Observing light in nature from an airplane window

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ABSTRACT

Photographs taken from commercial airplanes of optical phenomena in nature, such as rainbows, halos, glories, and sky colors, are shown to illustrate the variety of optical displays that can be observed by an informed and alert observer from an airplane window. Observing tips are provided to enhance the probability of seeing certain phenomenon, based on the time of day, location, and direction of travel of the airplane. Generally, a seat on the sun-ward side of the plane provides opportunities to observe halos, coronas, iridescence, glitter patterns, crepuscular rays, sunsets and twilight colors, while a seat opposite the sun provides opportunities to observe glories, rainbows, cloud bows, Earth's shadow, cloud shadows, contrail shadows, and other shadow phenomena. On flights at high latitudes, (north- or south-) pole-facing seats can sometimes provide opportunities for viewing somewhat more exotic phenomena, such as noctilucent clouds and auroras.

Keywords: Optics in nature, light and color, rainbows, glories, halos, glitter patterns, sky colors, meteorological optics

1. INTRODUCTION

An alert person can observe a wide variety of optical phenomena from an airplane window, making travel time more pleasant and educational. However, the ability to observe, recognize, and understand natural optical phenomena is enhanced with knowledge of where and when to look and what to expect. The objective of this paper is to provide motivation and basic information on how to observe light in nature from your airplane window. Detailed information on the optics of each class of phenomenon requires deeper study, which can be gathered through the web, books, and journal articles. Some of the best resources for this study include Les Cowley's *Atmospheric Optics* website,[1] several fabulous books,[2-13] and journal articles published in feature issues on *Light and color in the open air* (and similar titles), which are published approximately once every three years.[14-22]

The most important observation technique is to punctuate your work or reading with frequent, careful looks out the window, especially during take-off and landing when the plane often passes through clouds. Photographing optical displays through an airplane window is best done with manual focus and sometimes manual exposure. A digital SLR camera is ideal, but high-quality point-and-shoot cameras can do fine, although shutter delay becomes a problem on the rapidly moving airplane. It is important to focus at infinity, using manual focus, "scenery" mode, or "airplane photo" mode to avoid getting an in-focus image of window scratches (wipe off the window and use the least-scratched part). You may need to lean forward or back or hold the camera at unorthodox positions; be accepting of a non-level horizon and sub-optimal framing, since the optical display is rarely where you want it, and the airplane is often rolling or turning away from the display. At night, use your hand, a jacket or blanket to shade the window from reflections of cabin lights.

Watching the sky is best done from a window seat. I plan my seat based on what I think might be observable on a given flight, given its primary travel direction and time of day. For example, a seat on the left-hand side of the plane (for a forward-looking passenger) provides a view toward the sun on a north-south flight in the morning and away from the sun on a north-south flight in the afternoon or evening. A sun-side seat allows you to observe sunrises, sunsets, twilights, halos, coronas, iridescence, crepuscular rays, glitter patterns on water, etc. A seat on the side away from the sun allows you to observe glories, rainbows, cloud bows, earth's shadow, cloud shadows, contrail shadows, anti-twilight colors, moon rise, etc. On high-latitude flights, such as trans-Atlantic flights from the U.S. to Europe or flights to Alaska, I choose a seat on the side that provides the best view of the northern sky (southern sky in the southern hemisphere), where I might see auroras in winter or noctilucent clouds[23] in summer. The balance of this paper illustrates these principles with a variety of natural-optics photographs taken through an airplane window.

