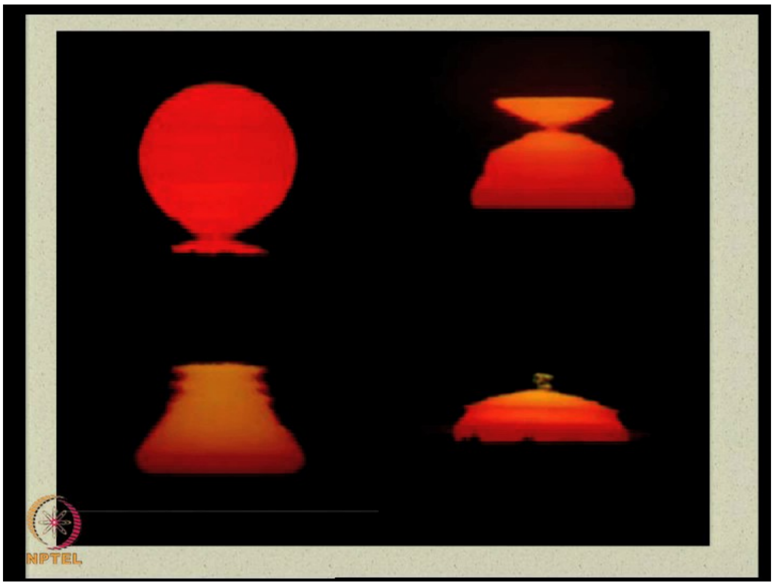

The most important is the distortion that is there; which, we will see is really linked to properties near the horizon. This is another example of unusual distortion as the sun sets.

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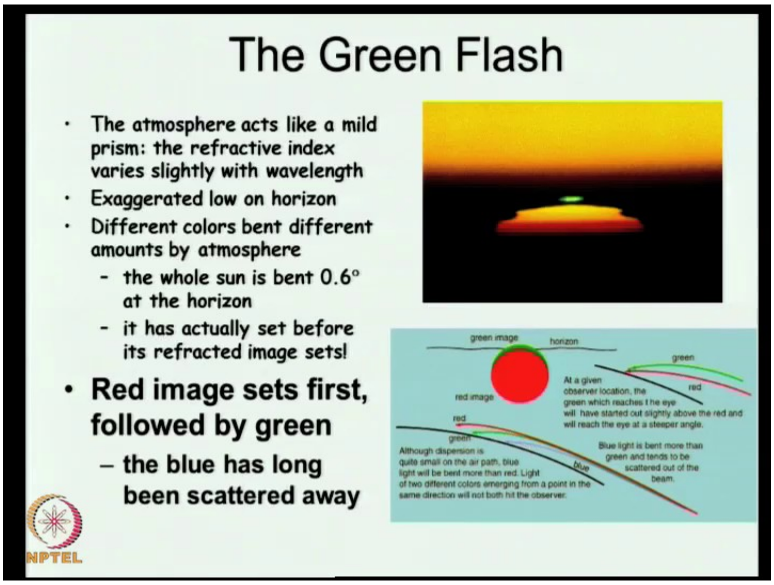

One of the most intriguing phenomena that is caused by refraction is the green flash. Atmosphere is acting like a prism. After the sun is set; there is a detached green flash we will see. This is happening because the refractive index varies with wavelength; that we already saw. When we go to very low position on the horizon, the depth over which the refraction occurring is very large.

So, the whole sun is bent by angle of 0.6 degrees. So, among the rays bending the red has a least amount of bending, and green and blue have much more bending. Therefore, this green we are seeing really is, are the rays of the sun after it was set. Those rays having bent bend much more, so the green light which we see is scattered out slightly above the red and it reaches the eye at a steeper angle because of more bending. Blue also scattered but might be it is scattered out.

