PROGRESS IN ATMOSPHERIC OPTICS AND LIGHT AND COLOR IN NATURE

BY STANLEY DAVID GEDZELMAN AND MICHAEL VOLLMER

The stunningly beautiful optical phenomena of the atmosphere—sky colors, rainbows, halos, coronas, iridescence, glories, mirages, etc.—have long inspired both artistic creations and scientific discoveries. The forum for communicating advances in the science of these and related optical phenomena is the series of International Conferences on Light and Color in Nature. Begun in 1978, and held every 3–4 yr, each conference attracts 30–50 participants, mainly from Europe and North America. The main theme of the meetings is to observe, measure, photograph, explain, model, and construct laboratory experiments of atmospheric optical phenomena that can be seen with the naked eye. A popular Web site designed by retired physicist Les Cowley, with photographs and illustrated explanations of subjects included in the meetings, plus many links, provides an overview (online at www.atoptics.co.uk).

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THE NINTH INTERNATIONAL CONFERENCE ON LIGHT AND COLOR IN NATURE

WHAT: Forty enthusiasts and scientists presented new observations, findings, models, and experiments of atmospheric optical phenomena that can be seen by the naked eye, and related topics on light and color in nature
WHEN: 25–29 June 2007
WHERE: Montana State University at Bozeman, Montana, and Yellowstone National Park

At the ninth conference, new findings and historical analyses were presented on atmospheric optical phenomena, including rainbows, halos, glories, coronas, cloud iridescence, mirages, auroras, and lightning, as well as the color and brightness of the sun, moon, and planets and of clear, hazy, and overcast skies.

KEYNOTE TOPICS. Each of the light and color conferences includes invited keynote talks on special topics that may or may not touch on atmospheric optics. A representative talk on a diverse topic at an earlier conference was on the colors of butterfly wings, bird features, and beetle carapaces. In the most recent conference, invited speakers included Ken Libbrecht (California Institute of Technology), Marko Riikonen (Ursa Astronomical Association, Helsinki, Finland), Stanley David Gedzelman (City College of New York), and Sönke Johnsen (Duke University).

Libbrecht reported on the many facets of snowflakes, looking closely at their patterns and forms at genesis (see www.its.caltech.edu/~atomic/snowcrystals/). Video and microphotographs of experiments in a cloud chamber revealed not only the growth of a spectacular array of beautiful crystal types but also abrupt changes of crystal form resulting from tiny changes in humidity and/or temperature. One example is that capped columns form when the growth mode changes abruptly from columnar to platelike as temperature increases from −5° to −2°C.

Riikonen reported on coronas, glories, fog bows, and Quetelet rings seen on the surface of ponds in Finland (see Fig. 1 and www.ursa.fi/~riikonen/). These phenomena are produced by a variety of algal and bacterial films, such as the golden alga *Chromophyton rosanoffii,* which include almost spherical globules about 5.5 μm in diameter that emerge from the water on stalks. Richard Fleet (Newbury Astronomical Society) presented photographs of similar phenomena observed on ponds in the United Kingdom; a poetic paean by Richard's wife, Nicky Fleet, accompanied his presentation.

Gedzelman presented radiative transfer theory of optical phenomena with simulations showing how the cloud, rain shaft, atmosphere, and background lighting reduce the maximum apparent brightness, contrast, and color purity of halos, rainbows, and coronas. The phenomena appear most vivid and colorful when backgrounds are dark and when cloud optical depth is between about 0.1 and 1. Extremely tenuous clouds have too few hydrometeors to scatter much light, while multiple scattering in thick clouds brightens the background disproportionately and fades the phenomena.

In a topic outside the normal realm of atmospheric optics, but in the spirit of the meeting, Johnsen reported on experiments that confirmed the existence of complex vision systems in certain insects. For example, the Nocturnal Hawk Moth has nocturnal