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2. SKY COLORS

The most obvious optical effect to observe through an airplane window is the variation of sky color from the aerosol-laden lower atmosphere to the boundary between troposphere and stratosphere. This transition is particularly striking when leaving humid or hazy air, as illustrated by Figure 1. This fisheye photograph was taken through an airplane window shortly after leaving Washington, D.C., and shows that the hazy lower atmosphere gives way to a rich blue sky above the high-altitude cirrus clouds (it also includes an interesting example of cloud shadows in the haze). The blue skylight is a result of scattering by atmospheric gas molecules (primarily N_2 and O_2), which follows the Rayleigh scattering 1/wavelength[4] falloff of scattered irradiance, coupled with the eye's (or camera's) inefficient detection of violet light. Much larger aerosols and cloud particles require a more sophisticated treatment, provided by Mie scattering for spherical particles.[24,25] Light scattered by optically large particles (comparable to or larger than the wavelength) has much less wavelength dependence than scattering by small particles. This is illustrated by Figure 2, which plots normalized Mie-scattered irradiance vs. wavelength for particles of radius r = 1 nm (Rayleigh scatter) and for a lognormal distribution of larger particles of mean radius r = 10 μm with standard deviation of 20% (similar to a typical cloud). The calculations were made with Philip Laven's MiePlot code.[26] This figure shows clearly that the small particles scatter predominantly blue (and violet) light, while the large particles scatter all visible wavelengths nearly equally.

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Figure 1. A rich blue sky is found when the airplane climbs above the hazy lower troposphere (fisheye photograph taken on a flight from Washington, D.C. to Minneapolis, Minnesota in June 2010).

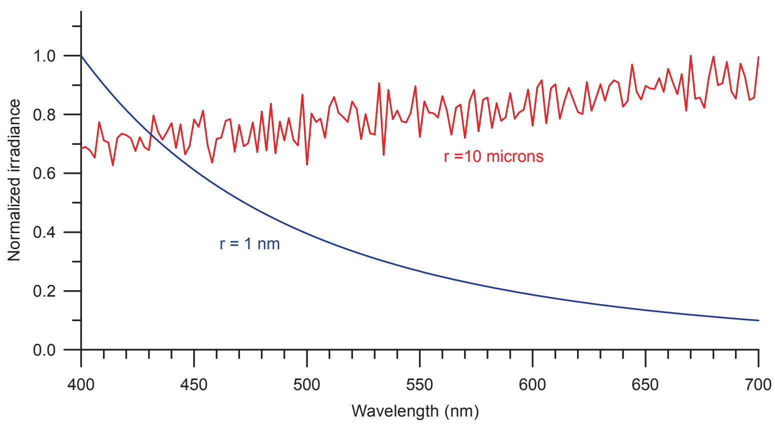

Figure 2. Normalized irradiance vs. wavelength calculated code for water droplets of radius 1 nm (Rayleigh scattering) with a lognormal distribution of water droplets of mean radius 10 μm and 20% standard deviation (Mie scatter).

Some of the best sky colors occur at sunset or sunrise, when sunlight passes through a long atmospheric path and experiences strong scattering that reddens the light that illuminates clouds or haze layers. The upper reaches of the pre-dawn or twilight sky can be an impressively rich blue color, or even purple through the combination of transmitted red sunlight and blue scattering in elevated haze layers. The two photographs in Figure 3 illustrate a red sunset with the sun peeking through a hole in a thick cloud layer (left) and the rich blue colors of Arctic twilight observed near Greenland on a trans-Atlantic flight (right).

