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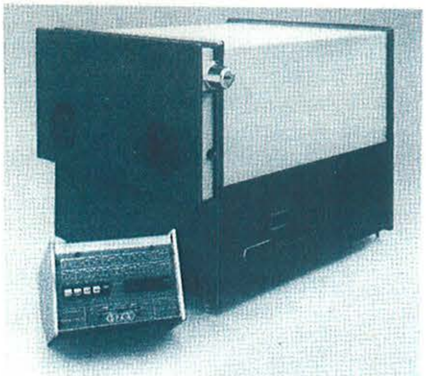

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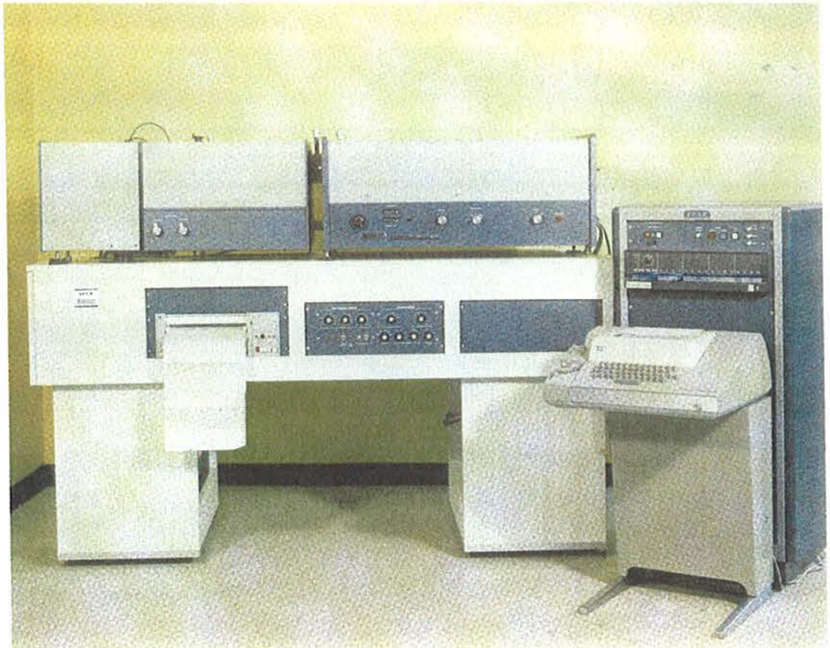

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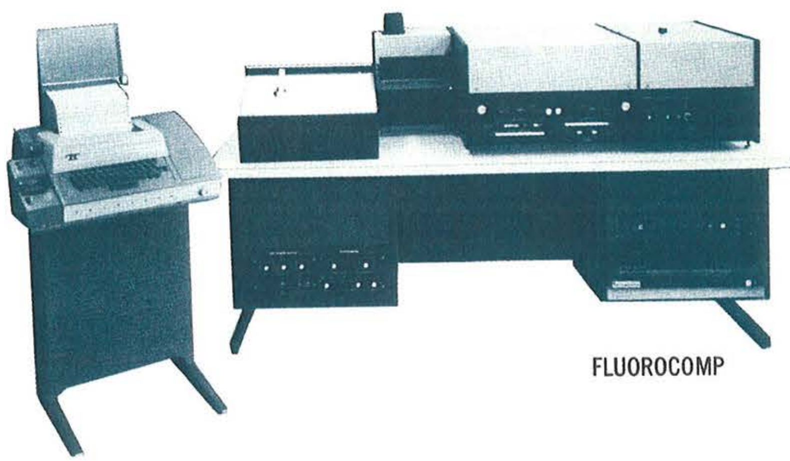

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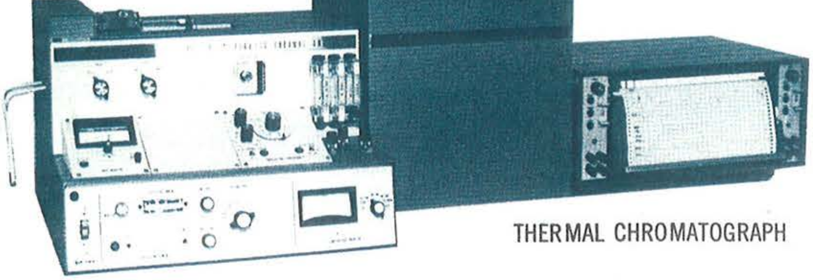
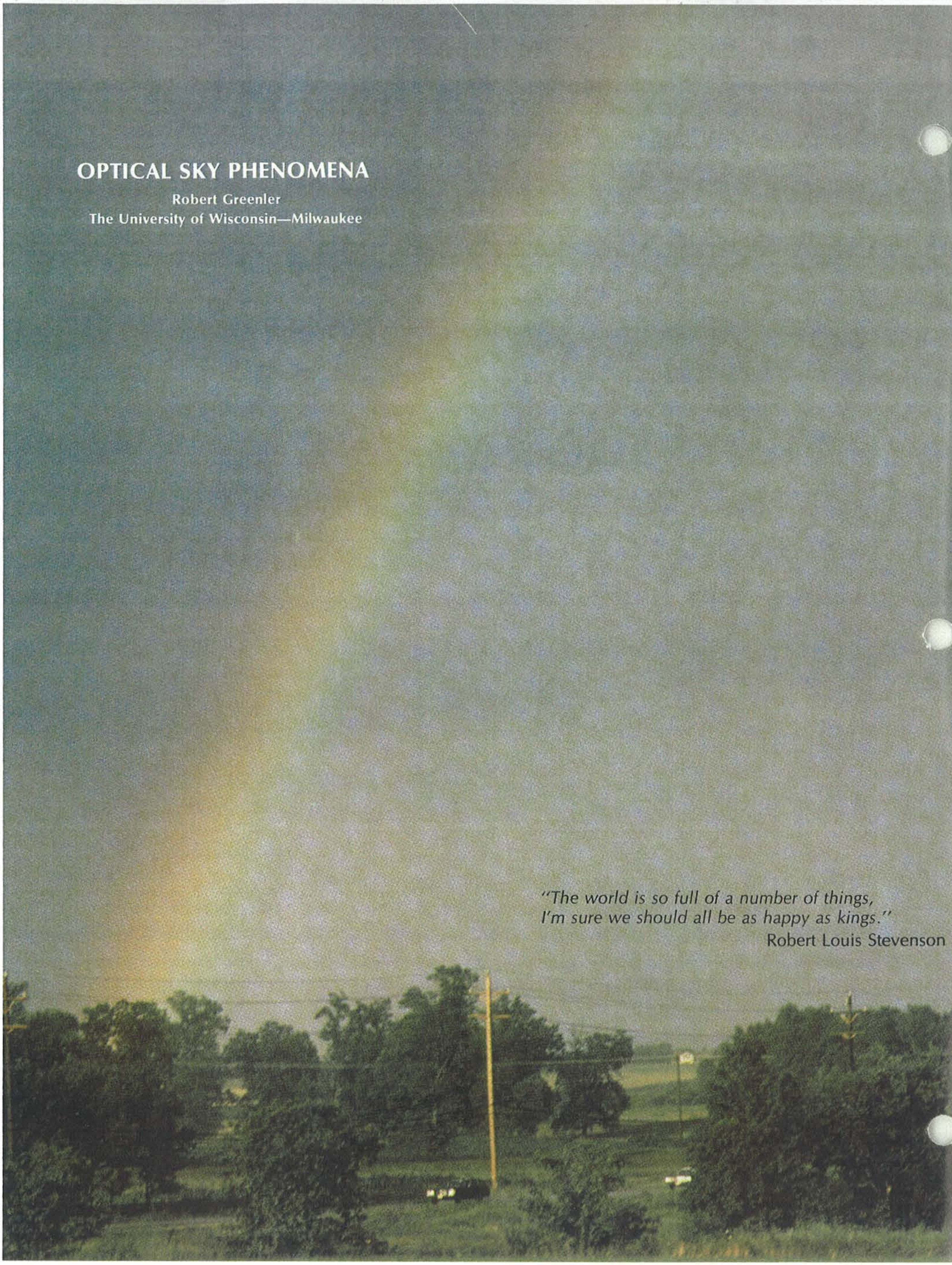


