Atmospheric Halos

Rings around the sun and moon and related apparitions in the sky are caused by myriad crystals of ice. Precisely how they are formed is still a challenge to modern physics

by David K. Lynch

Anyone who spends a fair amount of time outdoors and keeps an eye on the sky is likely to see occasionally a misty ring or halo around the sun or the moon. The phenomenon is well established in folklore as a sign that a storm is coming. Actually the halo is only one of a number of optical effects that arise from the same cause, which is the reflection and refraction of light by crystals of ice in the air. Whenever cirrus clouds or ice fogs form, arcs of light appear overhead, woven into the veil of cirrus in a splendid variety of circles, arcs and dots.

The effects are best seen when the clouds are thick enough to fill the air with ice crystals but not so thick as to hide the sun. The commonest effect is the 22-degree halo, so named because its radius subtends an angle of 22 degrees from the eye of the observer. The halo appears as a thin ring of light (about 1.5 degrees wide) centered on the sun; sometimes it is pale white and sometimes it is brightly colored, with red on the inside and blue on the outside. The colors are clearest when the clouds form a uniform, featureless haze. If the clouds are patchy, the halo may be incomplete.

Frequently the 22-degree halo appears in company with two "sun dogs," which are bright and sometimes colored patches of light on each side of the halo, either on it or just outside of it. The formal name for them is parhelia, from the Greek for "with the sun." Occasionally visible is a larger, fainter halo with a radius of about 46 degrees.

If the cloud cover is uniform, one can sometimes see a ring of light encircling the sky parallel to the horizon. It is the parhelic circle. It passes through the sun and the parhelia and, if they are visible, through the anthelion (a whitish patch opposite the sun) and the paranthelia (which are like the anthelion but are located at azimuths of plus and minus 120 degrees from the sun).

Other phenomena commonly observed are the circumscribed halo and the circumzenith arc. The circumscribed halo surrounds the 22-degree halo and is bilaterally symmetrical with it. At the top and bottom the two are tangent. The circumzenith arc appears as an inverted rainbow centered on the zenith, facing the sun.

Many other phenomena of this kind have been identified, and I shall describe a number of them. As the optical effects of atmospheric ice crystals are enumerated, however, a point is reached where their existence and properties become questionable. Rare, one-of-a-kind observations haunt the published material, and quantitative measurements are almost unknown. Was the halo real? Could it have been a known halo mistaken for a new one? Was it described accurately? Theoretical work by Robert G. Greenler of the University of Wisconsin at Milwaukee and his colleagues predicts certain arcs that have not been seen; have they been overlooked or is the theory incomplete?

Even though the theory of halos is primarily encompassed by classical optics, the principles of which have been known for centuries, the present understanding of these wonderful arcs is imperfect. Hence the study of halos is as fascinating now as it was 100 years ago.

The belief that a halo signifies the onset of bad weather has a basis in fact. A falling barometer is usually caused by an advancing low-pressure system. Violent convection carries moist surface air to altitudes of from 9,000 to 15,000 meters (30,000 to 50,000 feet), where the temperature is well below freezing. The air becomes supersaturated with water vapor, which condenses out and forms cirrus clouds. High-velocity winds above the system carry the wispy cirrus ahead of it, which is why halos can be seen in these clouds as the lovely first harbingers of foul weather.

Since the ice in the clouds is the source of the optical effects, one is led to consider its structure. The delicate snowflakes of winter show that ice is a hexagonal crystal. Such a crystal has four axes of symmetry: three *a* axes, which are of equal length and intersect at an angle of 120 degrees, and a *c* axis, which is of a different length and is perpendicular to the plane of the *a* axes.

Although many forms of ice can occur, only about four are important in meteorological optics. The others are either too rare or do not have smooth, regular optical faces. The important forms are the plate, which resembles a hexagonal bathroom tile, the column, the capped column and the bullet (a column with one pyramidal end).

In each of these forms, except for the single pyramid, the two end faces are parallel and lie perpendicular to the *c* axis. They are termed the basal faces. The angles between the crystal faces are always the same: 120 degrees for adjacent prism (side) faces, 60 degrees for alternate prism faces and 90 degrees for the junctions between ends and sides. The 60-degree and 90-degree combinations are responsible for nearly all of the halo phenomena.

Atmospheric ice crystals form by direct sublimation from air that is supersaturated with water. The type of crystal depends primarily on the air temperature, although the degree of saturation relative to ice can be a factor when the saturation is less than 108 percent. Then only plates and columns can form. Most of the optically interesting crystals form when the saturation is between 100 and 140 percent and the temperature is between minus 5 and minus 25 degrees Celsius. When the saturation is higher than 140 percent, the growth of crystals is so rapid that rime (an amorphous deposit of frozen droplets) grows on the crystals and destroys their optical faces.

The relations of temperature and saturation can be represented in a diagram in which different regions are designated by Roman numerals [*see illustration on page 151*]. Composite crystals are formed when the growing crystal moves from one region to another. For example, a capped column begins as a simple column. During its period of formation it passes from Region VII to Region II, perhaps because it is descending through a stratified cloud. Once it is in the plate-forming region the columnar growth stops but the basal faces continue to develop outward from the *c* axis. If the column initially has two flat ends, it grows a cap at each end and comes to resemble a spool. A plate will not form on a column that terminates in a pyramid. It is important to realize that a capped column and all other mixed forms originate as single crystals and go through two separate periods of growth; they are not separate crystals that came together after they were formed.