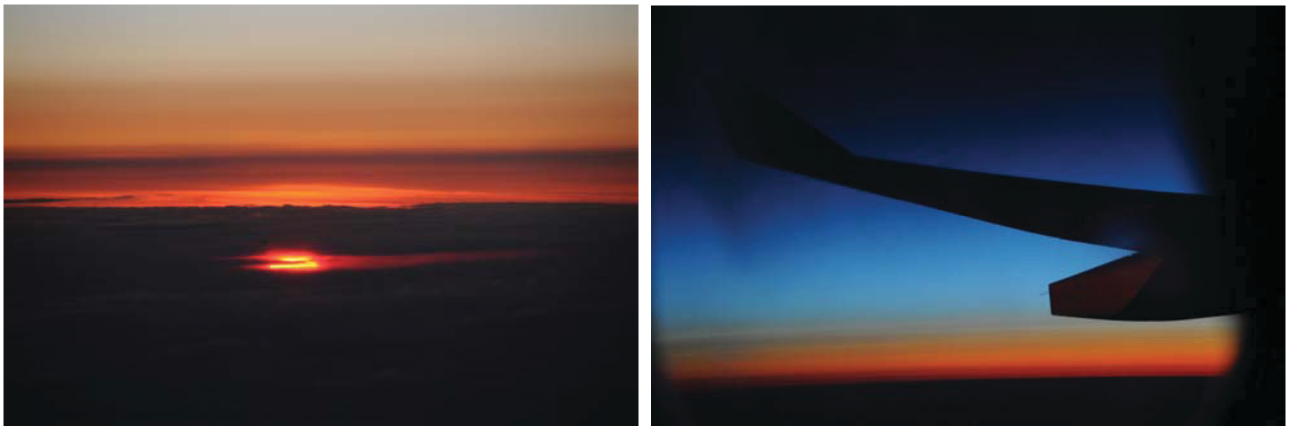

Figure 3. Sunset and twilight colors: (left) the setting sun is visible through a hole in the clouds (flight from Honolulu, Hawaii to Seattle, Washington, June 2008); (right) summertime Arctic twilight colors near Greenland (flight from Minneapolis, Minnesota, USA to Amsterdam, Netherlands, May 2010).

The photograph of Figure 4 shows a thin band of reddened light scattered in the hazy lower atmosphere about halfway between Minneapolis, Minnesota and Baltimore, Maryland. This photograph was taken looking south-southeast shortly after the sun set to the west (to the right in the photo). In this situation, the low-altitude haze scattered strongly reddened light from the setting sun, while the higher atmosphere still scattered blue light.

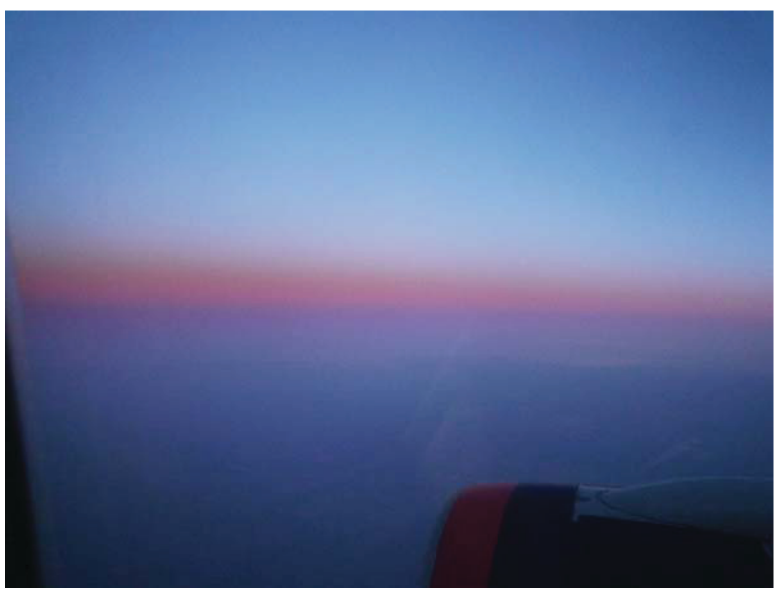

Figure 4. Pink anti-twilight band on the south-southeast horizon seen on an evening flight from Minneapolis, Minnesota to Baltimore, Maryland in May 2010 after the sun had set in the west (to the right of the photo).

3. SHADOWS

Shortly after taking the picture in Figure 4, I noticed a dark band on the southern horizon. While similar to the Earth's shadow, the light region below the dark band suggests that this is a giant cloud shadow spreading across the hazy sky.

