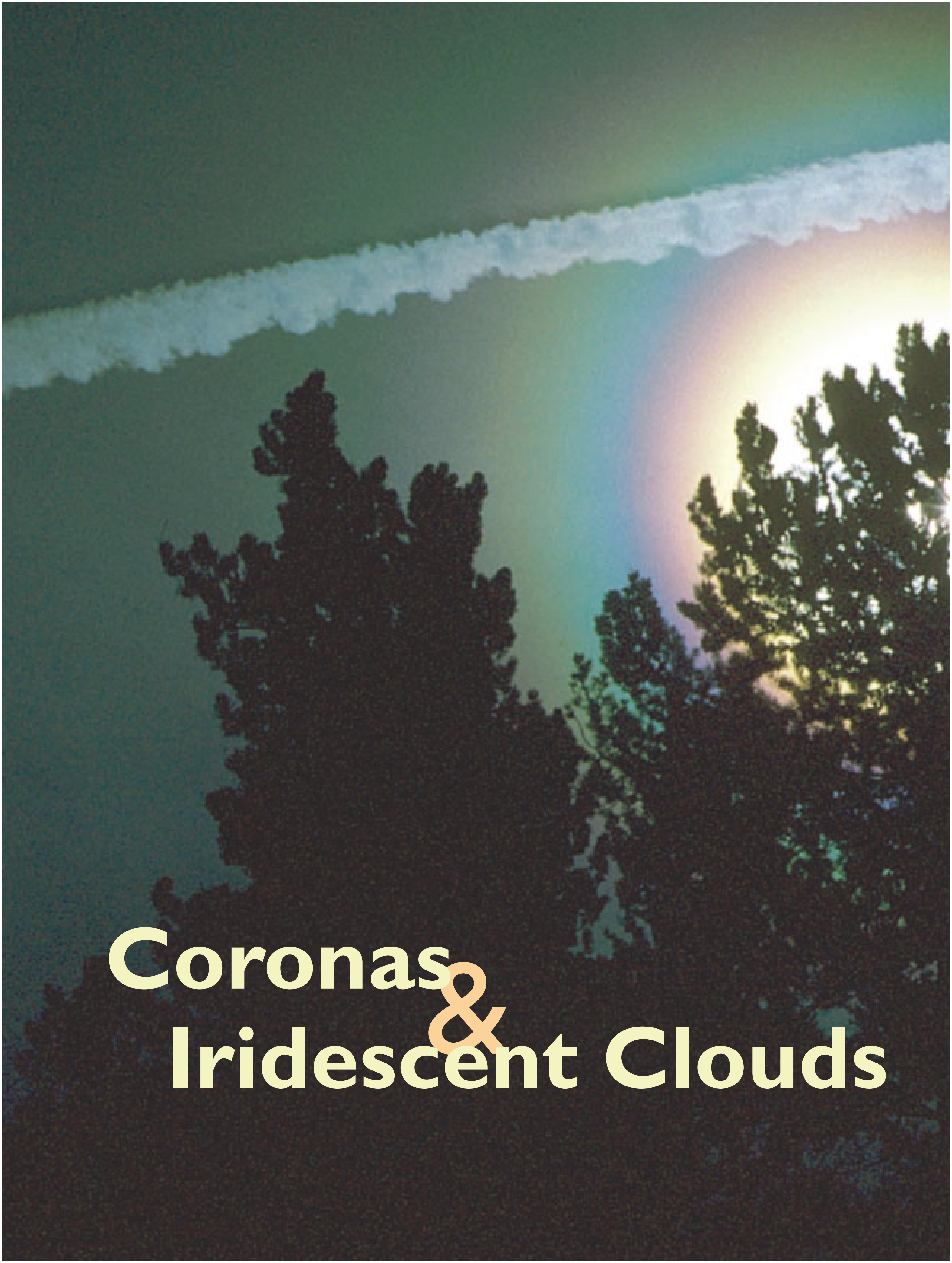

Coronas & Iridescent Clouds

**Joseph A. Shaw and
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Figure 1. Large, multi-order corona, created in a mountain wave cloud by sunlight diffracting from tiny, quasi-spherical ice particles.

