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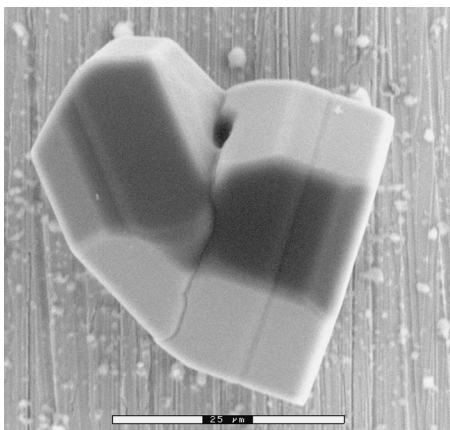
## Other Wedge Angles?

So far in this book we have studied halos made by ice crystals having prism, basal, and  $\{10\bar{1}1\}$  pyramid faces. These crystals have the familiar wedge angles listed in Table 8.1. Could there be other wedge angles on ice crystals? If so, then there might be other halos as well. What (contemporary) evidence is there for the existence of new wedge angles?

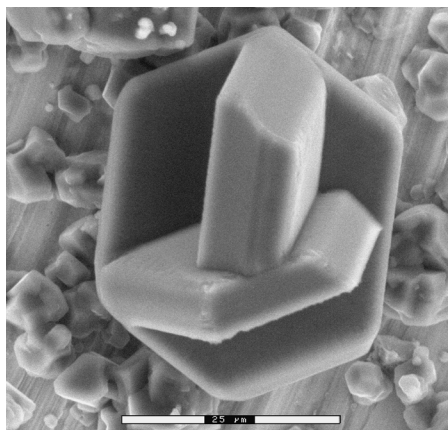
The most obvious way of getting new wedge angles is to have new crystallographic faces, that is, faces other than prism, basal, and  $\{10\bar{1}1\}$  pyramid faces. In looking at countless atmospheric crystals, we have not seen evidence for such faces. However, there are many complex or small crystals where it is difficult to identify the faces crystallographically. Moreover, we do not feel that in our observations we have yet exhausted the variety of crystals. New crystallographic faces may yet turn up.

In any case, new wedge angles do not require new crystallographic faces. Figure 18.1 is an example. It shows a polycrystal, that is, a “crystal” made up of two or more component crystals. Any wedge whose two faces are in different components is apt to have a novel wedge angle.

Polycrystals are common in some crystal samples, but they are relevant to halo theory only if the component crystals are joined to each other in some systematic way from one polycrystal to the next, so that the same novel wedge angle can occur in many crystals and thus perhaps make a halo. For polycrystals similar to that in Figure 18.1, in which the components of the polycrystal are more or less equidimensional pyramidal crystals, we have so far recognized no underlying crystallographic principle that controls the joining of the components; rather the components seem to be joined randomly. We therefore do not expect to get new halos from these crystals.



**FIGURE 18.1** Polycrystal whose components are pyramidal crystals. Photo © Kenneth P. Severin.



**FIGURE 18.2** Crossed pyramidal plate crystal, a candidate for novel wedge angles. Photo © Kenneth P. Severin.

The polycrystal in Figure 18.2 is another story. It consists of three crossed pyramidal plates joined in a very definite way. In fact, the line of intersection of any two of the plates is parallel to an  $a$ -axis in each, and this implies that the orientations of the plates with respect to one another are fixed.<sup>1</sup> Crystals like these would make new halos if they were large enough and occurred in sufficient numbers.

Thus the ice crystals themselves suggest the possibility of wedge angles other than those that make the standard odd radius halos that we have considered so far. Halo displays also give strong evidence for new wedge angles, as we will see momentarily.

## M-arc

Given that the modern theory of halos is several centuries old, it may come as a surprise that there are halos still unexplained. Perhaps even more surprising is the fact that new halos are still being reported from time to time. The M-arc is such a halo. The oldest record of it that we are aware of consists of a photograph by Jon Nickles in Anchorage, Alaska, in 1978 and published in *Alaska Geographic* [1, page 54]. The significance of the photo was not recognized until later, after Moilanen [47] had called attention to the existence of the new halo in displays from Finland and elsewhere.

In the photos in Figure 18.3 the M-arc is the vee-shaped arc above the sun and well inside the  $22^\circ$  halo. It might be mistaken for an upper  $9^\circ$  plate arc, but

<sup>1</sup> Kobayashi and Kuroda [36] offer some explanations for this configuration.