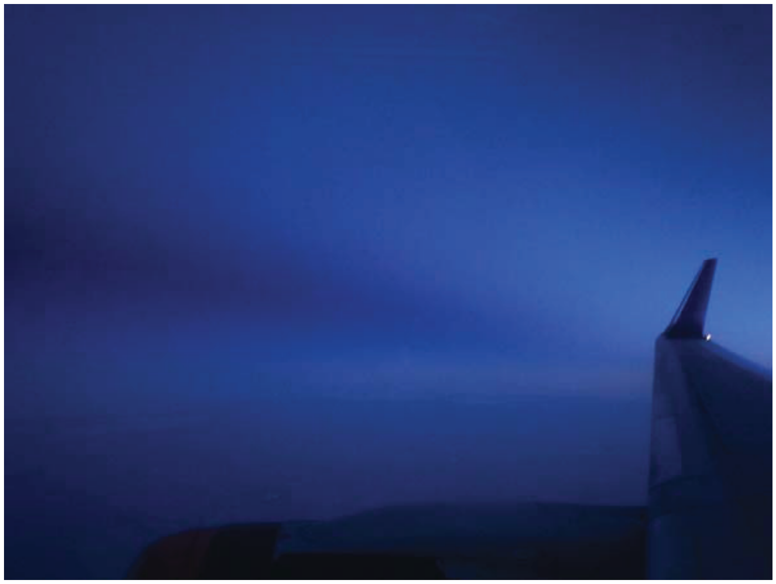

Figure 5. Giant cloud shadow formed by the distant setting sun (looking south on flight from Minneapolis, Minnesota to Baltimore, Maryland in May 2010.

The Earth's shadow is shown in Figure 6, rising from the eastern horizon as the sun sets in the west (and at the left edge of Figure 4). The foreground clouds scatter a soft pink light produced by long-path scattering from the setting sun. These clouds, in fact, help create the strong contrast between the Earth's shadow and the directly illuminated atmosphere above by intercepting the reddened light that would otherwise produce a pink band similar to the one shown in Figure 4.

Figure 6. Earth's shadow rising in the east at sunset on a flight from Salt Lake City, Utah to Bozeman, Montana in July 2004.

Airplanes are ideal platforms for observing shadow phenomena of all sorts. The photographs in Figure 7 show two additional examples. The left-hand picture shows the shadow of a contrail produced by the airplane in which I was flying (I could not see the actual contrail). This shadow was visible for a long time over clouds and haze, but is shown here as a narrow shadow line on otherwise sun-illuminated Lake Michigan. The right-hand picture shows cloud shadows that block sunlight, creating dark patches in an otherwise rich palette of colors arising from sunlight scattered in the clear waters near Honolulu, Hawaii. This water has a particularly low concentration of plankton, which allows us to see the purer blue and green colors that result from scattering of sunlight by water molecules and from underwater surfaces.

Figure 7. Shadows on water: (left) the straight dark line pointing toward the eastern shore of Lake Michigan is the shadow of a contrail created by the airplane I was flying in (flight from Minneapolis, Minnesota to Washington, D.C. in Feb 2004); (right) dark shadows of puffy clouds, which provide contrast from the beautiful colors of sunlight scattered in the clear water off the shore of Honolulu, Hawaii (flight from Honolulu, Hawaii to Seattle, Washington in June 2008).

4. GLITTER PATTERNS

In addition to seeing colors of light scattered from within water, flying over water also provides an opportunity to observe glitter patterns made up of a collection of specular reflections from the wavy water surface. If the water was perfectly calm and flat, there would be a single, bright reflection of the sun at the specular (mirror) angle. However, real water surfaces are rarely flat, and in fact have a collection of waves that can be treated from a geometrical-optics perspective as a randomly oriented collection of wave facets. These sloped wave facets produce specular reflections of the sun (or moon) at locations where a reflection would not occur on a flat surface, thereby broadening the single reflection into a broader pattern of glints called a glitter pattern.[27] Because most of the higher slopes on water are tiny capillary waves formed or sustained by wind, the shape of a glitter pattern is related to the wind speed. The shape also is a function of illumination and viewing angles. The small, relatively circular glitter patch in Figure 8 was a result of looking nearly straight down on the Great Salt Lake in northern Utah illuminated by a high sun.

Figure 8. Small sun glitter pattern formed by a high sun over the Great Salt Lake in Utah (April 2004).

Figure 9 shows two photographs of glitter patterns that are significantly different from Figure 8 in both shape and color. The longer, narrower shape of the glitter pattern in both cases results primarily from a very low sun. The color is a result of scattering on the long atmospheric path before (even after) the water surface reflection. The left-hand image is of a slightly yellow glitter pattern seen on a trans-Pacific flight, while the right-hand image is of a very orange-red glitter pattern on the Great Salt Lake created by the sun setting behind a thick haze layer. The latter image is a good example of what I wrote earlier about the need to sometimes accept technically inferior photographs when observing from an airplane; in this case, I used a zoom lens to take the picture out the window on the opposite side of the airplane (past all the heads of people sitting between me on one side and the window on the opposite side of the plane).