Coronas and iridescence occur when light is diffracted by small particles of liquid water or ice in the atmosphere. Diffraction colors are particularly vivid in mountain wave clouds because of the small particles and narrow particle-size distributions. The photographs shown here provide evidence that wave cloud diffraction displays are often created by unusually tiny, quasi-spherical ice particles.

During Captain Richard Scott's ultimately tragic *Terra Nova* expedition to Antarctica (1909-12), meteorologist George Simpson described in his journal a display of brilliantly colored rings that surrounded the sun as a thick fog dissipated.[1] Simpson recognized the rings as a corona caused by diffraction of sunlight by cloud particles. Because the air temperature during this period varied between -26° and -29° C and a fogbow had been visible opposite the sun immediately preceding the corona display, Simpson concluded that the fog around him contained tiny droplets of supercooled liquid water of a diameter smaller than 25 μm. The explorers' fur sleeping bags and wool sweaters had in fact become coated with hoar frost, which Simpson called "a sure sign of supercooled water." These and other observations led Simpson to conclude after the expedition that coronas are produced only by liquid water, not by ice. He even suggested that the existence of a visible corona could indicate that a particular cloud was composed of liquid water.

It is a well-known fact that coronas are caused by scattering in the forward direction (i.e., diffraction) when light impinges on cloud particles.[2-6] However, in contrast to Simpson's claim that coronas are formed by liquid water alone, recent observations have demonstrated that coronas can instead be created by both liquid and ice.[5-9] Common hexagonal-needle ice crystals could cause a circular corona if they were oriented randomly, but the large crystal size (~ 100 μm and larger) would result in a rather small corona with an angular diameter of less than one degree. Most coronas are five to ten times larger, a finding that at first seems to support Simpson's claim that coronas exist only in liquid clouds.

Recently we began studying photographs that we have collected over a number of years of coronas and iridescence that we observe quite often in mountain wave clouds on the lee side of the Rocky Mountains. However, when we started analyzing the meteorological conditions for some of our corona photographs, we were surprised to find that most of the photographs were of clouds that were much too cold to contain even supercooled liquid water. Furthermore, Fraunhofer diffraction theory[10,11] showed that the diffracting particle diameters in our coronas had to

Figure 2. Oblong corona with larger rings at the top and smaller ones at the bottom, indicating the opposite trend for mean cloud-particle sizes.

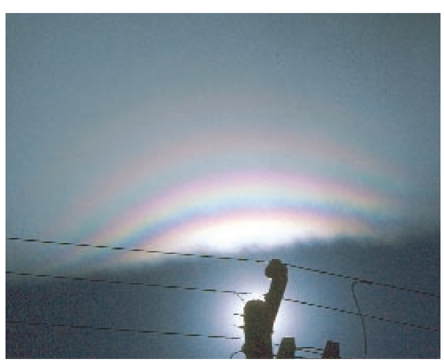

Figure 3. Multi-order corona with ring radii asymptotically increasing toward the edge of the cloud, where the particles are smallest.

Figure 4. Discontinuous corona, indicating a sudden transition from large cloud particles at the bottom to small particles at the top.

Figure 5. Corona with ragged edges, likely caused by mixed-phase cloud particles.

Figure 6. Brilliant iridescent wave cloud above the horizon near sunset.

be much smaller than common ice crystals (~ 10-20 μm vs. ~ 100 μm).[5,6] This left us with the question of whether wave clouds could be composed of ice particles that were so small and apparently spherically shaped.