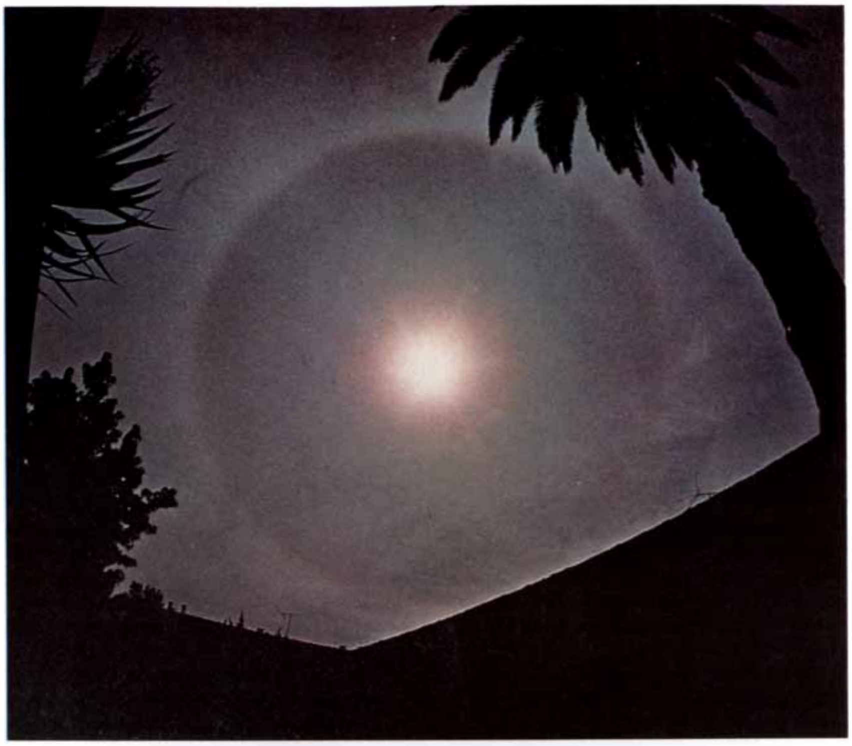
The orientations of the ice crystals as they fall through the air are responsible for the wide variety of halos. Exceedingly small crystals (less than about 20 micrometers in diameter) are subject to Brownian motion, the random movement resulting from the impact on the crystals of the molecules of the air. The random collisions with air molecules cause the crystals to tumble constantly, so that all orientations are present.

When the crystals reach a size of from 50 to 500 micrometers, aerodynamic lift dominates the Brownian motion and forces the crystals into certain positions relative to the direction of their fall. If all of the ice particles are of one kind, they become aligned with one another. (Imagine what such a cloud looks like on a microscopic scale: billions of sparkling prisms lined up uniformly, glinting in the sunlight, each one producing its own family of tiny halos. Most halos are formed in this way.) When the ice crystals reach a size of from .5 millimeter to three millimeters, they tend to spin as they drift downward. These whirling crystals produce yet another class of halos, to which I shall return.

The 22-degree halo is formed by sunlight that passes through alternate side faces of randomly oriented crystals. All the crystals are less than 20 micrometers in diameter and all have 60-degree faces. Since the sunlight strikes the ice crystals at every possible angle, it may seem strange that a cloud composed of countless independent crystals should direct light chiefly at an angle of 22 degrees.

The principle underlying this effect is called the principle of minimum deviation. It is a cornerstone of classical optics and finds application in many areas of meteorological phenomena, including rainbows. Since the crystal faces are inclined to one another by 60 degrees, the problem of the 22-degree halo becomes one of understanding the passage of light through an ordinary spectroscope prism in a plane perpendicular to the *c* axis.

The angle between the incident ray and the emergent ray is termed the deviation; it is the angle by which the light changes direction in the crystal. As the angle of incidence increases from zero degrees (perpendicular to the face) the deviation decreases steadily, reaches a broad minimum and then increases again. In the vicinity of the minimum a



COMMON HALO, known as the 22-degree halo because its radius subtends an angle of 22 degrees from the eye of the observer, surrounds the sun. The photograph was made in Pasadena, which is why one sees a border of palm fronds. The halo is the result of randomly oriented ice crystals in cirrus clouds. This photograph and the one below were made with a wide-angle lens.

HALO COMPLEX was photographed near the South Pole. Visible are the 22-degree and 46-degree halos, the parhelic circle and its parhelia, the upper Parry arc and the circumzenith arc. The variety shows that the cirrus clouds had various shapes and orientations of ice crystals.

SUN AND PARHELION were photographed from White Mountain in California. The parhelion, or "sun dog," is the bright spot at the right. The formal name is derived from the Greek for "with the sun." Frequently two parhelia are visible on opposite sides of the sun.