CHROMALYTICS
CONCENTRATOR
GC / ES
MASS CHROMATOGRAPH

THERMAL CHROMATOGRAPH

OPTICAL SKY PHENOMENA

Robert Greenler
The University of Wisconsin—Milwaukee



*"The world is so full of a number of things,
I'm sure we should all be as happy as kings."*
Robert Louis Stevenson

The world is full of fascinating things that most of us have never seen — obvious things which exist in front of our eyes but which we never see. Again and again I am impressed with our blindness to things, however obvious, which we do not already know about. Some of us have areas of particular interest where we can look at the world with fresh eyes, but I believe that this is a rare trait. It is a trait, hopefully, that can be fostered and developed. A person who is able continually to expand the number of areas in which he can perceive new things has a source of excitement and satisfaction that is denied those who see only what they are instructed to look at.

This article describes some pretty things that can be seen in the sky; things that can be seen without special equipment, without any special location; things that may be seen by anyone who can see. I hope that some of you who read this article will become sensitized to the wealth of beautiful optical effects of the sky, which you may not have seen, but which you will now see and enjoy.

I can hardly imagine a sighted person who has not had his attention arrested by a dazzling stroke of lightning accompanying a summer storm. The basic idea of a great electrical discharge between a cloud and the ground (as seen in Fig. 1) is simple enough to understand but the details of the lightning mechanism and the wide variety of lightning displays are less than fully understood.

The northern lights shown in Fig. 2 can be seen by many people in the northern United States who watch the sky by night. Though much quieter than the lightning display, the aurora, changing form and color over vast expanses of sky, can be a moving sight. Again, the basic idea of the aurora is not complicated.Oxygen and nitrogen molecules in the upper atmosphere emit light after being excited by impact with charged particles. The connection between the auroral display and sunspots is also understood to a degree. Great magnetic storms on the sun's surface, which we can see as sunspots, emit charged particles which trigger off the aurora when they reach the vicinity of the earth. The detailed interaction between these particles from the sun and electrons trapped in the earth's magnetic field to produce the aurora is more complicated.

Many colorful optical effects produced by the interaction of sunlight with water droplets or ice crystals in the earth's atmosphere can be seen in the daytime sky. The glory (shown in Fig. 3) can often be seen from an airplane when we fly over a deck of clouds. The diffraction rings are seen around the anti-solar point (the point directly opposite the sun, marked by the plane's shadow). There have been a number of recent attempts to explain the details of the glory but there seems at this time to be no entirely-satisfactory, simple explanation.

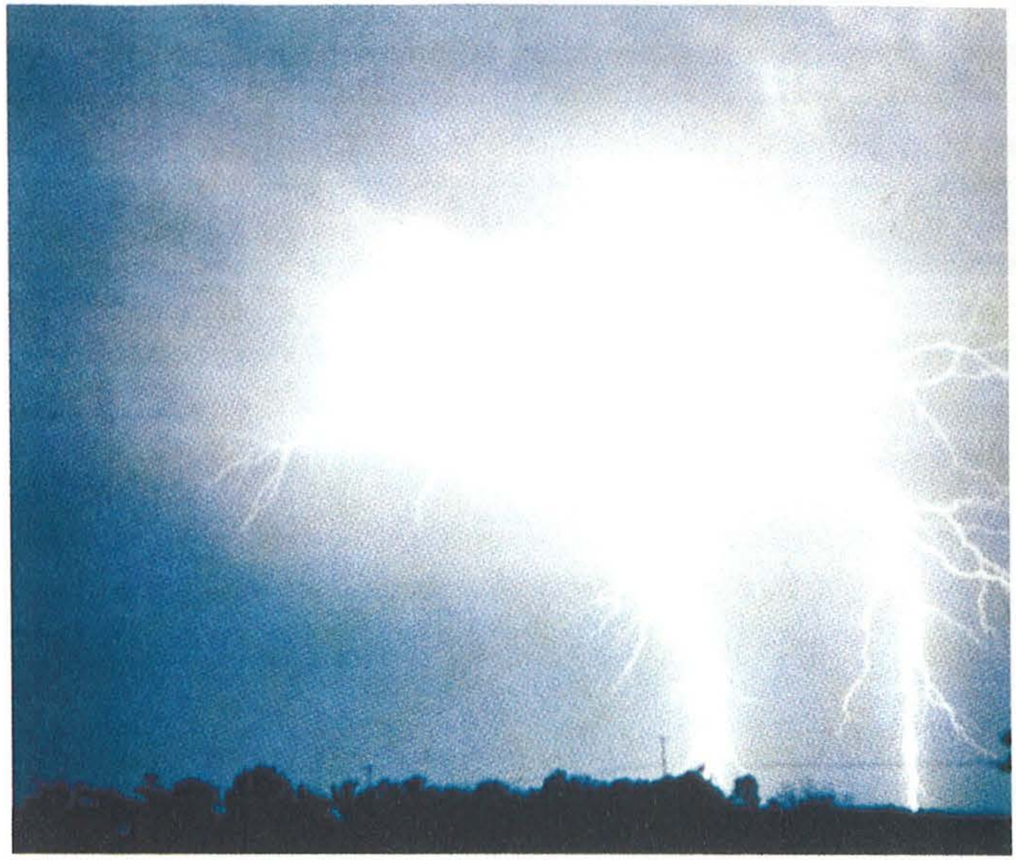


Fig. 1 Cloud-to-ground lightning stroke. The direction of the discharge can be identified by the direction in which the lightning stroke branches.

Fig. 2 Aurora photographed at 43° north latitude in Wisconsin.