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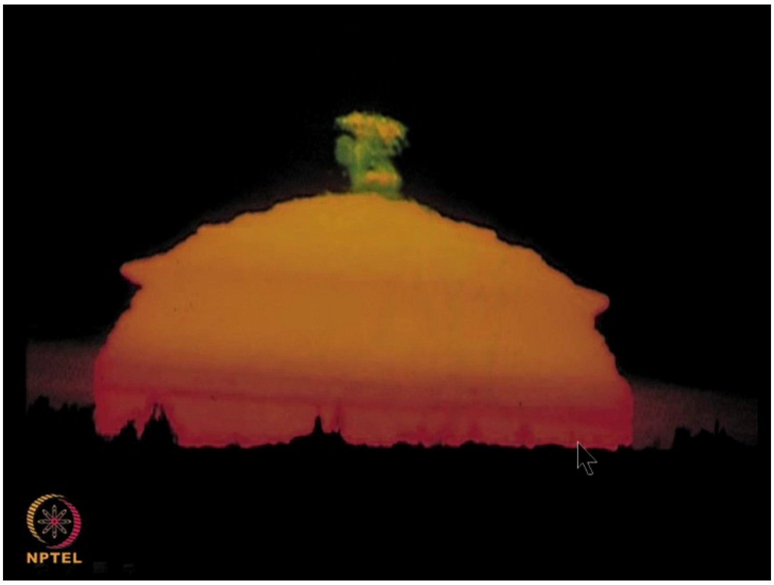

Now, this green light distance is visible here. The green light is visible very, very clear above the sun. And this is the image of the sun that is set few seconds earlier. And the rays of the sun were bent by the atmosphere and it appears above the orange sun. This red has a less bending due to refraction than the green and that is coming out. These are rare phenomena, not observed every day because we need very, very clear sky; no clouds, no rainfall, which can cause distractions. It requires lot of patience to able to photograph these unusual optical phenomena of the sun.

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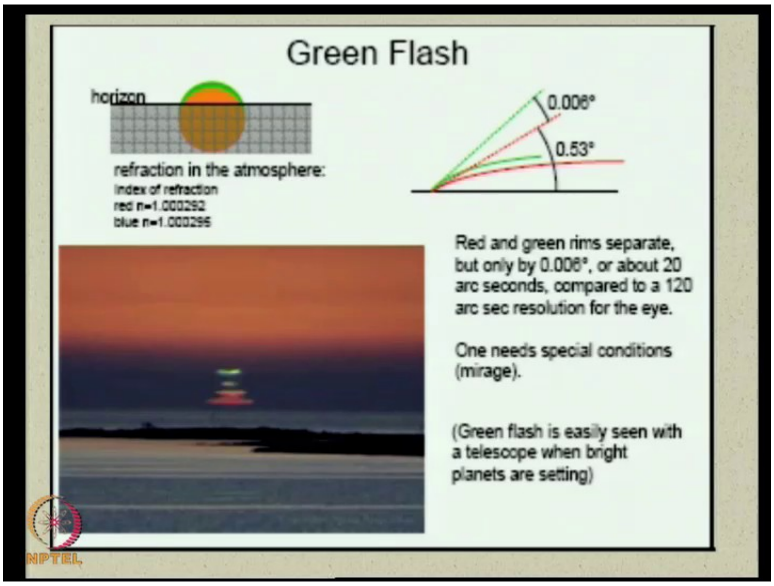

Now, here is a more detailed explanation. The refractive index of the red light is 1.000292 and refractive index of the blue light is 1.000295. They are different in the sixth decimal place; still, you see a very clear distinct effect of refraction here with the red and green separated; were separated, but 0.006 degrees or 20 arc seconds. This range is small.

Normally, we will not see it because the eye will resolve only 120 arc seconds, but under special conditions you see this. We also see this flash when bright planets like Venus and Mars, Jupiter are setting; same phenomena are at work. But, for that we need a telescope. Astronomers who watch this from the telescope have observed these phenomena quite distinctly.

