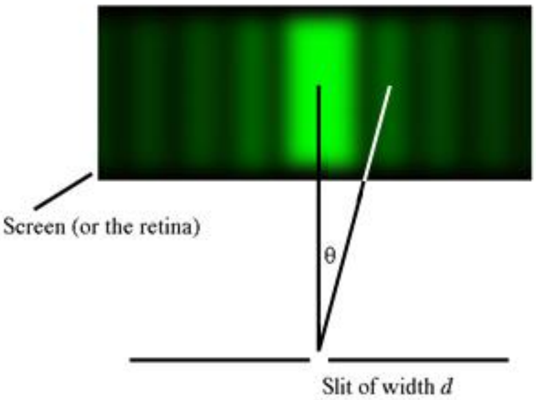
Diffraction Coronae

Ian Jacobs, Physics advisor, KVIS, Rayong, Thailand

Coronae are diffraction rings around the sun or moon due to water droplets, pollen or ice at high altitudes. The name is from Greek via Latin. The plural is either coronae or coronas. To explain how a corona is formed and the relationship between its angular size and particle diameter we begin with a monochromatic single-slit diffraction pattern. (Monochromatic meaning of one colour or wavelength.)

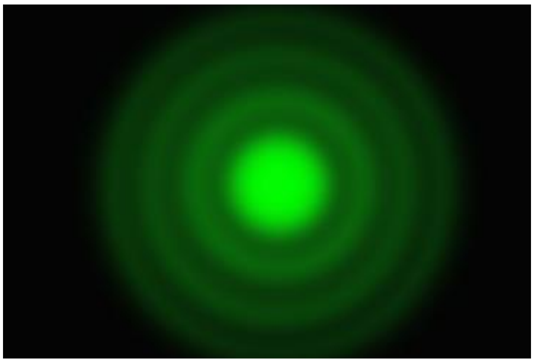


Far from the slit and for small angles for which $\sin\theta$ and θ in radians can be taken as equal, the angle θ in radians (from the centre line to the first bright fringe) is …

$$\theta = \lambda/d \qquad [1]$$

... where λ is the wavelength and d is the slit width.

If the slit is replaced by a small round hole the diffraction pattern becomes circular and under the same conditions the angle θ to the first bright fringe is increased a little.

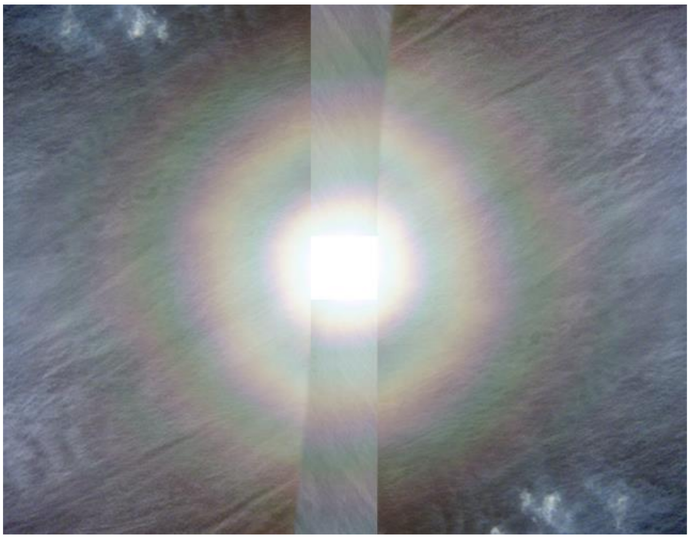


For a monochromatic circular pattern made with parallel light and observed far from the hole, (Fraunhoffer diffraction), the angle to the first bright fringe is given by …

$$\theta = 1.22\ \lambda/d \qquad [2]$$

For coronae in the sky the light source is the sun, which is neither a point source nor monochromatic and the diffraction is due to obstacles not holes. White light diffraction patterns are coloured because the size of the pattern depends on wavelength. The coloured diffraction pattern below was made by placing a narrow strip of bamboo in a beam of sunlight. In this case, and in general, an obstacle has the same diffraction pattern as an opening of the same size and shape.