Tiny ice particles in mountain wave clouds

We asked Andy Heymsfeld,[12] a well-known expert on mountain wave cloud microphysics, who excitedly assured us that wave clouds do indeed quite often contain very tiny ice particles with nearly spherical shapes. Wave (or orographic) clouds, which are formed when air is deflected rapidly upward by mountain barriers, are often physically and optically quite thin. Particles are carried into and out of the cloud so rapidly that there is not much particle growth within, a factor that results in both a remarkably narrow particle-size distribution and a small mean particle size. Because of its lens-like shape, a common type of orographic cloud is also referred to as a lenticular cloud.

Lenticular wave clouds are composed of particles the sizes of which, typically < 25 μm,[13,14] are much smaller than those found in the more common ice-crystal cirrus clouds (typically ~ 100 μm). Wave cloud particles are usually supercooled liquid of approximately -36° C, a temperature below which they freeze spontaneously into quasi-spherical ice particles that may be somewhat larger than the original water droplet, but still almost always smaller than about 25 μm.[13,15] These quasi-spherical ice particles are the apparent source of the large-diameter coronas in extremely cold wave clouds.[5,6]

Diffraction analysis

Fraunhofer diffraction theory[10,11] provides a simple way to calculate the mean cloud-particle size from the angular size of each colored ring in a corona photograph when we know the focal length used to record the photograph.[5-9, 16-18] Particles with circular cross section diffract light into a set of concentric rings, described by the Airy function,[10,11] with blue (short wavelengths) on the inside and red (long wavelengths) on the outside of each diffraction order. The colored rings, which surround a zero-order central peak that is very bright and colorless, decay in brightness rapidly, making it unusual for observers to see more than one or two sets of concentric rings in atmospheric coronas. When you can see more of them, consider yourself fortunate, cherish the opportunity and… take a picture!

For small angles, the angular diameter of the Airy rings (θ) can be related to the wavelength (λ) and particle diameter (D) as $\theta = (m \times \lambda)/D$, where m is 0, 1.635, 2.679, 3.699, 4.710... for maxima and 1.220, 2.233, 3.238... for minima.

This simple equation tells us that longer-wavelength (e.g., red) light will form larger rings than shorter-wavelength (e.g., blue) light. It also tells us that small particles produce larger rings than large particles. The best diffraction displays occur in thin clouds with small particles and narrow particle-size distributions. Wave clouds satisfy these conditions almost ideally, whereas in many other cloud types, diffraction displays suffer from: greater thickness, which produces excessive multiple scattering; large particles, which create diffraction rings too near the sun; or broad particle-size distributions, which smear colors together.

Recently we wrote two papers about the analysis of corona photographs that are particularly interesting for their clarity, vivid colors and interesting shapes.[5,6] One paper focuses on the optics of these photographs[5]; the other focuses on their meteorology.[6] Here we present many of the photographs, along with a brief qualitative explanation.

Figure 1 is a photograph of a large, multi-order corona that was created in a mountain wave cloud by sunlight diffracting from the tiny quasi-spherical ice particles described earlier.[5,6] From the angular radius of each colored ring, we inferred a mean particle diameter of 20.4 ($\pm$0.5) μm. The tree at the center blocks the bright central scattering peak, which helps reveal the colors in the surrounding rings. In fact, the first visible colored ring in this photograph—actually the outer ring of the first order—is red; the first blue ring is buried within the bright central peak. The full range of colors is visible in the second-order rings.

Noncircular coronas and iridescence

Sometimes coronas are noncircular, either because of particle shape (this is the case, for example, for some nonspherical pollen particles[19-21]) or because of gradients throughout the cloud in the mean particle size. In both cases, the particle-size distribution must remain narrow for the corona to be visible. Figures 2-5 are photographs of coronas that have noncircular shapes because of variations in mean particle size. The oblong corona rings in Fig. 2 decrease in radius gradually from the top to the bottom of the photograph, corresponding to a gradual increase of mean cloud-particle size from 19.5 μm at the top to 24.3 μm at the bottom. The likely cause of this gradient is particle growth in the upward-motion portion of the cloud.