THREE CROSSED ARCS meet at the antisolar point, which is always below the horizon when the sun is up. The arcs result from multiple reflections off the side faces and one end face of column-shaped crystals. The optics are much the same as in an ordinary kaleidoscope.

change in the angle of incidence produces no change in the deviation. Light therefore accumulates at the angle of minimum deviation. The 22-degree halo is this concentration of light, and it is circular because all orientations are present. Since the deviation of light can be more than 22 degrees but not less, the halo is actually doughnut-shaped, with a bright and sharp inner edge due to minimum deviation and a diffuse outer region resulting from the rays that traverse the crystal at other angles.

Two quantities determine the angle of minimum deviation: (1) the angle between the faces and (2) the index of refraction. The mean index of refraction for ice is about 1.31; as in all solids, however, it varies slightly with color, that is, with wavelength. This property is termed dispersion. It causes white light to be split up so that each component color travels in a slightly different direction. Hence the angle of minimum deviation is a bit different for each color, being smallest for red light. Thus the halo is in fact composed of a continuum of superposed halos, each of a slightly different color and size.

Without dispersion the overlapping halos would combine and would appear pure white, like the light from which they originated. Since the reddish halos are smaller than the others, however, they are seen at the inner edge of the composite halo. Being slightly separated from the rest, their colors are washed out the least. Other colors are considerably smeared because red rays near the minimum deviation can fall on them at the minimum deviation, whereas the opposite effect is impossible.

The 46-degree halo is formed in exactly the same way except that the crystal faces that refract the light are a basal face and a side face that share an edge. Such faces always intersect at 90 degrees rather than 60 degrees. Other halos formed by minimum deviation in randomly oriented crystals are rarely observed, but they can be explained in terms of the prisms with pyramidal terminations. They include six halos ranging in size from eight to 32 degrees.

The commonest optical effects caused by oriented crystals are the parhelia. They are at least as common as the 22-degree halo and are much easier to see because they are brighter. The crystals responsible for these "mock suns" are capped columns, bullets of moderate size and plates, all with vertical *c* axes. Aerodynamic lift forces the crystals to descend in this position.

As before, the light passes through alternate side faces. Since the faces are vertical and the sun is above the horizon, however, sunlight enters the crystal obliquely, and the plane on which the light travels is not perpendicular to the *c* axis. Thus a true minimum deviation does not occur. A "quasi-minimum" deviation does take place, and it concentrates light; the angle is always more than 22 degrees, however, so that the parhelia are formed outside the 22-degree halo. Only when the sun is on the horizon are the conditions for true minimum deviation fulfilled, and then the parhelia do lie on the 22-degree halo.

The colors of the parhelia, which are often dazzling, result from refraction, as within the 22-degree halo. Like most oriented crystals, the plates and capped columns tend to wobble around their mean orientation; the movement smears out the optical effect. The brilliance of a parhelion can be affected by the degree of alignment of the available crystals. Parhelia often show a bluish-white tail that extends horizontally away from the sun. It is caused by the rays that traverse the crystal near but not at the quasi-minimum deviation. The tail is most evident when the sun is low.

Analogous to the parhelia of the 22-degree halo are the parhelia of the 46-degree halo. They are rarely reported and indeed may not exist at all. If the phenomena reported as parhelia of the 46-degree halo are really that, they are formed by a quasi-minimum deviation in a 90-degree prism of a crystal that

VARIETY OF OPTICAL EFFECTS appear in another photograph made near the South Pole. The sun, which is obscured by the flag, is surrounded by parts of the 22- and 46-degree halos and the colorful circumzenith arc, which is the concave arc near the top of the photograph.

TWO EFFECTS, a column and an upper tangent arc, are visible in this photograph. The column rises upward from the sun, and the arc is the bright spot above it in the sky. Such an arc is sometimes seen tangent to a 22-degree halo; from the air one sometimes sees the lower arc.

has its *c* axis horizontal and its refracting edge vertical.

One of the loveliest members of the halo family is the elusive circumzenith arc. Although it is formed in the same crystals (capped columns and bullets) as the parhelia are, it is observed far less often because it can occur only when the sun is below 32.2 degrees of elevation. (Moreover, people seldom look straight up, which is the direction of the arc.)

In forming such an arc light enters the upper horizontal face of a crystal and emerges through a vertical side face. At elevations larger than 32.2 degrees the light is totally reflected internally. At 32.2 degrees the emerging light travels straight down. Hence the circumzenith arc appears as a bright spot at the zenith. As the sun drops below this elevation the spot opens up into a splendid arc of color centered on the zenith and facing the sun. Although the circumzenith arc is not a mimimum-deviation phenomenon, it does achieve its maximum brightness when the sunlight passes through the crystal at the minimum deviation. That happens when the solar elevation is 22.1 degrees, at which point the 46-degree halo and the circumzenith arc are tangent.