Random collections of *well separated* objects (like water droplets in clouds) have the same diffraction pattern as a single object of the same size and shape. The solar water droplet corona below has the coloured ring structure that, *if our eyes were super sensitive*, we would see when looking at the sun through a single round pinhole of the size of the water droplets that formed it.



The illustration is a composite 360º view (note the joins and duplication of clouds either side). It has been selectively contrast enhanced to show fragments of the faint third outer ring more clearly. Additional rings are too faint to be seen. The sun was directly overhead. An image of half the pattern was taken through an almost closed window covered with reflecting film that removed more than 95% of the light. The cirrus cloud sheet was in formation. The super-cooled water droplets were small and of nearly uniform size, giving three outer rings that are well defined. The inner ring (yellow to reddish) is the outer edge of the bright central disc called the aureole (or Airy disc). This inner ring is not present in a monochromatic diffraction pattern but appears in sunlight diffraction because blue light of shorter wavelengths has a smaller aureole. The net effect is to superimpose discs of different colours and sizes leaving red on the outside. In this image the central aureole is overexposed and appears to be white not bluish.

Simulations

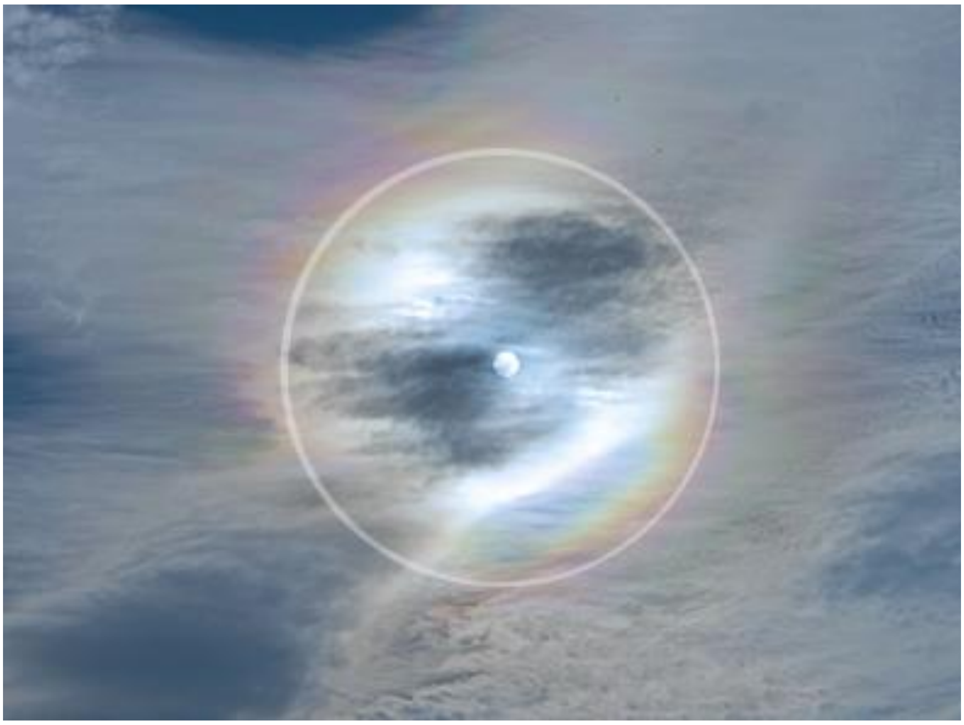
A solar corona is a white-light pattern without clearly defined bright outer rings to define the size of the diffraction pattern of a single hole in monochromatic light. Equation 2 can be applied approximately to a corona in sunlight by guessing where the bright rings would be for red light, but the appropriate wavelength is somewhere between 600 and 640 nm. Added to that, water droplets are not completely opaque and have a distribution of sizes. A better approximation involves a detailed Mie simulation that takes these factors into account. IRIS, from Les Cowley, (http://www.atoptics.co.uk/droplets/dload.htm) runs on a PC and will do that, avoiding what were once long tedious calculations. The illustration below shows a Mie simulation made with this program for droplets of uniform size fitted to the original in the illustration above showing almost half the diffraction pattern. The match is remarkably close, considering that average droplet size over the field of view may not have been the same everywhere which would have distorted the corona in the sky and the camera introduces some additional distortion, especially along the right hand edge. Simulations are usually fitted to outer rings because the position of the reddish outer edge of the aureole depends on exposure and is a less reliable indication of droplet size.