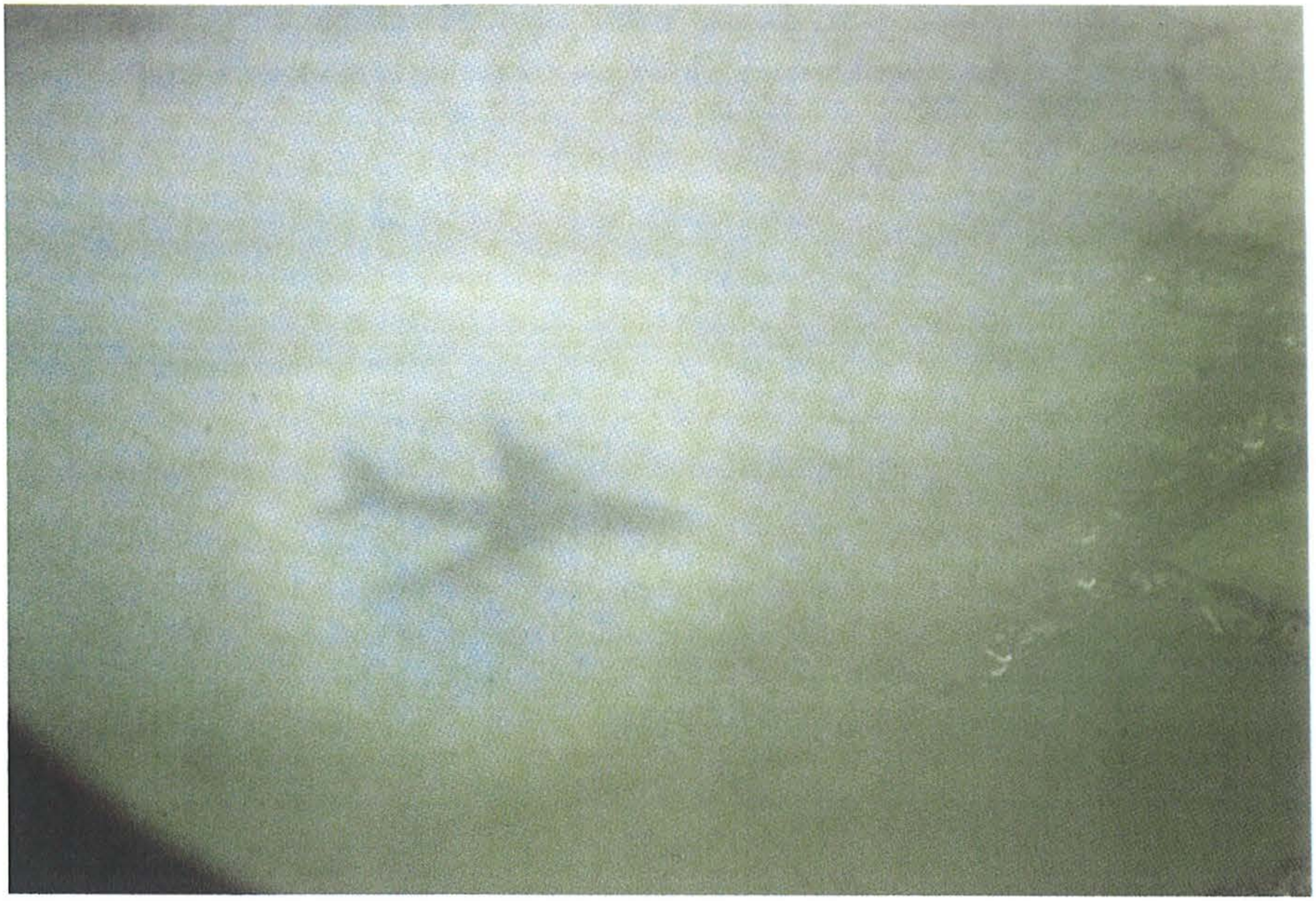


Fig. 3 The glory around the airplane shadow on a thin cloud layer. Note that the rings are centered about the personal anti-solar point of the photographer, showing him to be seated right behind the wing (in the tourist section).

The irridescence of clouds lying in a direction near that of the sun is somewhat better understood. Fig 4 pictures a beautiful display in a cloud only a few degrees from the sun. This effect is actually quite common but is not observed readily by most people because of the dazzling brightness of clouds near the sun. However, when I look at the reflection of the sky in water puddles or car windows, the resulting reduction in light intensity makes it easy for me to see these colors. They seem to be satisfactorily explained as resulting from diffraction by small water drops or ice crystals. In a sky veiled over with a cloud of uniform-sized particles, the effect could produce colored rings around the sun. In this situation the angular diameter of a ring depends on both the particle size and the wavelength. The small, colored rings frequently seen around the moon are explained in this way. In an isolated cloud the particle size is not constant but may be smaller for particles evaporating on the edges of the cloud than for particles in the interior. In this situation the appearance of a particular color is determined both by the angular distance from the sun and the varying particle size within the cloud.

Fig. 4 Irridescent cloud, a few degrees away from the sun.

What beautiful optical effects of the sky have you seen? Certainly many people would cite the rainbow (see Fig. 5). Attempts to explain the origin of rainbows form the theme of rainbow myths and legends common to most cultures. In more modern times, the list of well-known scientists who have contributed to the understanding of this beautiful bow is quite impressive; Descartes, Newton, Bernoulli, Halley, Airy and many others. Indeed the rainbow is a spectacular display and could well be the subject of this entire article, but I have chosen differently. From March 1973 to March 1974, I kept records which show that in the course of my usual daily rounds during this year I saw natural rainbows on only three different days. (By natural rainbows I mean the usual bows appearing in the sky, opposite the sun. Those of us who are really hooked on rainbows see them in the spray from waterfalls, fountains, lawn sprinklers, breaking waves, water thrown up on wet roads by automobile tires and dew drops suspended from spider webs.) On the other hand I saw some halo phenomena, resulting from light passing through small prisms of ice in the atmosphere, on 78 different days! Most of the time I work inside, in an office or lab with no window, so I am sure that these effects were visible a number of other times as well. If you have never seen any of these effects, you have a treat in store! Let me describe the origins of some of these effects in more detail.

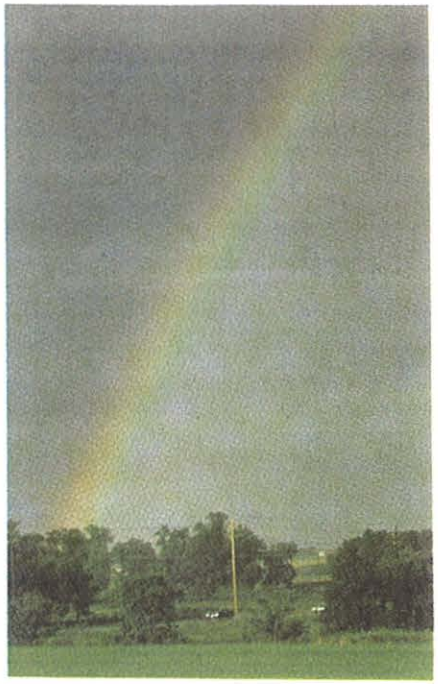


Fig. 5 Rainbow. Note that the sky background inside the bow is brighter than outside. This is a standard feature of rainbows which you can easily observe.