Complementing the circumzenith arc is the colorful circumhorizon arc. It is formed in the same crystal but by light that enters through a vertical side face and leaves through the bottom horizontal face. On the basis of symmetry one can readily infer that the circumhorizon arc cannot appear when the sun is below an elevation of 57.8 degrees (90 degrees minus 32.2 degrees). The arc starts out as a ring of color on the horizon. As the sun rises so does the encircling circumhorizon arc. The maximum brightness again occurs at the minimum deviation, when the elevation of the sun is 67.9 degrees (90 degrees minus 22.1 degrees). Because this arc is a high-sun phenomenon it is one of the few halos that cannot be seen from any place on the earth. It is visible only in the Temperate Zone latitudes from 55.7 degrees north to 55.7 degrees south, where the sun can get high enough. Since the sun's elevation is highest in the summer, when cirrus clouds are less likely to form, the circumhorizon arc will probably always remain a rare sight.

Analogous to the circumzenith and circumhorizon arcs for the 60-degree faces are the upper and lower Parry arcs, named for an arc phenomenon described by the British explorer Sir William Parry in 1821. The arcs are formed just above and below the 22-degree halo. They change shape dramatically with changes in the elevation of the sun. This relation has undoubtedly caused confusion in identification, since the arcs can masquerade in many forms. The associated crystals are columns that are oriented with their *c* axes horizontal and with two side faces also horizontal, one on the top and one on the bottom.

Two halos, the parhelic circle and the solar pillar, deserve special attention because they are formed primarily by external reflection from oriented crystals. They are therefore colorless. The parhelic circle is formed by reflection from the vertical side faces of capped columns and plates (*c* axes vertical) and from the end faces of horizontal columns. Since there is no preferred azimuthal orientation, the side faces scatter light in all horizontal directions while preserving the vertical component. Thus light appears to come to the observer from every point of the compass but from a single altitude. The parhelic circle is seen as a horizontal ring of light running through the sun and encircling the sky parallel to the horizon. It is seldom seen in its entirety because the clouds usually do not cover the sky uniformly.

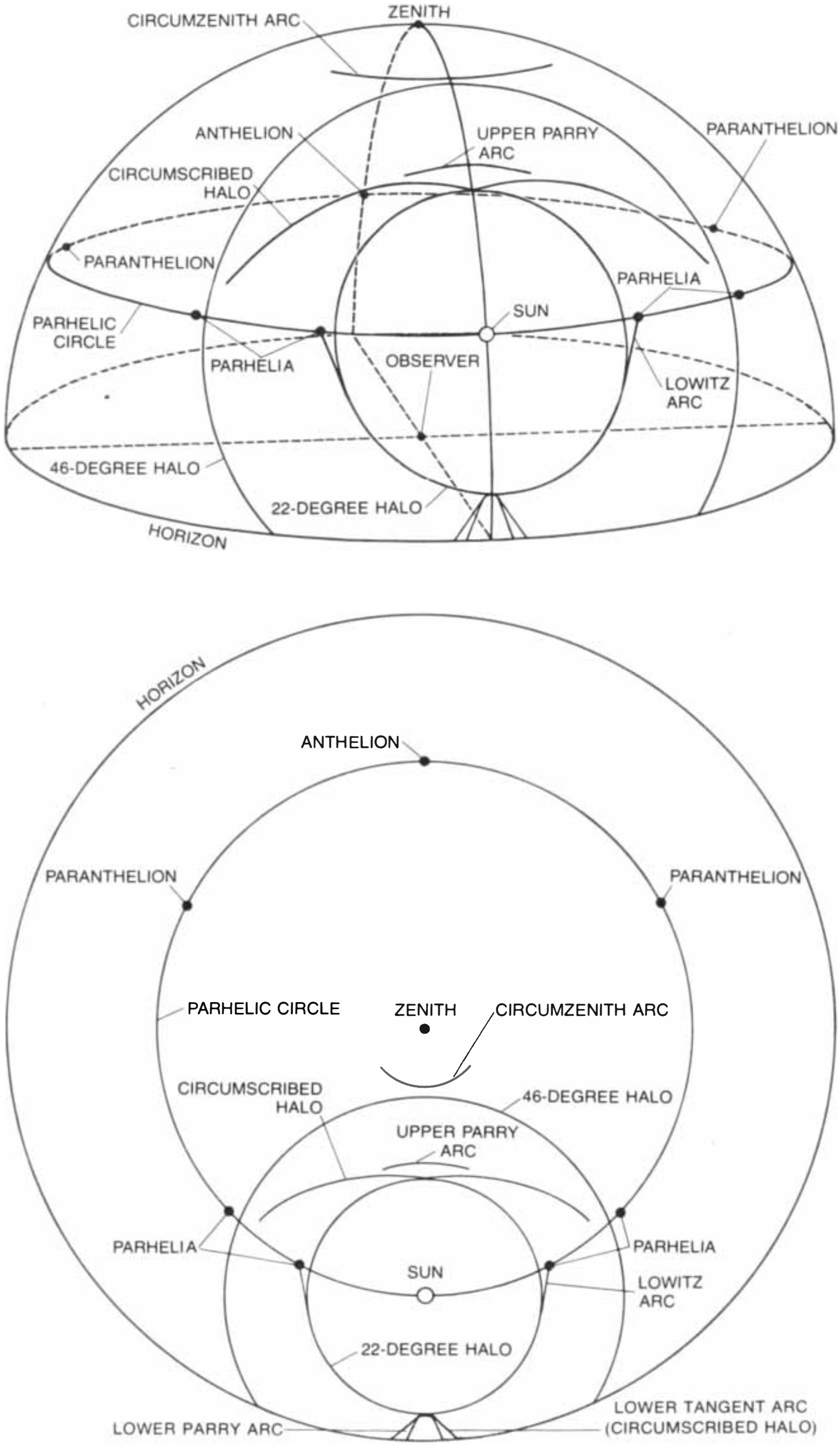
The solar pillar, a commoner phenomenon, is a vertical shaft of light extending upward from the sun. It is most often observed above the rising or setting sun. Occasionally it is tilted or seen below the sun. The pillar is caused by reflection from the basal faces of plates and capped columns. As the crystals descend (with their *a* axes horizontal, like a leaf) they wobble around the mean orientation and smear the reflected solar image out vertically. Pillars therefore provide strong evidence of oriented crystals and also show that the crystals oscillate. Although pillars produce no color of their own, they take on the color of the sun and so often appear to be orange or red.