Simulation matching: further reading http://www.atoptics.co.uk/droplets/corim3.htm

Estimating droplet size

If the half-degree solar disc appears in an image it can be used to calibrate the field of view to find the ring diameter in degrees. Very often cloud droplet size has a standard deviation of 20–30% or more and the only feature of a diffraction pattern around the sun or moon is the central aureole with a reddish outer edge. If no outer rings are seen droplet size based on the aureole is an estimate only. A calibrated Mie simulation can be used to find droplet size for multi-ring patterns but the rings are seldom perfectly round when formed in clouds. Any estimate of average droplet size will be approximate and the simple Fraunhoffer relationship (equation 2) will often give a satisfactory result.

A diffraction corona in the sky



The composite image was taken in Bangkok, Thailand, as a sheet of cirrocumulus cloud was forming. It shows the solar disc and two outer rings but not the inner ring at the outer edge of the aureole which is overexposed. A white ring has been added to estimate the average diameter of what is taken to be the first outer ring.

Comparing the diameter of the solar disc in pixels with the diameter of the white circle (10:180) gives the red ring diameter as 9°. Taking the wavelength of red light as 620 nm and converting degrees to radians gives the average drop diameter d as ...

$$d = (1.22 \times 620 \times 10^{-9})/0.078 = 9.7 \times 10^{-6}\ \mathrm{m}$$

The average droplet diameter is estimated to be close to 10 microns. Because the outer rings are well defined the standard deviation of diameters is relatively small (less than 5%). If the droplet size is less than 5 microns the corona becomes larger and less intense. This is a bright well defined corona: a typical example of the type formed by recently condensed clouds with relatively uniform small droplets between 10 and 20 microns in diameter.

Mie simulation

MiePlot, a free download from http://www.philiplaven.com/index1.html, and/or IRIS, shows that a full Mie simulation gives a first outer ring radius of 4.5° for droplets of 8 microns in diameter. The reader might like to try these simulations for themselves if time permits, but for droplets over about 5 microns in diameter, a simple Fraunhoffer diffraction calculation gives a satisfactory estimate.

Questions

1 A half-degree disc has been added to the image below using the estimated field of view of the camera.

Estimate the average droplet size using the half degree disc and equation 2.

2 Diffraction in cirrostratus cloud. The image was taken in Bangkok, Thailand outside my house at midday.

a What additional information would establish a degree scale on this image?

**How would you suggest I could do that*?

b By looking at the image, what can you say about the average droplet size?

c After reading this article do you think the X on the image marks the second or third outer ring in the diffraction pattern? Briefly give your reasons.

3 A full moon corona photographed at KVIS. The sight is not uncommon and is known as a *Bishop's ring*. Only the aureole is visible in this image. *Estimate the average droplet size.*

Note: distinct outer rings are seen only when diffraction is by particles with diameters from about 10 to 25 microns in diameter with low standard deviations. What is seen in a normal hazy or dusty sky is the aureole, bluish in the centre, transitioning through yellow to reddish for high elevations as here, but near sunset invariably salmon in the centre to orange/red because the blue has been removed by scattering over a long atmospheric path length.

4 Sunset at KVIS. The solar disc is clearly defined. Only the aureole is seen.

a Estimate the average droplet size.

b Why are your estimates in this case and above for the lunar corona not likely not to be accurate? (Three or more reasons).