Ice crystals in the form of hexagonal prisms (See Fig. 6) frequently exist in the atmosphere. Even in the summertime, the air temperature at moderate altitudes is below freezing and we can see ice clouds. An amazing variety of optical effects result from light which is refracted in passing through these crystals or which is reflected from their surfaces. Fig. 7 shows that light passing through alternate faces of a hexagonal ice crystal, will be refracted exactly as if it were passing through a 60° prism of ice. Rays passing through the prism are deviated through an angle which depends on the orientation of the prism. For rays passing through a principal section of a 60° ice prism (i.e., traveling in a plane which is perpendicular to the refracting edge) there is a minimum angle of deviation of 22°. Rays which strike the face of the prism with greater or smaller angles of incidence than the minimum-deviated ray are refracted through larger angles than 22°. If a large number of prisms are present, with all different orientations, there would be a concentration of light refracted near this minimum angle of deviation.Suppose the sky were filled with ice crystals of all different orientations, where should we look to see light deviated by 22° in its passage through these crystals? Fig. 8 shows that we should see this light coming from a direction 22° away from the sun; that is, from a circle around the sun, with an angular radius of 22°. This is the 22° halo which, if you look will become quite familar to you. The halo is shown in Fig. 9. The red inner edge results from the fact that the minimum angle of deviation for red light is less than for other colors, so the red circle is smaller than those formed by the other colors.

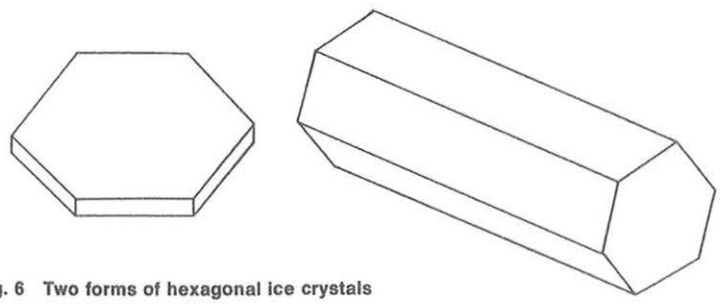


Fig. 6 Two forms of hexagonal ice crystals occuring in the atmosphere.

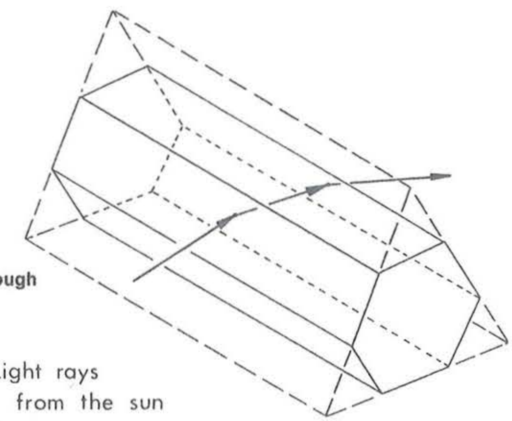


Fig. 7 Light ray passing through a hexagonal ice prism.

Fig. 9 The 22° halo around the sun.

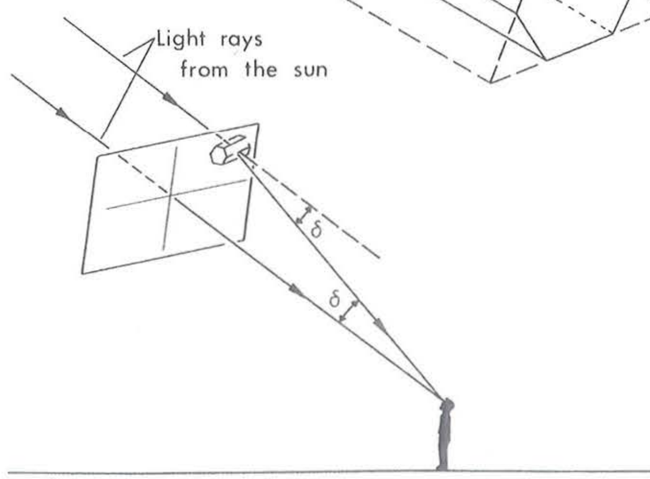


Fig. 8 An observer viewing a ray of light which is refracted by an ice crystal.

To get the complete halo we need to have all orientations of ice crystals present in the sky, so that at each part in the halo, there are some crystals present with the correct orientation to refract light to the eye. However the ice crystals do not always tumble with random orientations as they fall. The flat-plate crystal shown in the sixth figure will tend to fall with its axis vertical, the flat bases oriented nearly horizontally. (If this seems strange think of the way a leaf drifts to earth.) Given a skyful of ice prisms with their axes vertical, we would not expect to see the entire halo. With the sun low in the sky, these plate crystals would have the proper orientation to refract light from the sides of the halo to the observer, but not from the top of the halo. The effect is shown in Fig. 10. The better the orientation of the ice crystals, the smaller and brighter are the resulting spots on either side of the sun. In some cases they can be quite bright and of an apparent size comparable to that of the sun. Folk sayings have several names for these bright spots: false suns, mock suns, or sun dogs. Scientific folk sometimes call them parahelia. Figure 11 shows a typical pair of sun dogs flanking the sun. In this picture you can see a tail of white light extending outward from each of the sun dogs. This is the result of the rays that pass through the ice prism at angles other than minimum deviation. All the colors overlap here giving a streak of white light.

Frequently we can observe both the 22° halo and the sun dogs together. For higher elevations of the sun, the sun dogs move outside of the 22° halo. This effect can be seen in Fig. 14C, along with some other effects which I will discuss later. In such a case the light rays do not pass through a principal section of the ice prisms but are skew rays. The angle of minimum deviation increases for skew rays, accounting for the separation between halo and parahelia. The same explanation suffices for another effect familiar to many spectroscopists: a prism spectrograph produces curved spectral lines when a straight entrance slit is used. The rays from the ends of the slit go through the prism as skew rays and are deviated more than rays from the center of the slit.

Fig. 10 A limited portion of the 22° halo, which might be called a diffuse sun dog.

Fig. 11 Sun dogs on either side of the sun.

There are two ice crystals shown in Fig. 6. They are both hexagonal prisms but they differ in ratio of length-to-width. I call the long, thin crystal a pencil crystal, due to its resemblance to a common wooden pencil. Under different temperature conditions, crystal growth may be more rapid on the side faces or on the end faces of the crystal, producing in one a plate crystal and, in the other a pencil crystal. Pencil crystals falling in still air tend to become oriented with their axes horizontal. (Throw a blade of grass in the air and see how it falls.) What kind of display in the sky should we see from light passing through these ice prisms with their refracting edges nearly horizontal? This seemed to be a much more difficult question than the one about the distribution of plate crystals which produces sun dogs. We decided to apply some of our modern technology to answer this question. We can write down a set of equations which describe a light ray going through an ice crystal, as illustrated in Fig. 7. The equations are written for an arbitrary orientation of the crystal and elevation of the sun above the horizon. The only physical principle needed to determine the direction of the ray after it leaves the crystal is the law of refraction (Snell's Law) applied both when the ray enters and when it leaves the crystal. The resulting general expression is quite hairy and, were it not for the existence of modern computers, we would probably have given up at this point. However the computer can be fed this general expression and instructed to do the calculation 100,000 times for 100,000 different orientations of the crystal. Knowing the direction of the light ray leaving the crystal is equivalent to knowing where to look in the sky for light coming to your eye from a crystal with that particular orientation. We can construct our own computer picture of the resulting effect by putting a spot on a paper corresponding to the place in the sky from which each light ray comes to the eye. The resulting spot diagram should represent the intensity pattern in the sky which we expect to see from a cloud of ice crystals having the distribution of orientations we have chosen for our calculation. Actually, to obtain a good picture of the effect we have to concern ourselves with another set of details. Different amounts of light will get through