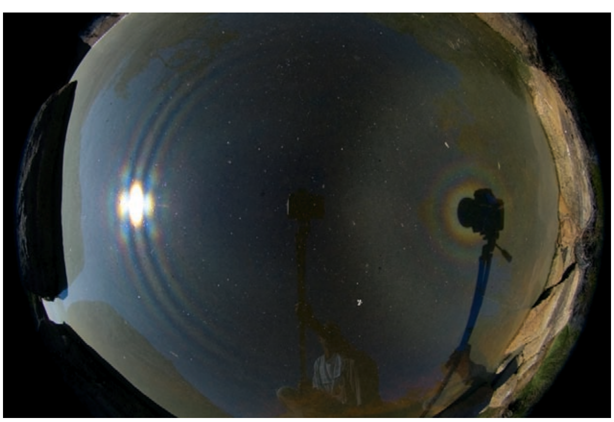

Fig. 1. Photograph of a rock pool on Furuskär Island in the Gulf of Finland Archipelago in Jul 2006, showing Quetelet rings traversing a spotted corona on the left and a glory surrounded by a diffuse fog bow on the right. These phenomena were produced by *Chromophyton rosanoffii,* a single-celled alga belonging to the group of the golden algae in a Finnish pond. Algal cells are spherical, around 5.2 μm in diameter, and they emerge fully from the water surface on tiny stalks. Also visible is the faint reflected image of Marko Riikonen holding the camera. (Photo: Marko Riikonen, used with permission.)

Fig. 2. Diamond dust halos at 1203 UTC 11 Dec 2006 at Sudelfeld Pass, Wendelstein Area (Bavarian Alps) Germany, including the 22° halo, upper tangent arc, lower tangent arc, parhelic circle, and supralateral tangent arc to the 46° halo. The points of light are produced by individual ice crystals very close to the camera (see www.glorie.de/ae-index.htm). (Photo: Claudia Hinz, used with permission.)

and crepuscular color vision (see www.biology.duke.edu/johnsenlab/).

PRETTY PICTURE SESSION. Each of the conferences features a special showing of photographs and videos of outstanding or unusual displays of optical phenomena. All of the participants are invited to show their photographs, describe the settings, and provide brief explanations. The special photography session attracted a large audience from Montana State University and included many citizens of Bozeman. Figure 2, showing a halo complex photographed by Claudia Hinz (German Meteorological Service) in the Bavarian Alps, represents one fine example of the many magnificent photos and videos. In this case the "diamond dust" halo complex was produced by ice crystals so close to the photographer that thousands of spots of light from individual crystals can be seen.

YELLOWSTONE EXCURSION. The meeting featured a 1-day nature excursion to Yellowstone National Park where, in addition to Yellowstone's famed geysers, hot springs (Fig. 3), and wildlife, participants observed halos, glories, cloud iridescence, and anomalous sun and sky colors from the nearby West Yellowstone Fire.

GENERAL TOPICS. The conference commenced with an overview of rainbow theories and observations by John Adam (Old Dominion University). A photographic essay on fog bows was then presented by Fleet and a rare case of a third-order bow was documented by Ken Sassen (University of Alaska).

Refraction of light through the atmosphere has long been known to affect the apparent position of stars and planets, the appearance of the sun and moon seen near the horizon, the length of the day (discussed by Russell Sampson, Eastern Connecticut University), and mirages [discussed by Waldemar Lehn, University of Manitoba, and illustrated with a magnificent video by Pekka Parviainen (Polar Image)]. Lehn also used results based on Newton's unpublished mathematical models of atmospheric refraction to show that Newton properly derived the expressions for refraction of light in atmospheres in which density decreases both linearly and exponentially with height.

Refraction coupled with scattering and absorption also accounts for the light and color of the moon during total lunar eclipses. Michael Vollmer (University of Applied Sciences, Brandenburg, Germany) and Elmer Schmidt (SRH University of Applied Sciences, Heidelberg, Germany) modeled and measured the light of the moon during eclipses, showing that scattering in the atmosphere reddened and dimmed the luminance of the umbra to less than 10^{-4} of full moonlight, while absorption in the Chappuis bands of ozone gives the fringe of the umbra a blue cast. Hinz and Gunther Können [Royal Netherlands Meteorological Institute (KNMI)] documented the limiting visibility of stars and atmospheric optical phenomena during solar eclipses. Much dimmer stars become visible during totality because sky radiance is lower by a factor of 4,000 than during normal bright daylight. However, at the moment of totality, the signal-to-background ratio of diffraction for coronas, halos, and rainbows is reduced by a factor of 250 compared to full daytime lighting. As a result, coronas are still visible (and circular), halos may be, and rainbows are not.