When the pillar, the parhelic circle and the 22-degree halo appear together, they often form crosses in the sky. This effect has undoubtedly led some people to interpret halos as signs from heaven. The most famous account of a well-timed cross resulted from an incident in the Swiss Alps in the summer of 1865. Edward Whymper and his companions were returning from the first ascent of the Matterhorn when four of them fell and were killed. Some hours later Whymper saw a circle with three crosses in the clouds, "a strange and awesome sight, unique to me and indescribably imposing at such a moment."

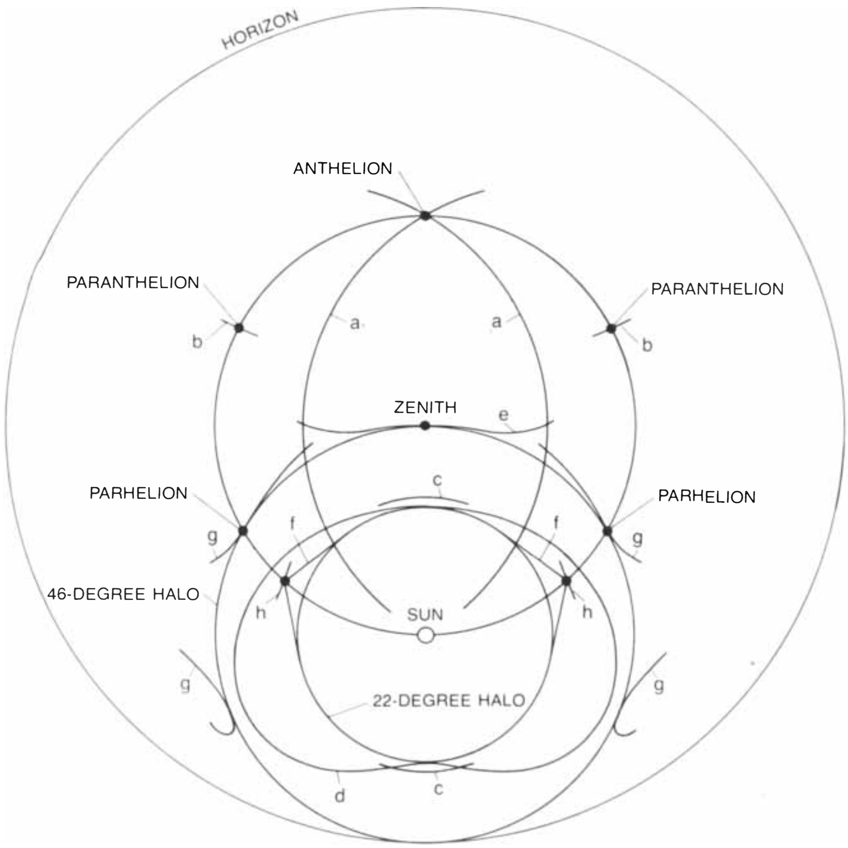
Most of the halos I have described are visible in the general direction of the sun. Looking the other way one finds several interesting phenomena. The colorless anthelion (counter-sun) and the two paranthelia (with the counter-sun) are often visible, looking like beads strung out along the parhelic circle. They also can appear when the parhelic circle is absent. Both are at the elevation of the sun. The anthelion is at an azimuth of 180 degrees relative to the sun, and the parhelia are at plus and minus 120 degrees.

Another class of halos arises from spinning crystals. Nine different arcs, attendant on either the 22-degree or the 46-degree halo, can be identified in this group. Because they are refractive phenomena they can be brightly colored.