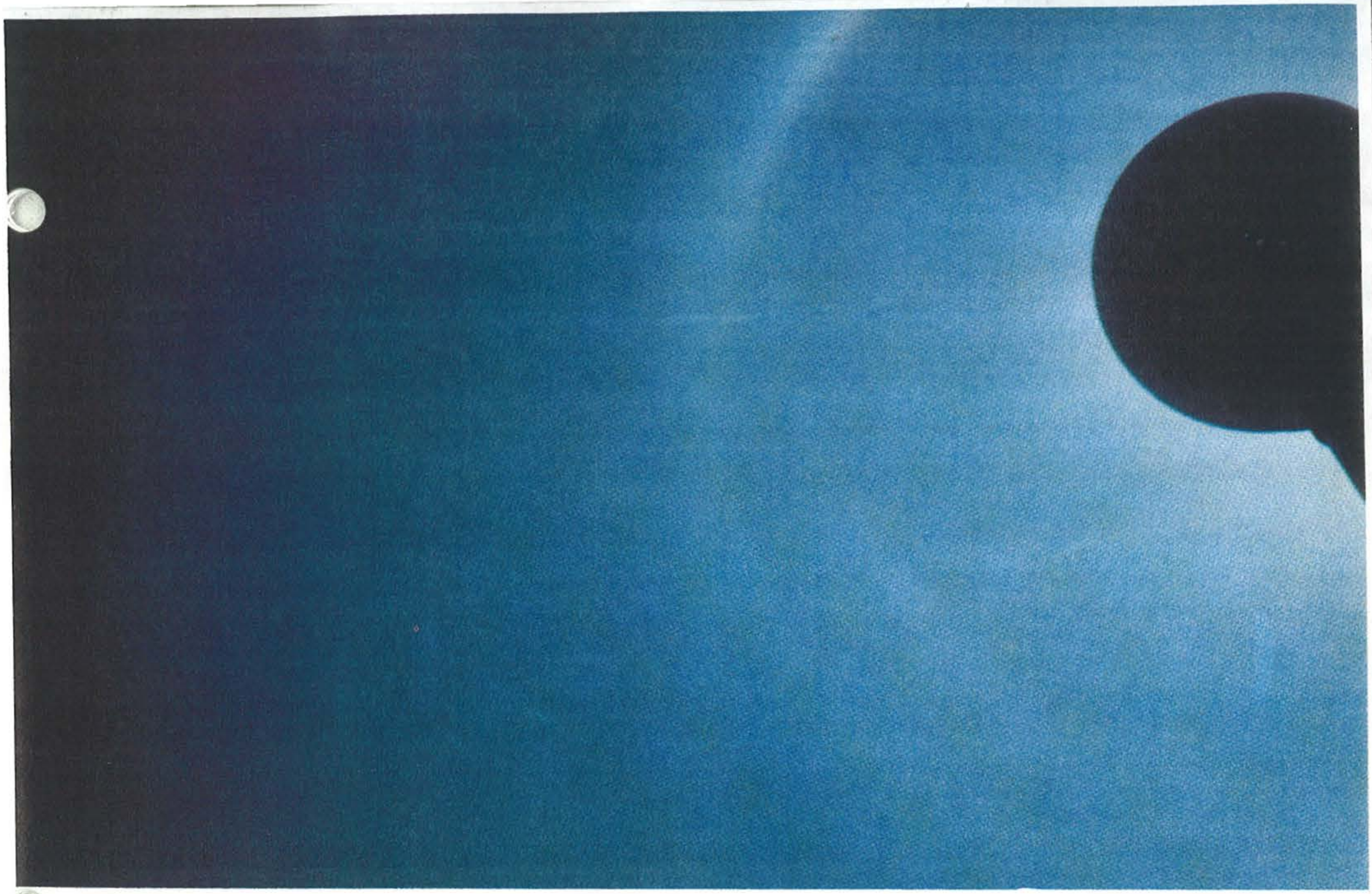


Fig. 12 The parahelic circle along with the 22° halo and the circumscribed halo.

crystals with different orientations. Two kinds of factors determine how much light is transmitted by the crystal: one is the cross section of the incident light beam which enters the entrance face and impinges on the exit face inside the crystal; the other concerns the light lost by reflection at both the entrance and exit faces of the crystal. The first factor is a matter of geometry. We consider a pencil crystal to be long compared with its width and we calculate the cross-sectional area of the entrance beam that gets through the crystal for an arbitrary orientation of that crystal. The transmitted beam is limited both by the entrance face and by the exit face and we can calculate just how these faces affect the transmitted beam area. The second factor is not difficult to calculate. The reflection loss at each surface depends only on the index of refraction of ice and the angle of incidence of the light on the surface. These two factors combined give us a relative intensity factor for the light transmitted by the crystal in every different orientation. How can we take account of the varying intensities of the rays when the presence of a ray is represented by a spot on our spot diagram? One possibility would be to vary the size of the spots according to their calculated intensities. Another approach seemed to be more convenient; we take account of relative intensities by using these calculated values to discard an appropriate number of the points whose positions we have calculated. For example, if we calculate an intensity factor of 0.4, we will play a game of chance to decide whether or not to plot that point. The dice will be loaded in this game to give only four chances out of ten that the point will be plotted. The game of chance is actually done mathematically in the computer by comparing the intensity factor with a random number between zero and one. Only where the factor is smaller than the random number does the point get plotted.

We started with the relatively simple case of a distribution of ice crystals having exactly horizontal axes but with random rotations about that axis and random orientations of the axis in a horizontal plane. (See Fig. 15.) Some of the results of the computer simulation are shown in Fig. 13 for different elevations of the sun. In each case a 22° circle is drawn in for reference and the horizon is represented by a heavy line. For low sun elevations there are separate arcs, tangent to the 22° halo, above and below the sun. When the sun is at an elevation above the horizon greater than about 40°, the upper and lower tangential arcs join to form another complete halo about the sun, the circumscribed halo. In Fig. 14 are photographs showing the upper arc and circumscribed halo for comparison with simulation. In the pictures of Fig. 14 , the 22° halo can be seen along with the tangential arcs and circumscribed halo, probably indicating a layer of oriented crystals at one altitude and a layer of crystals with no preferred orientation at a different altitude. With the sun nearly on the horizon the upper arc in Fig. 14A is in the form of a V and is well represented by the simulation for sun angle 0°. Figure 14B shows that at a sun elevation of about 20°, the upper arc has flattened to the shape predicted by the simulation. In this picture the arc is only clearly visible on one side. Figure 14C taken with a very wide-angle lens shows both the upper and lower arcs and a trace of the circumscribed halo for the sun elevation of 40°. Figure 14D represents my solution to taking a wide-angle picture before I had a wide-angle lens. The picture is a reflection of the sky in a reflecting sphere which is sitting on the ground. (The reflecting sphere is not a very sophisticated optical element—it is a Christmas tree ornament.) The tripod and camera, of course, show in the picture and the entire 360° horizon is included in the circle. An artifact of this wide-angle view is that the 22° halo is compressed vertically and so is not circular on the picture. The two halos can be seen to be separated on the sides in the picture. (The presence of the author in that picture may be interpreted either as a/ him using his head to avoid lens flare from the sun or b/ pure vanity.)