Figure 9. Sun glitter patterns formed by low sun: (left) long, yellow glitter pattern on the Pacific Ocean (flight from Seattle, Washington to Tokyo, Japan in November 2004); (right) wide, orange glitter pattern on the Great Salt Lake with color created by the sun setting behind a thick layer of hazy pollution (flight from Bozeman, Montana to Salt Lake City, Utah in February 2010).

5. LIGHT SCATTERED BY LIQUID WATER DROPLETS

Many interesting atmospheric optical displays are created by scattering of sunlight or moonlight by optically large liquid water droplets. However, there is a big difference in the optical display for “large” and “very large” droplets, as is illustrated by the Mie scattering calculations shown in the next two figures. The plot in Figure 10 shows relative irradiance vs. scattering angle (angle between the original ray and the scattered ray) for a collection of physically small (radius = 0.5 mm), but optically very large, rain drops in 650-nm red light. To interpret this plot and Figure 11, identify 0° with forward scattering, or what you would see looking directly toward the light source. Similarly, 180° is backward scattering, or what you would see looking at the anti-solar point with the sun directly behind you.

With these ideas in mind, it should be fairly easy to identify the primary rainbow and secondary rainbow as the two peaks near 140° and 130°, respectively. Therefore, to see the red band of a primary rainbow, you should face the anti-solar point (away from the sun) and look in a circular arc of radius approximately 180°-140° = 40°. The secondary rainbow lies at smaller scattering angle, or at a larger angle from the anti-solar point; consequently, it is a larger circle than the primary bow. Repeating these monochromatic Mie scattering calculations at different wavelengths would show that the secondary bow has a reversed color order from the primary bow. Notice also the fringes, or “supernumerary bands,” at the larger-scattering-angle side of the primary bow and the smaller-scattering-angle side of the secondary bow. These arise from interference of light traveling slightly different paths through the rain drop. Supernumerary bands are visible when the raindrops are small with a narrow drop-size distribution. Repeating the Mie scattering calculations with a larger standard deviation would smooth these features out. The plot also shows very distinctly the dark band of light between the primary and secondary rainbows (angular regions from where light was scattered to create the bows).

Two additional features to note in Figure 10 are the two peaks of forward-scattered light near 0° and backward-scattered light near 180°. Note that the forward-scattering peak actually extends to a value greater than 10^{14} at 0°, but has been truncated for clarity of the rest of the plot. These two peaks mark the location of the corona (near 0°) and the glory (near 180°), but in this case the large droplet size causes these to be so small that they appear as small localized regions of bright scattered light with little or no visible color.

The corona and glory both become wider and (in multi-wavelength plots) more clearly colored when the scattering droplets are much smaller, as in typical thin-cloud water droplets. Figure 11 is a Mie-scattering calculation of relative irradiance vs. scattering for a lognormal distribution of such water droplets with mean radius of 10 μm and standard deviation of 5%. These relatively small but still optically large droplets scatter light in a manner similar to the rain drop case of Figure 10, but with much broader and less distinct rainbow features and with broader and more apparent corona and glory features at forward and backward scatter angles, respectively. Notice also that the (non-truncated) 0° peak is multiple orders of magnitude smaller in this case. This illustrates the fairly non-intuitive truth that increasing the size of optically large particles (below the geometrical optics limit) results in an increased fraction of forward-scattered light.