Fig. 3. Photo of the participants of the 2007 optics conference standing in front of the Grand Prismatic Spring in Yellowstone National Park. The deep water in the center of the spring is deep blue. Colors along the perimeter of the spring are produced by pigmented bacteria in microbial mats and range from green, to yellow, to orange, to red at the outer fringe. The color depends on the ratio of chlorophyll to carotenoids, which depends on season and water temperature. (Photo: Joseph Shaw, used with permission.)

Scattering and absorption are responsible for the light and color of the sky. A simple Rayleigh scattering model with absorption was developed by David Lynch (Thule Scientific) to explain the colors of smoke clouds composed of fine, dry particles. The light that penetrates the smoke is dominated by scattering and therefore is blue near the fringe where the optical depth is small. In the optically thick parts of the smoke cloud, absorption dominates, which depletes the scattered light more rapidly than direct sunlight, and hence it is red. Backscattered light is blue when the cloud is thin but turns white as the optical depth of the cloud increases. Lynch also used scattering theory to demonstrate that optically and geometrically thin clouds seen more than 140° from the sun appear darker than most backgrounds, including clear skies.

Skylight renders stars and planets invisible during the height of the day, but these bodies can be seen when the sun approaches the horizon. On one day of the conference possibly the earliest recorded afternoon observations of Jupiter by the naked eye were made by the group, led by Sampson. This exemplifies the fact that the sighting and discovery of many phenomena require simply knowing when and where to look, although the altitude and clear air at Bozeman certainly helped.

Eyewitness accounts of historic halo displays have included drawings of halos and arcs that cannot occur at the same time (e.g., circumhorizontal and circumzenithal arcs). Some accounts consisted of descriptions without accompanying illustrations. Despite the difficulty of interpreting only from words what was being seen, Eva Seidenfaden (Vissinggaard) was able to demonstrate that the written reports of the Rome Halo displays of 1629 and 1630 were inadequate to support claims for sighting the 28° and other rare halos, but that these reports nevertheless helped to initiate and inspire halo research.

Because the rarely seen Lowitz arcs are still considered problematic, Cowley presented computer simulations of Lowitz arcs that matched old drawings and photographs. Walter Tape (University of Alaska) developed geometrical techniques similar to those used in optical mineralogy to determine the precise geometry of various halos and arcs. Tape also showed that Huygen's theory, which states that halos are caused by concentric cylindrical crystals, was as mathematically reasonable as other contemporaneous theories, given the lack of knowledge of ice crystal clouds at the time.

Photography was used to analyze and quantify observations of optical phenomena. Joseph Shaw (Montana State University) described an instrument that uses sky luminance to automatically detect and photograph auroras, thereby eliminating the need to stand outside under harsh conditions, all night every night. Phil Laven (British Broadcasting Corporation) presented a technique to document spatial variations in the size of cloud droplets by applying glory model calculations to photographic measurements of angular radii of noncircular glories. Supplementing the development of his geometrical techniques, Tape used stellar positions to determine angular distances with sufficient accuracy to distinguish the various odd radius halos (9°, 18°, 20°, 22°, 23°, 24°, 35°, and 46°) produced by crystals with pyramidal ends (Tape and Moilanen 2006). Riikonen used a photographic stacking technique to enhance faint and rare halos, even though this was acknowledged as a form of "cheating" at a conference devoted to phenomena that could be observed with the naked eye. Javier Hernandez-Andres (University of Granada) presented a calibration technique using a spectroradiometer that enables trichromatic charge-coupled device (CCD) digital cameras to provide spectral estimation of sky colors. He then showed how the spectral data could be used to determine properties of cloud and atmospheric aerosol particles. Ray Lee (U.S. Naval Academy) used spectral analysis to demonstrate that overcast skies have a surprisingly wide range of colors and brightness values, even under the most seemingly uniform conditions. Lynch demonstrated that although the curvature of the Earth can be seen from an elevation of 35,000 ft, claims to see it at sea level are always suspect because virtually all camera lenses project an image that suffers from barrel distortion. To accurately assess curvature from a photograph, the horizon must be placed precisely in the center of the image, that is, on the optical axis.