Rapid water-droplet growth toward the interior of a wave cloud from the upwind cloud edge resulted in the spectacular display, which we call an *asymptotic corona*, shown in Fig. 3. The tiny particle size near the upwind cloud edge (bottom of Fig. 3) resulted in asymptotically large diffraction rings there, while the larger particles in the cloud's interior generated diffraction rings with much smaller radii. It is evidence of the remarkable characteristics of wave clouds that such a rapid variation in mean particle size could occur while a particle-size distribution sufficiently small that there are four distinctly visible diffraction orders was maintained. Fraunhofer diffraction analysis reveals mean particle sizes of 12.3, 14.5, 15.8 and 16.6 μm for the first four diffraction rings above the sun, and 7.6 μm for the asymptotic first-order diffraction ring near the cloud edge (to the sides of the sun).

A step discontinuity in diffraction-ring radius in Fig. 4 indicates a sudden change of mean cloud-particle size from 18.1 μm at the bottom to 14.4 μm at the top. We are not certain of the cause, but it is likely a sudden transition from supercooled liquid water droplets to ice. This conclusion, supported by the meteorological analysis of this photograph, suggests that we serendipitously captured photographic evidence of the sudden liquid-to-ice phase change known to happen when the temperature in a cloud drops below -36° C, as discussed previously. A different kind of transition is indicated in Fig. 5, which shows a corona in the vicinity of layered wave and cirrus clouds, with edges that we believe are made ragged by a nonuniform collection of ice particles that were probably nonspherical and randomly oriented.

The extreme limit of noncircular coronas is the swirling patterns of color found in iridescent clouds, such as the display shown in Fig. 6. These color patterns are caused by diffraction in local cloud regions containing narrow particle-size distributions but characterized by high spatial variability of mean particle size (analogous to colored interference patterns in oil films).

High-order diffraction may help to explain, at least partially, the somewhat different colors observed in coronas and iridescence. Whereas most authors describe coronas as consisting of primarily pink and green rings, we have observed consistently that mountain wave cloud coronas exhibit more blue than green.[5] In fact, the most intensely blue coronas we have seen were caused by diffraction of moonlight in extremely thin wave clouds.[22] In wave clouds we see more green iridescence than green coronas, but in nonorographic clouds we see more green than blue in most diffraction displays. Therefore, we believe that wave cloud coronas are unique in some respect that leads to enhanced blue content. In both coronas and iridescence, the reds become pink, just as the greens and blues take on a pastel cast, because of the high white-light content.

Observing coronas and iridescence

Observing coronas and iridescence requires looking at clouds near the sun or moon. Because most people do not spend much time doing this, they do not realize how common these kinds of diffraction displays can be. Of course you should not expect to see examples like the ones shown here every day (or even every year!), but some color can be seen in almost every cloud that passes near the sun or moon, even if it is only a subtle red or blue fringe at the cloud edge (like the iridescent fringe shown in Fig. 7). We often use trees, street lights or other objects to block intense direct sunlight or moonlight; you can either do the same or use your thumb to block the source and carefully observe the region near the sun or moon to find diffraction colors. You will be especially successful in regions of thin clouds or on cloud edges (but be sure never to look directly at the sun or its reflection).

The key, however you choose to do it, is to reduce the relatively intense amount of light that is concentrated near the sun or moon. You can look at reflections from black glass (available from many glass shops), observe clouds reflected in windows or water or simply use sunglasses while blocking the direct sun. In the Rocky Mountain region, October through February seems to be the most common period of wave cloud occurrence, and it is therefore an excellent time to observe diffraction in clouds. In other places, altostratus clouds often offer the best viewing.[23]

As we observe the optical world around us, we continue to think about questions such as why mountain wave clouds are such a vivid blue instead of green, and how we can relate the subtle details of what we see to the physics of clouds. Although we do not yet fully understand the detailed colors of coronas or how coronas change with cloud type, we are happy to spend time observing, photographing and pondering the implications of diffraction displays in the sky.

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