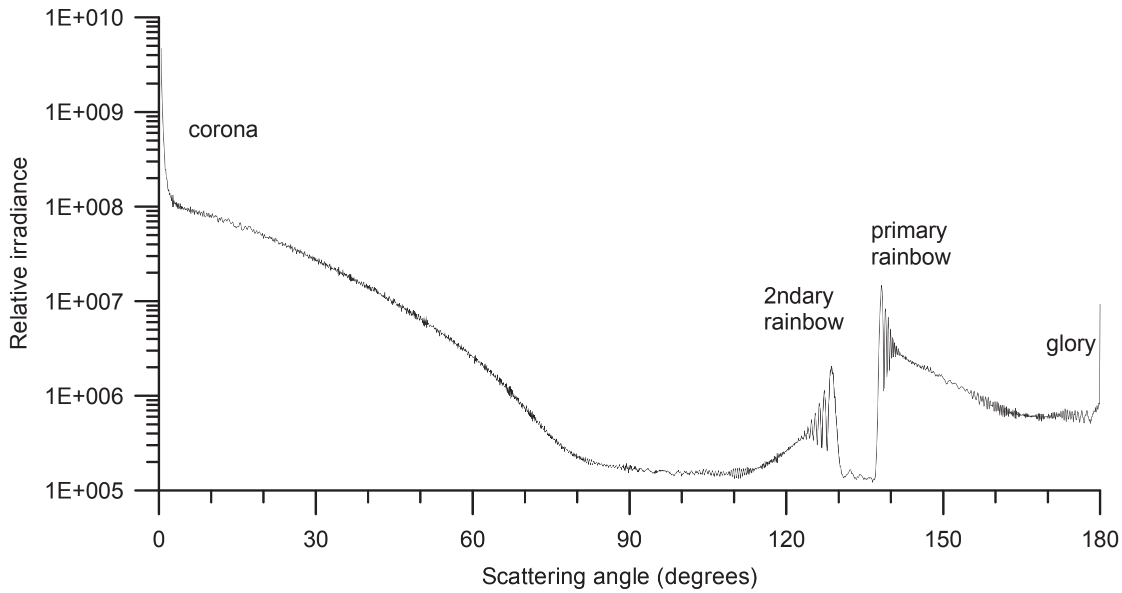

Figure 10. Relative Mie-scattered irradiance at 650-nm wavelength plotted vs. scattering angle for rain drops with a log-normal size distribution of 500-μm mean radius and 5% standard deviation. Note that the 0° peak has been truncated here, and otherwise would extend past 10^{14}.

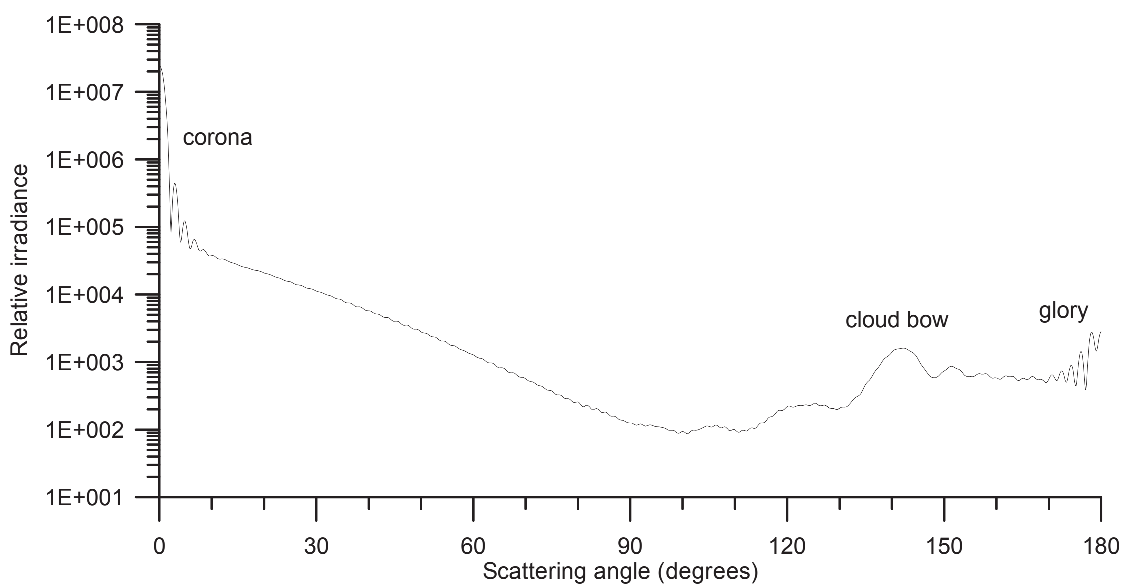

Figure 11. Relative Mie-scattered irradiance at 650-nm wavelength plotted vs. scattering angle for water droplets with a log-normal size distribution of 10-μm mean radius and 5% standard deviation (i.e., a thin cloud).