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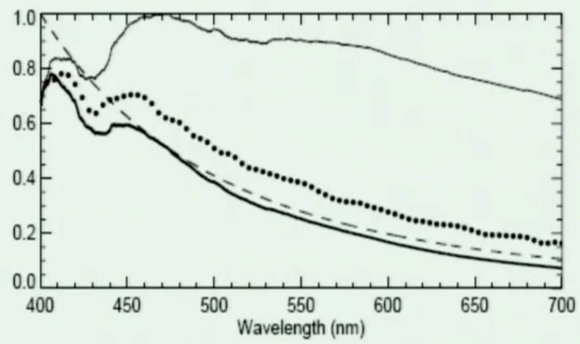

Figure 8.1: Overheard skylight around noon measured in spring in Central Pennsylvania (circles). The thick solid curve is the product of Rayleigh's scattering law (dashes) normalized to one at its greatest value and the solar spectrum (thin solid curve) outside Earth's atmosphere normalized to one at its peak.

Now, all of us know that the color of the sky is blue. What this curve shows is the observed skylight. This is observed intensity of skylight in the visible region. The thin one is solar spectrum to solar spectrum, by Rayleigh's scattering law. That is, one over lambda to the power of four. We can see that it can fully explain why the observed maximum in the blue is there.

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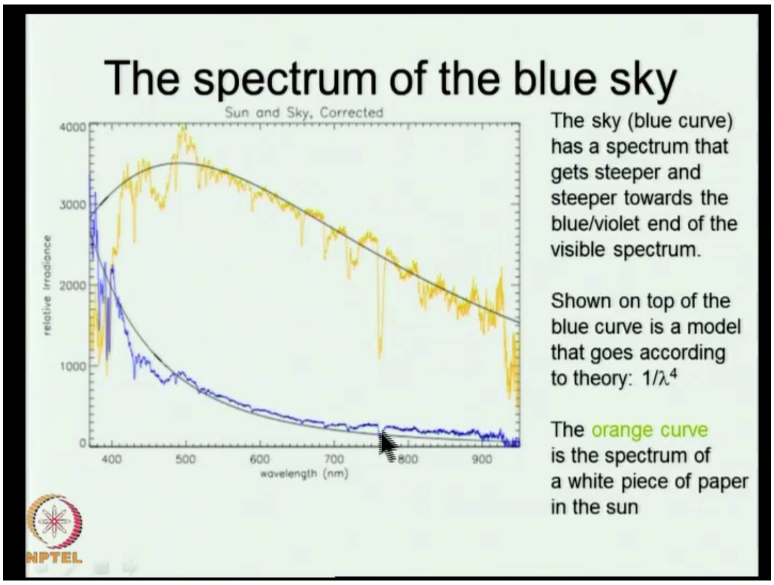

So, the blue curve is a model that goes i lambda to the power of four. Orange curve is the sun's spectra. So, clearly shows that due to that violet scattering by molecules, the peak of the reflected scattered radiation occurs closer to violet and blue compared to the sun's spectra, which maximizes around green-yellow region. This is green-yellow region and this is violet-blue region and this is by Rayleigh's scattering, which scatters more light in this region than this region.

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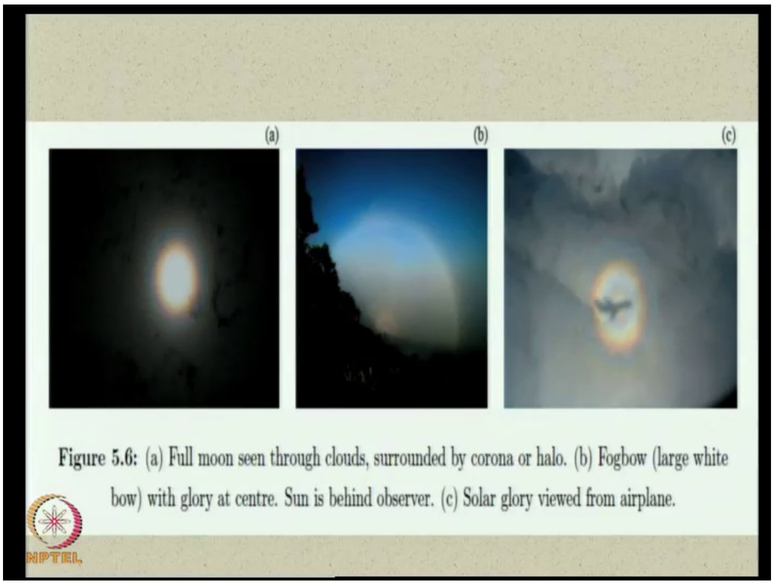