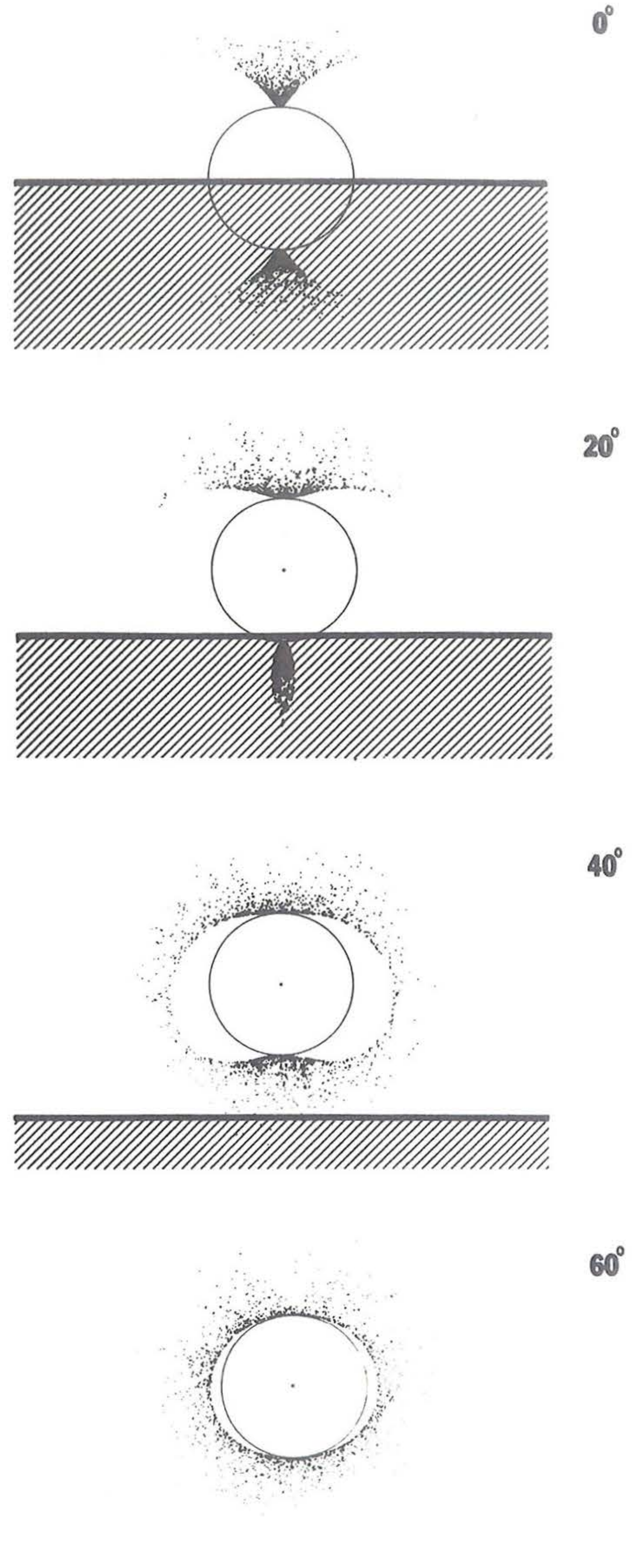


Fig. 13 Simulation of the circumscribed halo for different elevations of the sun. The circle marks the inner edge of the 22° halo and the heavy horizontal line represents the horizon.

Fig. 14 Photographs of the circumscribed halo for elevations of the sun matching those given in Fig. 13.

When the sun has a low elevation, the lower tangential arc shown in the simulations lies below the horizon. Normally when you look below the horizon you will see only the ground in front of you; but, if you were to look down from an airplane into an ice cloud containing the oriented pencil crystals, you should be able to see the lower arc. In fact it has been seen and photographed.

The conclusion we reached by comparing such simulations with a number of photographs is that the model we have used explains the shape and intensity distribution of the tangential arcs and circumscribed halos in quite good detail and indeed appears to be the correct explanation for these beautiful effects.

We have seen that light passing through the hexagonal crystal as in Fig. 7 is effectively going through a 60° prism. Note that light going into a side face of the crystal and emerging from the ends (or vice versa) is going through a 90° prism. Visible light cannot ordinarily pass through a 90° glass prism but it can go through the lower refractive index prism of ice, with a 90° prism angle. The angle of minimum deviation for this case is 46° and by the same argument previously advanced, we would expect a 46° halo. Indeed, it is seen; not as frequently as the 22° halo, but neither is it very rare. In Wisconsin, I see portions of it a few times a year. Of course, special orientation of either plate or pencil crystals can give rise to a number of arcs, resulting from the 90° refraction angle. A number of the rarer effects are still poorly understood. Without exhausting the wealth of effects which can be explained by refraction through these hexagonal crystals, let me describe some effects which result from reflection of light from the surface of these same kinds of ice crystals.

When plate crystals fall with their axes vertical the six side faces are oriented vertically. What would you expect to result from light reflected from the side faces? Consider the effect of a sky filled with little vertical mirrors. To see a reflection of the sun in a vertical mirror you would always have to look up at an elevation angle equal to the sun's elevation. The band of reflected light seen at a constant elevation above the horizon is in the form of a circle around the sky. It is parallel to the horizon and passes through the sun. Since it is a reflection effect, we would expect the circle to be white without the kind of colored edges introduced by refraction. I'm really going about the explanation process backward. The parahelic circle has been observed, presumably before men recorded any observations of it, and the description of its formation, which I have just given, followed the observation. Figure 12 shows a section of the parahelic circle along with the 22° halo and the circumscribed halo. In the photograph the parahelic circle appears to be curved but this is just the effect you would get if you photographed a section of a large horizontal hoop suspended over your head. Since the sun dog is quite faint in this picture, it is probable that the parahelic circle here results from the end faces of the same horizontal pencil crystals which give rise to the circumscribed halo. These end faces would be oriented vertically and could also give rise to the reflected circle of light.

Several other reflection effects are frequently observed. When you fly in an airplane over ice clouds, often you can see a bright spot in the clouds below the sun. (See Fig. 16.) It is called the sub-sun and can be understood as a reflection of the sun in the nearly-horizontal faces of oriented plate crystals. From the angular dimensions of the spot, we can deduce the degree of orientation of the surfaces. Measurements which I made on one photo indicate that the reflecting surfaces were oriented horizontally to within about one half of a degree!

Fig. 16 The sub-sun as seen from an airplane.