A few experiments of optical phenomena were also presented. These make for always compelling and often quite simple classroom demonstrations. For example, Vollmer presented a simple way to reproduce Quetelet fringes using a mirror with water droplets condensed from his breath. Glenn Shaw (University of Alaska) developed a cloud chamber that produced coronas. When a light was shined through a cloud of small droplets, the coronas would appear. The brilliance and color purity of the coronas was limited by the size variations of the droplets. Chuck Adler (St. Mary's College, Maryland) used glass cylinders (in place of spheres) to produce rainbows.

In addition to the night devoted to the slide show, a number of presentations emphasized the aesthetic aspects of magnificent optical phenomena rather than scientific discoveries. This included photographic records of noctilucent clouds (Parviainen), odd-radius halos (Shaw), and diffraction patterns in spider webs (Bill Livingston, National Solar Observatory). Hinz presented an awesome photographic record of atmospheric optical phenomena observed from the Wendelstein mountaintop observatory in Germany and also showed that circular coronas and halos form up to the moment of totality during solar eclipses (see www.glorie.de/).

Bob Greenler (University of Wisconsin, Milwaukee) presented an historical summary of accomplishments and scientific discoveries made since the inception of the conference series on light and color in the atmosphere. Knowledge of atmospheric optics had been summarized by Marcel Minnaert in his classic, *The Nature of Light and Color in the Open Air* (Minnaert 1954). After that, research in atmospheric optics virtually ceased until 1966 when Greenler with several colleagues presented results of the first numerical simulations of sun pillars at a meeting that Minnaert attended. Minnaert realized that this would help revive interest and research in atmospheric optics. Since that time, armies of observers have traveled around the world photographing extraordinary, and in some cases previously unknown, optical phenomena, including a number of halos (e.g., see Herd 2007). Most of the optical phenomena have also been examined and illustrated by ingenious laboratory experiments and demonstrations, and simulated in color on computers. In a few cases simulations have led to new discoveries of previously unknown halo arcs. One of Greenler's abiding motives for his work in atmospheric optics has been the assumption that knowledge does not diminish, but rather increases both the appreciation and sense of wonder of the beautiful and awe-inspiring atmospheric optical phenomena.

Shaw then concluded the meeting by awarding both Greenler and Lynch the first Rayleigh Prize for service and scientific accomplishments in the field of atmospheric optics (for additional information, see the "Award ceremony" sidebar below).

FURTHER DETAILS. Color photographs and scientific papers have been published in dedicated issues of *Applied Optics* about 18 months after each of the previous meetings (see, e.g., Adler and Lee 2005). Papers from the 2007 meeting are scheduled to appear in *Applied Optics* in the 1 December 2008 issue (Vol. 47, No. 34). The next meeting will be held in 2010 at St. Mary's College, St. Mary City, Maryland. (Information about upcoming meetings and publications appear online at www.optics.montana.edu/light&color2007.html).

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AWARD CEREMONY

Robert Greenler, author of *Rainbows, Halos and Glories* (Greenler 1980), and Dave Lynch, coauthor of *Color and Light in Nature* (Lynch and Livingston 2001), were joint recipients of the First Rayleigh Award. The award was presented in honor of Lord Rayleigh for their long, dedicated, and inspirational service to the field of atmospheric optics. Greenler, a former president of the Optical Society of America, and professor emeritus of physics at the University of Wisconsin, Milwaukee, inspired the conference series and launched the field of computer simulations of atmospheric optical phenomena. Dave Lynch, president of Thule Scientific, a prolific researcher in all aspects of atmospheric optics, organized several of the conferences.

REFERENCES

Adler, C. L., and R. L. Lee Jr., 2005: Light and color in the open air: Introduction to the feature issue. *Appl. Opt.,* **44,** 5623–5623.

Greenler, R., 1980: *Rainbows, Halos and Glories.* Cambridge University Press, 205 pp.

Herd, T., 2007: *Kaleidoscope Sky.* Abrams, 240 pp.

Lynch, D. K., and W. Livingston, 2001: *Color and Light in Nature.* 2nd ed. Cambridge University Press, 292 pp.

Minnaert, M., 1954: *The Nature of Light and Color in the Open Air.* Dover Publications, 362 pp.

Tape, W., and J. Moilanen, 2006: *Atmospheric Halos and the Search for Angle X.* Amer. Geophys. Union, 238 pp.