Some other phenomena like glory and fogbow which we saw in the scattering signature can be seen on full moon days. Here is a halo; here is a fogbow.

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Sometimes, we will see double Sundogs. We have double sundogs; one, two and there is one more.

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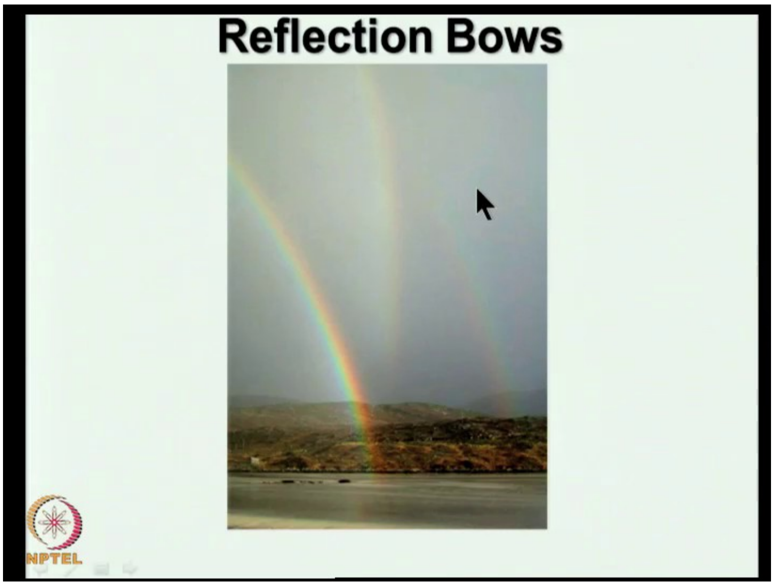

The other interesting phenomenon that you see is light reflecting of a lake also undergoes; If we see a primary rainbow here, second rainbow here and a reflecting rainbow, so this is the sun's ray reflected from the lake. After reflection the raindrops and then causing this third rainbow; whose, angle is quite different from the secondary and primary rainbow. So, all this are easy to explain through rate raising or using miss scattering formula.

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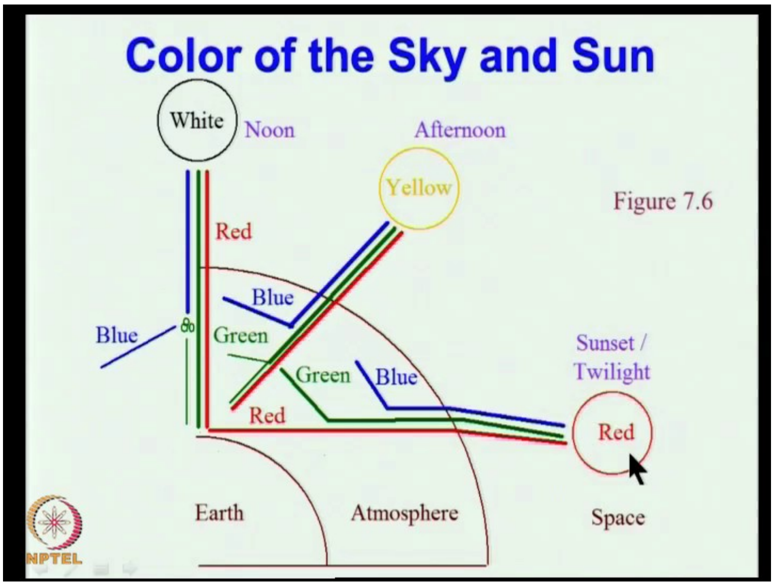