In Figure 12 is a photograph of a corona produced by near-forward scattering (i.e. diffraction) of sunlight by small cloud droplets. The corona has a nominally circular shape because of spherical scattering droplets, but can take on oblong or other shapes when there are changes in particle shape or size distribution.[28] Also, special conditions that are often satisfied in thin wave clouds can produce a corona with unusually tiny ice droplets rather than liquid droplets.[28]

Figure 12. Near-forward scattering of light by small cloud droplets creates colored corona rings around the sun (or moon). This photo was taken on the ground, but coronas can be seen from an airplane in clouds.

The rainbow feature in Figure 11 is smoother than the ones in Figure 10, a result of diffraction broadening and smoothing out the otherwise distinct rainbow bands. This happens in a cloud or a fog, whose water droplets are much smaller than rain drops. The resulting bow is called a cloud bow (or fog bow), and appears most often as a ghostly white bow around the anti-solar point. The photographs of Figure 13 illustrate a rainbow segment (left) and a cloud bow segment (right). The small rainbow segment in the left-hand photograph appeared in a distant rain shower below a distant cloud, while the cloud bow segment in the right-hand photograph appeared at the top of a thick cloud layer and persisted for tens of minutes of flight time. Notice also that at the lower-left corner of the cloud bow picture (at the anti-solar point) there is a small, bright ring. This is the glory, which was predicted by the wiggles near 180° in Figure 11.

Figure 13. Bows formed with scattering of sunlight by water droplets: (left) rainbow segment seen in distant rain shower on flight from San Diego, California to Salt Lake City, Utah in Aug. 2004; (right) cloud bow (and glory) seen on top of cloud deck on flight from Albuquerque, New Mexico to Salt Lake City, Utah in Feb. 2010.

The small ring of light at the anti-solar point in the cloud bow photograph of Figure 13 is a glory, a back-scatter phenomenon that has no geometric optics explanation (unlike the rainbow, the main features of which can be predicted from simple refraction and reflection in rain drops). A glory can be seen almost any time the anti-solar point is visible on a cloud deck out the airplane window. Sometimes it is nothing more than a bright circle of white light at the anti-solar point, which is marked by the airplane shadow when the cloud is relatively close. But at other times, a fairly spectacular glory can be seen, as shown in the photographs of Figures 14 and 15. In the left-hand photograph of Figure 14, the glory is formed on the top of a thick cloud deck far below the plane, so there is no visible airplane shadow. However, if you look very closely at the right-hand photograph in Figure 14, you may just detect the airplane shadow at the center of the glory that in this case was very colorful because of the small droplets in the thin edge of a thin cloud. The photographs of Figure 15 show two fairly impressive examples of glories with clearly visible airplane shadows. Notice that the center of the glory (the anti-solar point) always marks the position of the photographer. Therefore, you can tell that for the left-hand photo I was sitting just behind the wing and for the right-hand photo I was sitting just ahead of the wing.

Figure 14. Glories seen at the anti-solar point: (left) glory in low, thick clouds filling the Gallatin Valley in southwestern Montana (flight from Bozeman, Montana to Salt Lake City, Utah in February 2010); (right) glory in thin clouds on descent during flight from Fairbanks to Anchorage, Alaska in April 2004.

Figure 15. When the airplane is close to the cloud the airplane shadow is visible, with the photographer's location at the anti-solar point: (left) Multiple-order glory rings photographed from behind the wing (near Anchorage, Alaska in Sep. 2004); (right) single-order glory rings photographed from in front of the wing with the airplane very near the cloud (near Bozeman, Montana in May 2010).