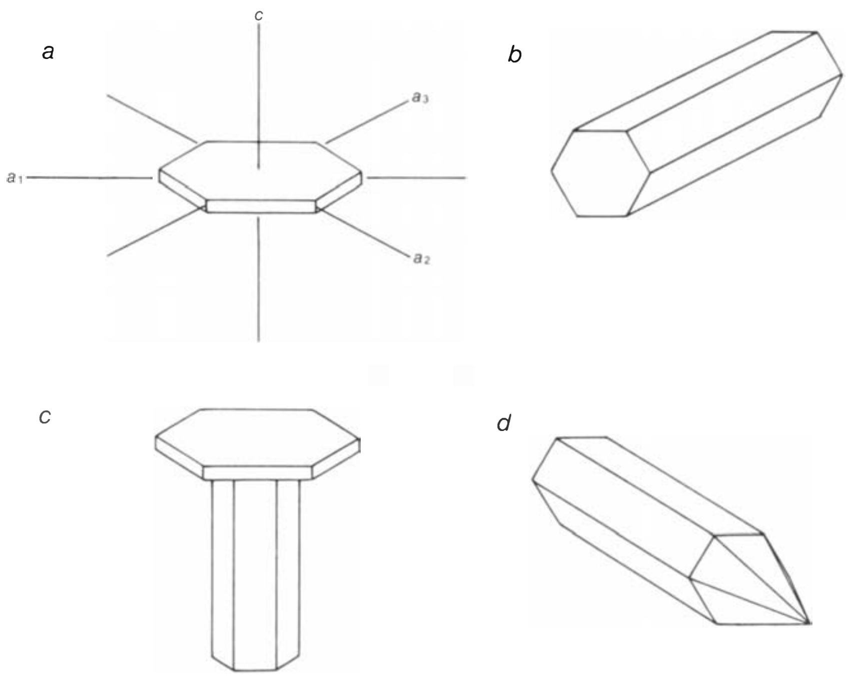
The mechanism begins with crystals of moderate size that are drifting down through the air. They quickly become oriented and reach a terminal velocity of about 20 centimeters per second. At that point the force of gravity is balanced by lift and viscous drag. Air flows smoothly around the crystal and remains relatively undisturbed after its passage. As the crystal grows, the grace-



COMMONEST HALOS occur in the general direction of the sun and are portrayed here in two ways: in a perspective (*top*) from outside the hemisphere and in a view (*bottom*) straight upward to the observer's zenith. The same atmospheric optical effects appear in both views.



OTHER EFFECTS can be seen in every part of the sky. As identified here by letters they are the anthelic arcs (*a*), the paranthelic arcs (*b*), the upper and lower Parry arcs (*c*), the circumscribed halo of the 22-degree halo (*d*), the upper tangent arc of the 46-degree halo (*e*), the supralateral arc of the 22-degree halo (*f*) and the supralateral arc of the 46-degree halo (*g*). An extra arc, the mesolateral arc (*h*), runs through the parhelion of the 22-degree halo. For reference some optical effects shown in the illustration on the preceding page are repeated.



ICE CRYSTALS usually responsible for atmospheric optical effects have these four forms. They are the plate (*a*), with its four axes indicated, the column (*b*), the capped column (*c*) and the bullet (*d*). Although the crystals are drawn to the same scale, they occur in a variety of sizes.

ful streaming becomes increasingly unstable. In time the flow acquires an entirely different character: it becomes turbulent. The crystal leaves a wake of vortexes and eddies, which cause it to spin as it falls.

The halos that result from spinning crystals are lateral arcs and tangent arcs. They can be divided readily into two categories: the arcs attending the 22-degree halo (the infralateral or Lowitz arc, the supralateral arc, the mesolateral arc and the circumscribed halo) and the ones that accompany the 46-degree halo (the infralateral arc, the supralateral arc and the upper and lower tangent arcs). There are actually nine arcs because at low solar elevations the circumscribed halo looks like an upper and lower two-tangent arc to the 22-degree halo. All of the arcs can be brightly colored because they are refractive phenomena.