Now, one more thing that we can explain from basic theory is as to why the sun is white at noon, somewhat yellow in the afternoon, somewhat red in the evening. And essentially at noon, the path through which the rays are travelling is fairly short. But, if we go to the afternoon, the path length increases, more and more blue radiation is scattered out. That is the blue sky. But, the remaining ray that incoming from the sun is richer in yellow than blue because blue is scattered out.

As we go past to the evening, the path length decreases even further here. Both the blue and the green gets scattered out we see only red. The color of the sun we see is based on how much color from the sun is scattered out; as the white color of the sun is scattered out due to scattering. That depends on the number of particles in your path.

In a clear day this is what you will see. But, on the day if there are all kinds of particles in the atmosphere like man matters, salts or naturally occurring dust or some other features. Then we can see some every interesting colors of the sun and moon on days when we have, let us say after a day with huge volcanic eruption, in which larger particles are put in this stratosphere. And these particles are easily uniform in size, and then they can do wonderful scattering phenomena. We can get a blue color moon, which is very rare. That is why is called, we call here, we all use this expression "once in a blue moon" because that kind of phenomena occurs only when there are major volcanic eruptions. Those volcanic eruptions occur once in twenty, thirty, forty years. These are rare phenomena. Now, with that we have covered the discussion on how scattering controls natural phenomena.

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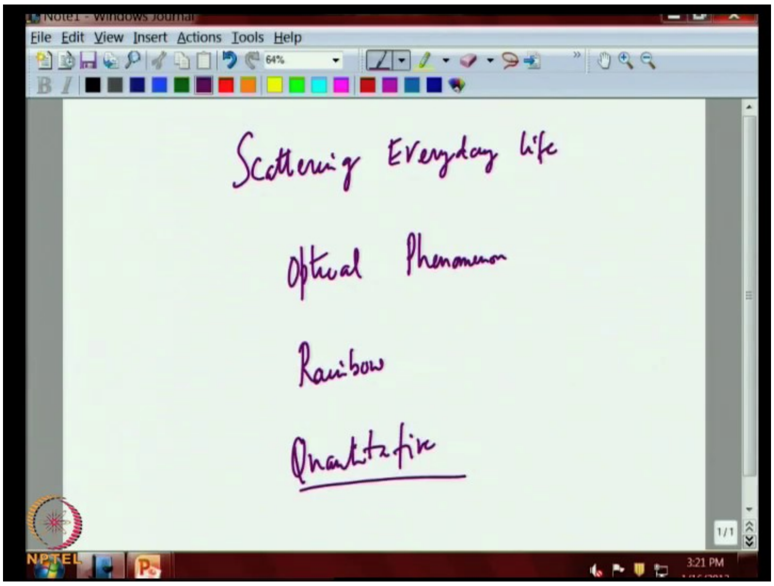

Now, we move on to actually quantitative aspects of the phenomena. What was discussed today was merely qualitative, in which we merely highlighted how we can explain various natural phenomena; the rainbow, halo, sundogs and so on through ray tracing or through Mie scattering algorithms. Some of them are quite quantitative. But, it is important to know how to calculate this scattering by particles and the net effect of scattering in quantitative terms.