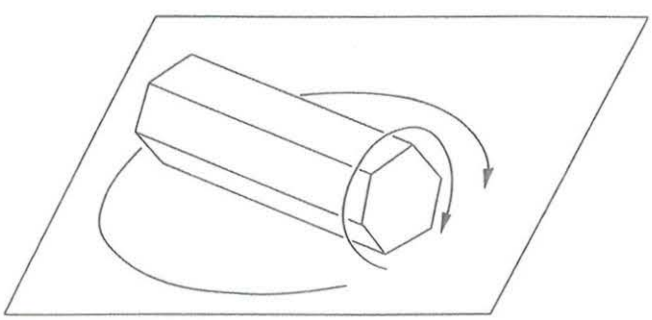


Fig. 15 An illustration of the orientation of the pencil crystals which are used in the circumscribed halo calculation.

Fig. 17 A sun pillar, above the setting sun.

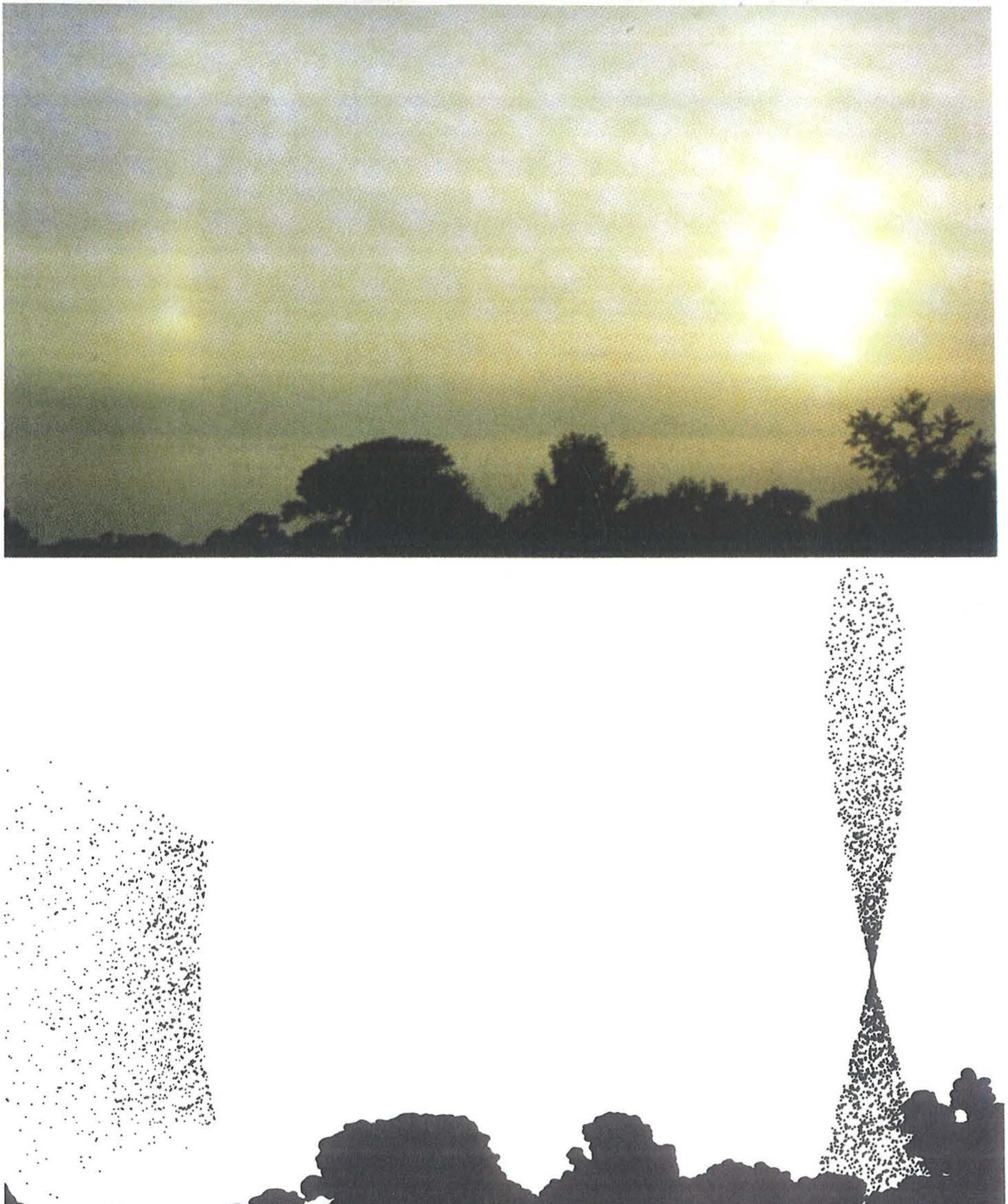


Fig. 18 (Top) Photograph of sun pillar and sun dog. (Bottom) Simulation, assuming that the two effects result from reflection and refraction by the same set of flat-plate ice crystals.

Sometimes, when the sun is low in the sky, we can see a vertical column of light rising above or extending below the sun. Fig. 17 shows such a typical sun pillar. For many years it was assumed that the sun pillar resulted from the light which was reflected from the base surfaces of oriented plate crystals having only small tilt angles from the horizontal. According to such an explanation, sun pillars would be analagous to the elongated image of the sun or of street lights when seen by reflection from a somewhat rough water surface. The explanation seemed reasonably satisfactory, but not entirely so. We decided that with this simple model we could use our computer simulation technique to predict the shape of sun pillars and to see how this shape depends on the degree of crystal orientation and on the elevation of the sun. We also wondered whether the horizontally oriented pencil crystals might possibly give rise to sun pillars. We considered the reflection from the faces of crystals with all the orientations indicated in Fig. 15 and, surprisingly enough, the simulations showed sun pillars which seemed to match some observations better than the conventional explanation. We planned to do both simulations for different sun altitudes and for different degrees of crystal orientation and see which model fit the observations best. But we came up with another way to demonstrate the correct explanation for sun pillars.

Figure 18 shows a photograph of a sun pillar plus a sort of an elongated sun dog on one side. It looks as if both of these effects could be explained by the presence of partially oriented plate crystals. We picked a distribution of plate crystals which would produce, with our simulation, a sun pillar of the height shown in the photo. Then, *through this same distribution of ice crystals*, we traced the refracted rays to see if we would get a sun dog which matched the extent of the one in the photograph. The agreement with the picture convinced us that here is a sun pillar produced by plate crystals (as had been suggested). However Fig. 19 shows another photograph including a pillar and an upper arc, that look as if they might result from pencil crystals. By considering both the reflected and the refracted light through the same group of pencil crystals with horizontal axes, we produced the simulation of Fig. 19 which agrees in amazing detail with the picture, leaving little doubt that sometimes, pencil crystals can also produce beautiful sun pillars.

It would appear that the computer simulation approach may be quite helpful in explaining other such effects. Keep in mind, however, that good photographs are essential to the explanation and that I am interested to see your contributions.

What I have discussed is only a beginning. I hope it stimulates some of you to look and to see things you have not seen before.