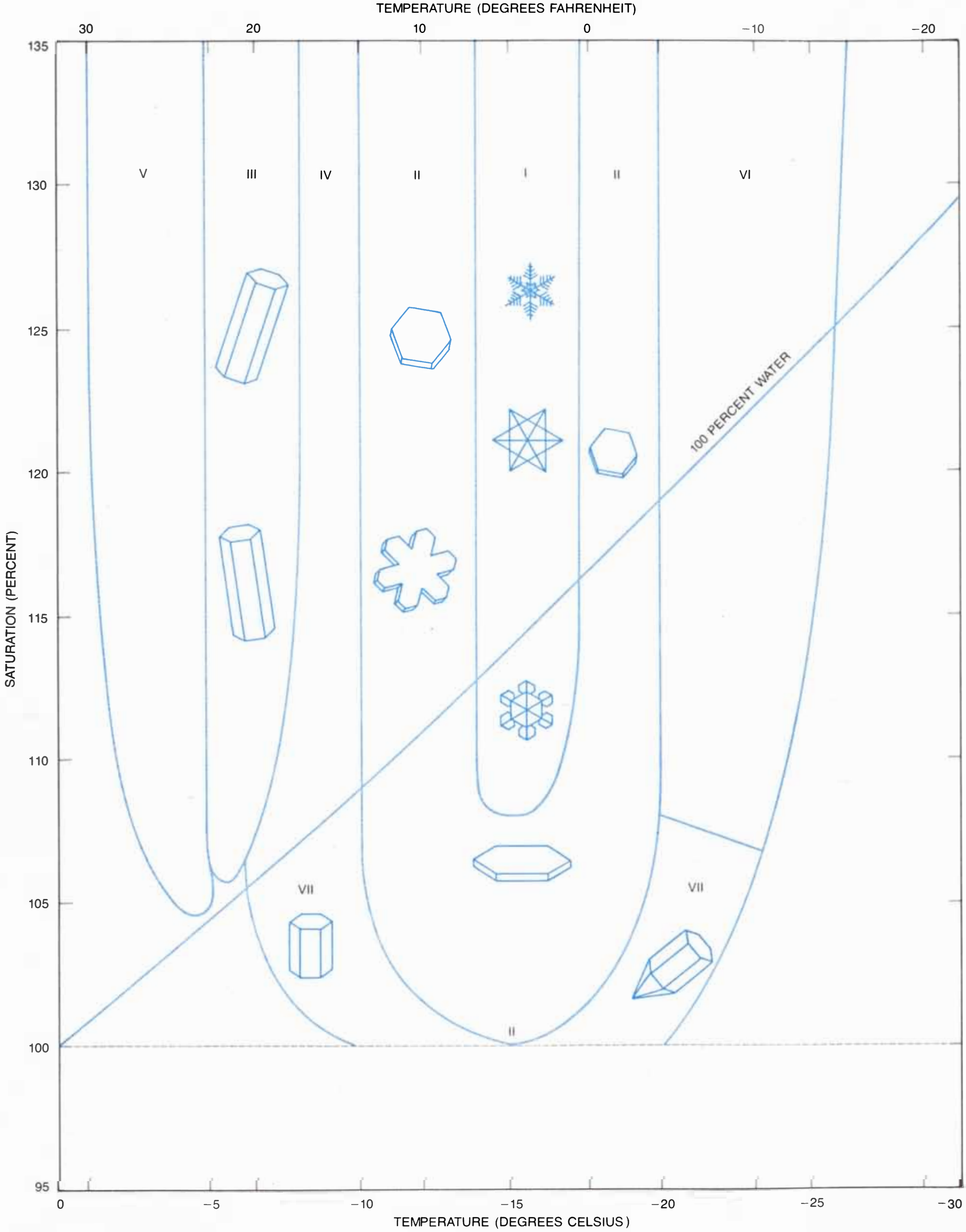
Some halos are formed below the horizon. In order to see them one must look down into the ice crystals. Until airplane travel became common such halos could be seen only from high mountaintops and cliffs. Bright halos can sometimes be seen below the horizon because of reflection from horizontally oriented ice faces. A sub-sun is frequently observed by people in airplanes and is a sure sign that sub-halos are about. I once saw (but alas did not photograph) a splendid sub-halo complex over Canada, consisting of a sub-sun flanked by two sub-parhelia.

The sun is not the only source of light for halos. At night the moon often has a halo. In northern regions where ice fogs occur pillars can be seen standing over street lamps and runway lights. When snowflakes lie horizontally, pillars and sub-lights can appear below the headlights of an automobile.

Many halos, some common and some rare, remain a puzzle. Anthelic arcs appear frequently, but attempts to explain them have not fully succeeded. They have been observed in so many forms that more than one crystal may be involved. A number of other halos are likewise not satisfactorily explained. Plainly much remains to be learned.

Research on halos is inching its way into the 20th century. So far, however, no work has been done beyond classical optics, and little progress has been made in the areas of polarization and diffraction. What is needed is a large number of observations, on which new theoretical work can be based.

This situation offers an opportunity to the interested skywatcher, who can do valuable research with modest equipment: a camera, a notebook and a sharp eye. Calibrated photographic observations are badly needed. The observer should record carefully the radius of any halo, the angular shapes and extensions of the arcs, the color characteris-