6. ICE-CRYSTAL OPTICS

Clouds in the upper regions of the troposphere, where the air is often colder than -40°C, contain ice crystals that can reflect and refract light to form beautiful halo displays. The most common one is a 22° halo, illustrated in the left-hand photograph of Figure 16 (this was taken from the ground, but I have seen a number of 22° halos from airplanes). This halo is formed by rays entering one face of a hexagonal ice crystal and exiting through an adjacent face oriented 60° from the first. The two refractions involved in this ray path direct the majority of rays into an angle near 22° (a "minimum deviation" refraction problem). If the hexagonal ice crystals are poorly oriented, the randomly oriented 22° bright regions form a bright circle – the 22° halo, as shown in the left-hand photo of Figure 16. If the hexagonal ice crystals are well oriented, with their horizontal faces flat or nearly flat, then bright regions appear to the right and left of the sun (or moon). These splashes of light are called parhelia, or commonly "sun dogs" (or "moon dogs"). An example is shown in the right-hand photograph of Figure 16, along with a cloud that is exhibiting an interesting effect called Kelvin-Helmholtz instability (the waves on the cloud top). The 22° halo or parhelia always have a red inner edge and fade to a whitish outer edge.

Figure 16. Ice-crystal halos: (left) 22° halo around the sun, photographed from the ground in Bozeman, Montana in March 2010; (right) right parhelion (sundog) above clouds with Kelvin-Helmholtz instability waves (photographed on descent during flight from Bozeman, Montana to Minneapolis, Minnesota in February 2005).

The high-viewing perspective from an airplane window provides excellent opportunities to see other halo features, especially ones that occur below the sun. Three examples are shown in Figures 17 and 18. The photographs in Figure 17 show a sub-sun and a bit of a light pillar below the sub-sun. Both can be explained as specular reflections from flat ice crystal faces. The sub-sun is a bright specular reflection from below the actual sun, which is analogous to the single sun image that would occur as a small glitter pattern on a very smooth water surface (see section 4). A bright, localized sub-sun indicates the presence of horizontally oriented ice crystals and can be extremely vivid. The right-hand photograph of Figure 17 is a zoomed-in image of the sub-sun, showing the light pillar that was formed below it by reflections from gently rocking but nearly horizontal ice crystals. Such a light pillar, which can extend above or below the sun or moon, is analogous to the glitter patterns on water shown in Figure 9. In the zoomed-in image on the right-hand side of Figure 17, reflections from individual ice crystals are readily seen.

The photograph in Figure 18 shows a relatively rare halo feature called a sub-parhelion. This is like the parhelion, but unlike the parhelion exists below the plane of the sun. Like the parhelion, it is formed by two refractions in adjacent ice crystal faces separated by 60°, but unlike the normal parhelion there is a reflection from a bottom crystal face that occurs between the two refractions. The result is that the originally downward-directed ray becomes upward directed, leading an observer to perceive the halo feature below the local horizon of the light source. In this photograph, the sun is located just beyond the upper-left corner. Managing to record a photograph of this somewhat rare halo feature was one of the highlights of some long hours I have spent looking out airplane windows.

Figure 17. Sub-sun formed by specular reflection from horizontally oriented ice crystals: (left) sub-sun below the over-exposed sun, light pillar below and right parhelion 22° to the right of the sun; (right) close-up view of individual ice-crystal glints forming light pillar below the sub-sun (flight from Bozeman, Montana to Minneapolis, Minnesota in Feb. 2005).

Figure 18. Relatively rare sub-parhelion photographed below and to the right of the sun (22° to the right of the sub-sun position) on a flight from Bozeman, Montana to Salt Lake City, Utah in February 2010. The sun is just beyond the upper-left corner of the image.

7. DISCUSSION AND CONCLUSIONS

There are many other optical phenomena that could be explored in a longer discussion. For example, noctilucent clouds, or literally “night-shining clouds,” appear at high latitudes during the summer. These are beautifully swirling, extremely thin clouds, which form at unusually high altitude near 80-85 km (compared to 10-20 km for the highest cirrus clouds).[23] Another high-latitude and high-altitude optical phenomenon is the aurora, caused by collisions of energetic particles, ejected from the sun and captured by Earth’s magnetic field, with upper-atmospheric atoms and molecules. This also can be a spectacular sight to behold, with its green and sometimes red or purple swirling colors. Keep your eyes open for these phenomena on the pole-ward side of the airplane when the sky is dark and you are flying in the sub-polar or polar regions. However, even when not in such unique conditions, I hope the photographs shown here motivate you to watch the sky carefully to see what optical sights are waiting for you, just outside your airplane window.

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