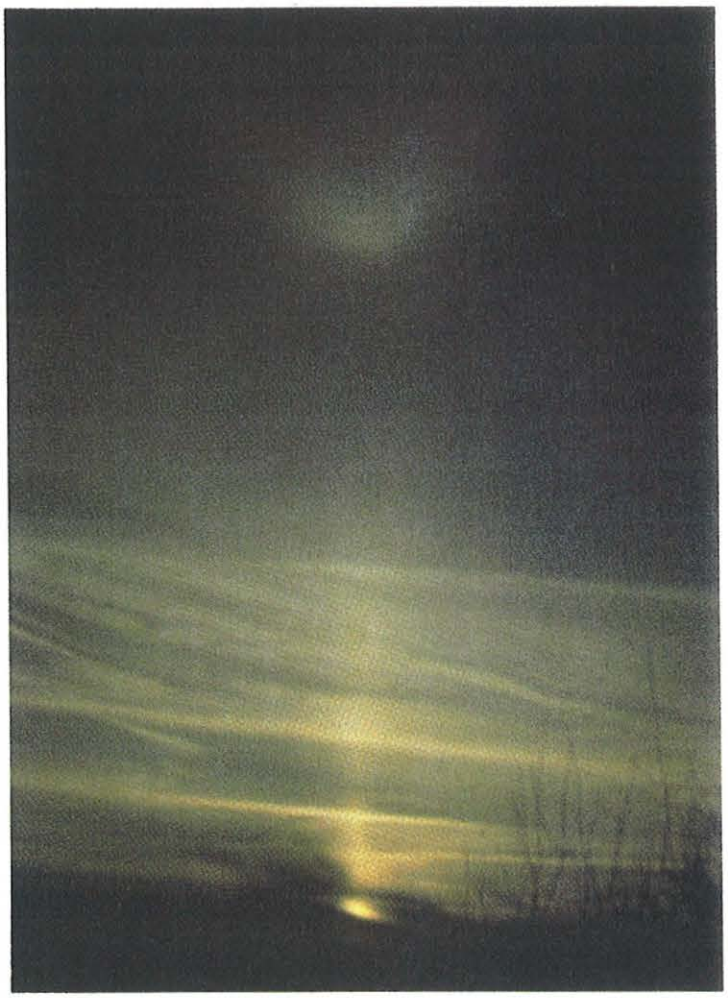
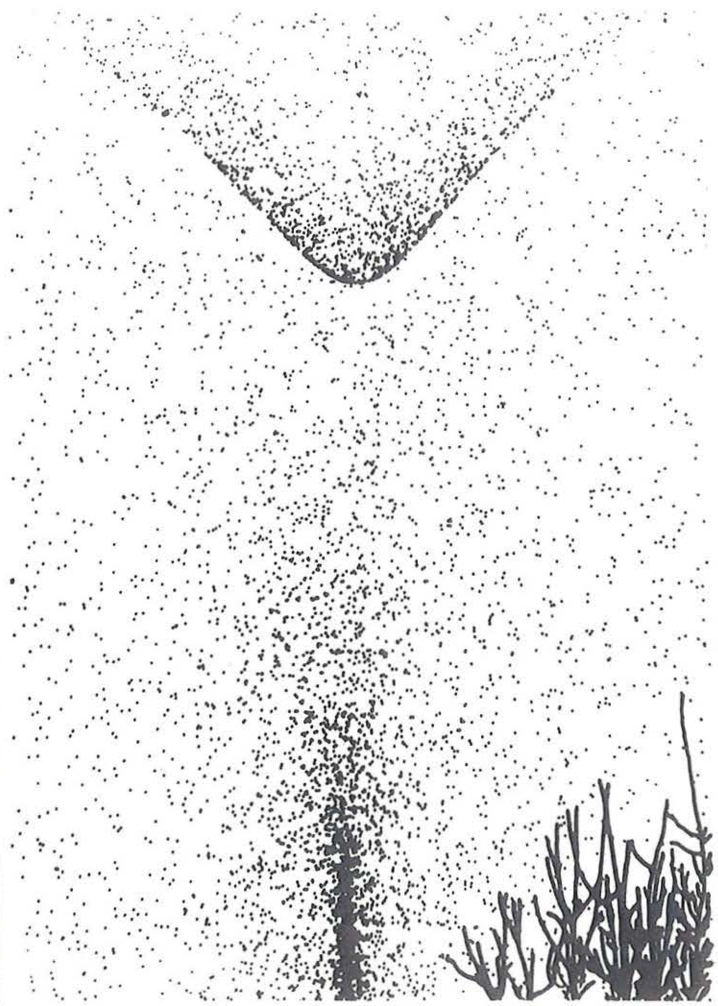


Fig. 19 Photograph of sun pillar and upper tangential arc.



Simulation, assuming that the two effects result from reflection and refraction by the same set of pencil ice crystals with horizontal axes.

The photograph in Fig. 19 was taken by Mr. James Mallmann of Milwaukee, all others were taken by the author.

The following books are good sources of information about optical sky effects:

Light and Color in Open Air by M. Minnaert (Dover Publication, New York, 1954).

Physics of the Air by W. J. Humphreys (Dover Publication, New York, 1964).

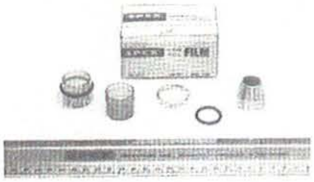
Introduction to Meteorological Optics by R. A. R. Tricker (American Elsevier Publishing Co., New York, 1970).

The Glory is the subject of a recent article in Scientific American (July, 1974).

For more details about the computer simulation work see:

The Origin of Sun Pillars by R. G. Greenler, M. Drinkwine, A. James Mallmann, and G. Blumenthal, American Scientist *60*, 292-302 (1972).

Circumscribed Halos by R. G. Greenler and A. J. Mallmann, Science *176* 128-131 (1972).



X-RAY CELLS & CAPS

PressuReactor

CZERNY-TURNER SPECTROMETERS

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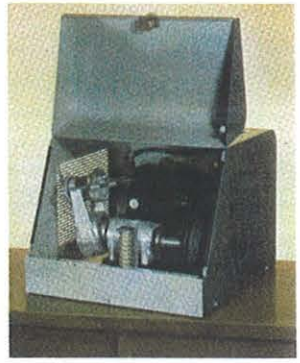
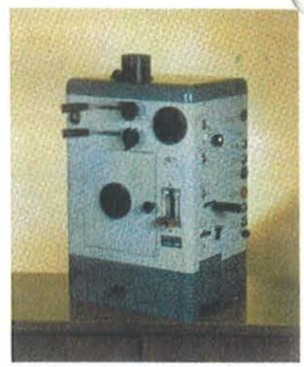


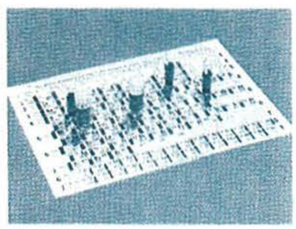
MIXER / MILLS



ARC/SPARK STAND

FREEZER / MILL

WIG-L-BUG



HIGH PURITY INORGANICS

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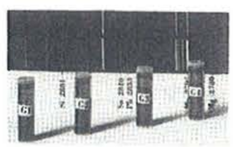

SPEX MIX & STANDARDS

MASTER PLATES

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