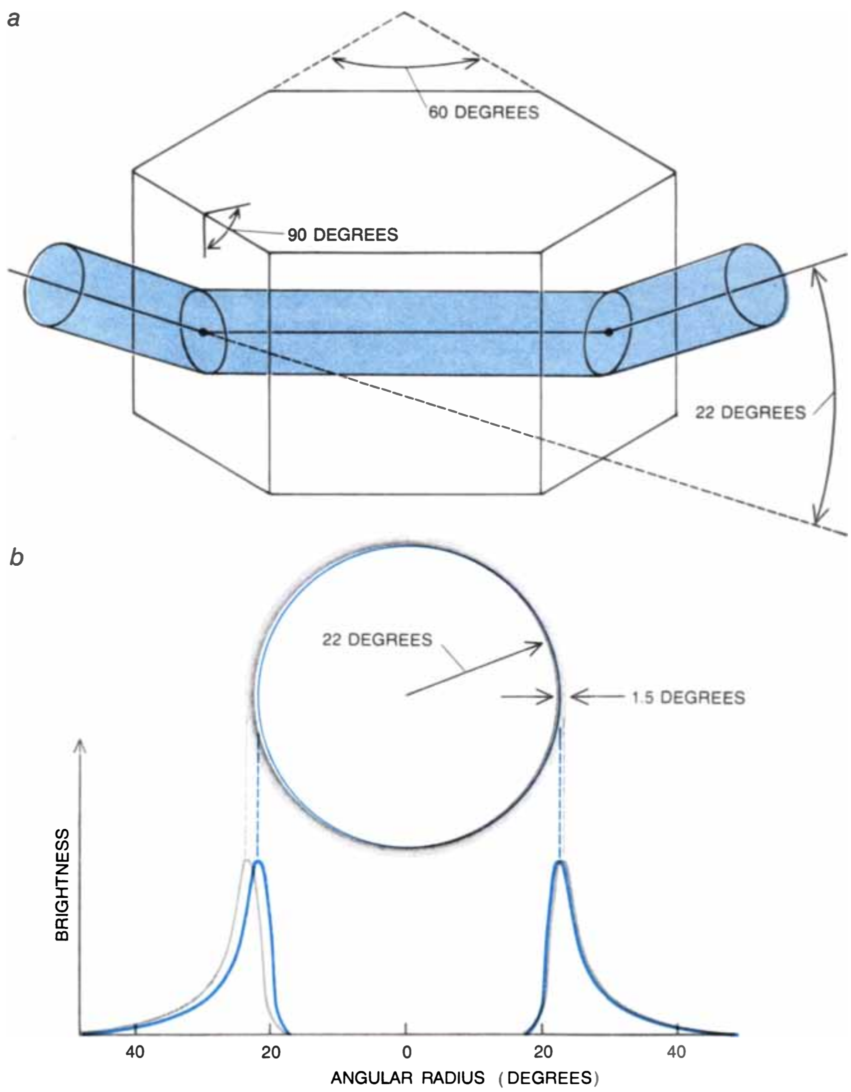


FORM OF CRYSTAL depends on the air temperature and the degree of water saturation of the ice. When the saturation is more than 108 percent, the temperature alone determines the type of crystal. The Roman numerals delineate regions with different forms, which can best be followed by reading the Celsius temperature scale from left to right. Irregular forms are not shown. The forms are irregular needles at minus 3 degrees (*V*), regular needles at minus 7 degrees (*III*), cups or scrolls at minus 9 degrees (*IV*), plates at minus 12 degrees (*II*), snowflakes at minus 15 degrees (*I*), plates at minus 17 degrees (*II*) and irregular plates at minus 23 degrees (*VI*). When the saturation is below 108 percent, only plates and columns grow. At saturations above 140 percent crystals grow so fast that they accumulate rime.

tics and the period of observation. Photographs made through a Polaroid filter at several orientations to the vertical are most important. The filter's orientation for each photograph should be noted. The meteorological conditions at the time of the observations should be recorded, along with the date, the time, the altitude of the sun and the geographic location. Neither a large monetary grant nor a laboratory full of advanced equipment can compete with hundreds of energetic observers who are at the right place at the right time to see and report on a halo complex.

Only in a few fields of physics will a casual glance at the laboratory reveal anything about the experiments in progress. When a halo is sighted in the icy laboratory overhead, however, one immediately knows the temperature of the cloud; the state of the water; the size, shape and orientation of the ice crystals; the conditions of temperature and humidity in which the crystals are formed, and the subtle optics that are producing the halo. If several arcs are observed, even more is known.

Halos stir one's mind and soul, since they probe both the physical environment of the cloud and one's awareness and appreciation of the natural world. From the chaos of billions of pale, microscopic, angular crystals of ice nature spins a colorful fabric of expansive, graceful curves. All of them are accessible to the observer who takes the time to look up.



MECHANISM OF 22-DEGREE HALO is depicted. The halo is formed by the refraction of sunlight passing through the 60-degree faces of ice crystals. The effect is shown here (*a*) for a single crystal. The average deviation (the angle between the incident ray and the emergent ray) is 22 degrees, which is the mean radius of the halo. The halo is circular because the light is passing through billions of randomly oriented crystals. Because of dispersion (*b*) the 22-degree halo is actually a continuum of overlapping halos, the smallest one red and the largest violet. The inner edge is reddish and sharply defined; the outer edge is bluish-violet and much fuzzier.

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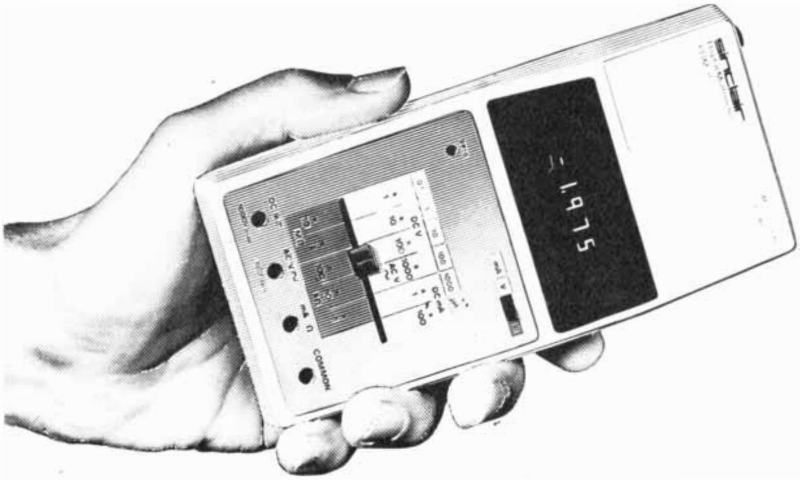

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