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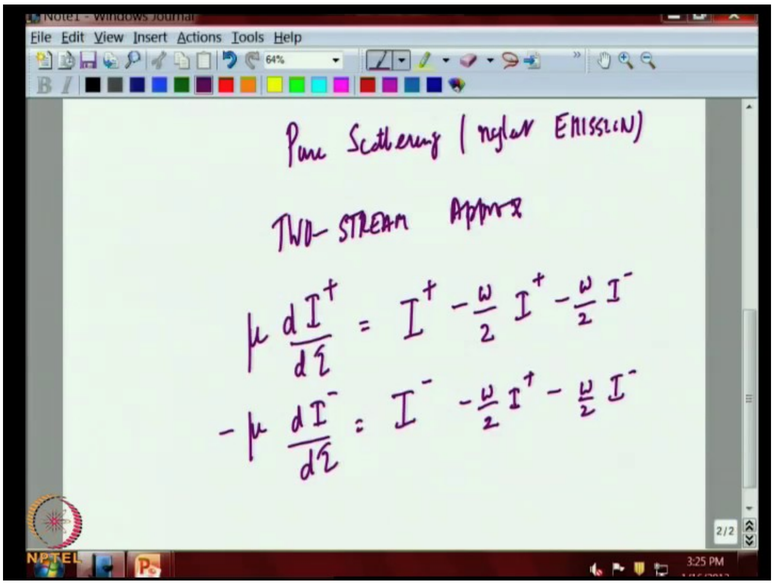

To do that, we go back to our equation for pure scattering; that is, we neglect emission. If we recall, in the radiative transfer equation, there is a term involving emission which requires the temperature of the medium and its variation. But, if the situation which we are dealing with the emission is occurring at very different wavelength and the wavelength of interest to us; like, for example, we understand how solar radiation is scattered and reflected by either cloud particles or all other particles, then the emission by the medium at wavelength around 10 micron would not be interesting to you because you are only focusing on, let see visible radiation. In such a case we can solve a pure scattering problem in a more elegant way. And we recall that we had well known two stream approximation, wherein we divided the radiative rays upwards and downwards; two hemispheres essentially.

We saw that the equation can be written I plus, upper going rays. We have on the other side I plus we have this single scattering albedo coming in here. This one is equation for the upper intensity. Similarly, the second equation for the downward intensity; which you have dealt earlier. Notice that these are two equations and two unknowns. The two unknowns are I plus and I minus in this case. All these can be solved.

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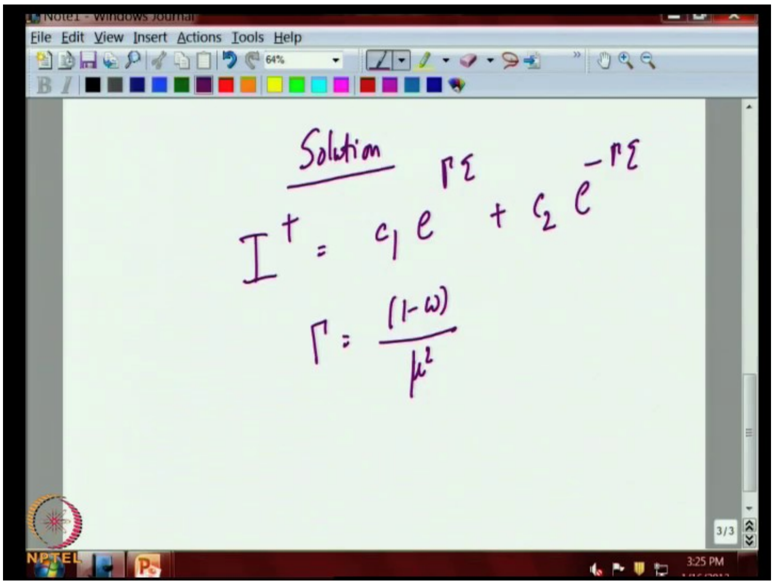

The solution is straight forward solution of coupled differential equation. The solution can be written as I plus, the upper going ray, is equal to c one e to the power of gamma tau plus c two e to the power of minus gamma tau; where gamma is the quantity which connects the single scattering albedo and the direction cosine square.

So, the decay of the intensity depends on the single scattering albedo as well as the direction it is travelling. We will continue this solution in the next lecture and show how the results obtained from the solutions of the equations helps us to intercept the various results that are relevant to both Engineering and Atmospheric Science.