**FIGURE 18.3** M-arc, the vee-shaped arc directly above the sun. (*Top*) Viitasaari, Finland, January 8, 1999. Photo © Rainer Vilkkilä. (*Bottom*) Anchorage, Alaska. Photo © Evelyn Trabant.

neither the shape nor location is quite right. Moreover, a  $9^\circ$  plate arc as bright and sharply defined as these M-arcs would be expected to be accompanied by other odd radius plate arcs, which we do not see in the photos.

The M-arc can easily be simulated using a wedge having wedge angle  $\alpha \approx 34^\circ$ , but what real ice crystals have such a wedge angle? Crossed plate crystals do, and so do various other polycrystals. Simulations made using these crystals can passably reproduce the M-arc, but they tend to produce other halos as well, halos that are not seen in the real displays. The M-arc remains an open problem.

Whatever its explanation, the M-arc seems to be an example of a “doubly odd radius” halo, that is, a halo that cannot be produced by our standard Steinmetz and Weickmann pyramidal crystal model (Figure 9.5).

## The Lascar display

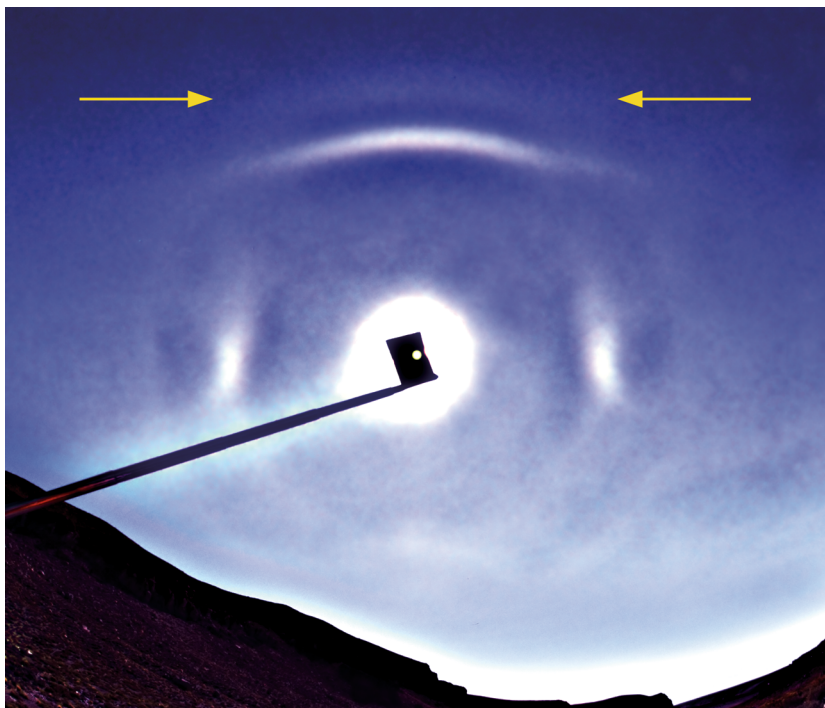
The remarkable Lascar halo display was seen by Marko Riikonen, Leena Virta, and Daniel Sullivan while camped on the flanks of Lascar volcano in northern Chile in 1997. Both Riikonen and Virta were members of the Finnish Halo Observers Network, and they had the halo expertise to appreciate what they were seeing. They managed to take approximately 100 photographs of the display over the course of two days. One of their photos is reproduced in Figure 18.4.

Without describing the display in detail, we will just say that it seems to contain at least one doubly odd radius halo. In fact, one after another of the Riikonen–Virta photos shows an arc with  $\Delta_{\min}$  somewhere around  $28^\circ$ —nowhere near the standard  $\Delta_{\min}$ -values of Table 8.1. In Figure 18.4 this arc appears faintly in the 12:00 position at the level of the two yellow arrows. Suggestions of a  $28^\circ$  circular halo are also present, especially to the left and right of the sun.

Riikonen et al [62] analyzed the Lascar display and concluded that many of the halos were odd radius plate arcs from standard pyramidal crystals, as in our Chapter 15, but that other halos, in particular the  $28^\circ$  arc, were due to a rare variety of ice known as cubic ice. Cubic ice has internal symmetry that is cubic (isometric) rather than hexagonal, and cubic ice might therefore come in cubeoctahedral crystals, that is, crystals having cubic and octahedral faces. It was these cubic and octahedral faces that gave Riikonen and his colleagues the wedge angles that they needed to reproduce the strange halo radii in the Lascar display. Using cubeoctahedral crystals together with standard pyramidal crystals, they were able to make simulations that approximated the Lascar photographs.

We—Tape and Moilanen—disagree with each other somewhat on the explanation of the Lascar display. Moilanen, who was one of Riikonen’s coauthors, believes that the cubic ice explanation may yet turn out to be correct, though he sees some weaknesses in it. Tape is nervous about the cubic ice explanation for



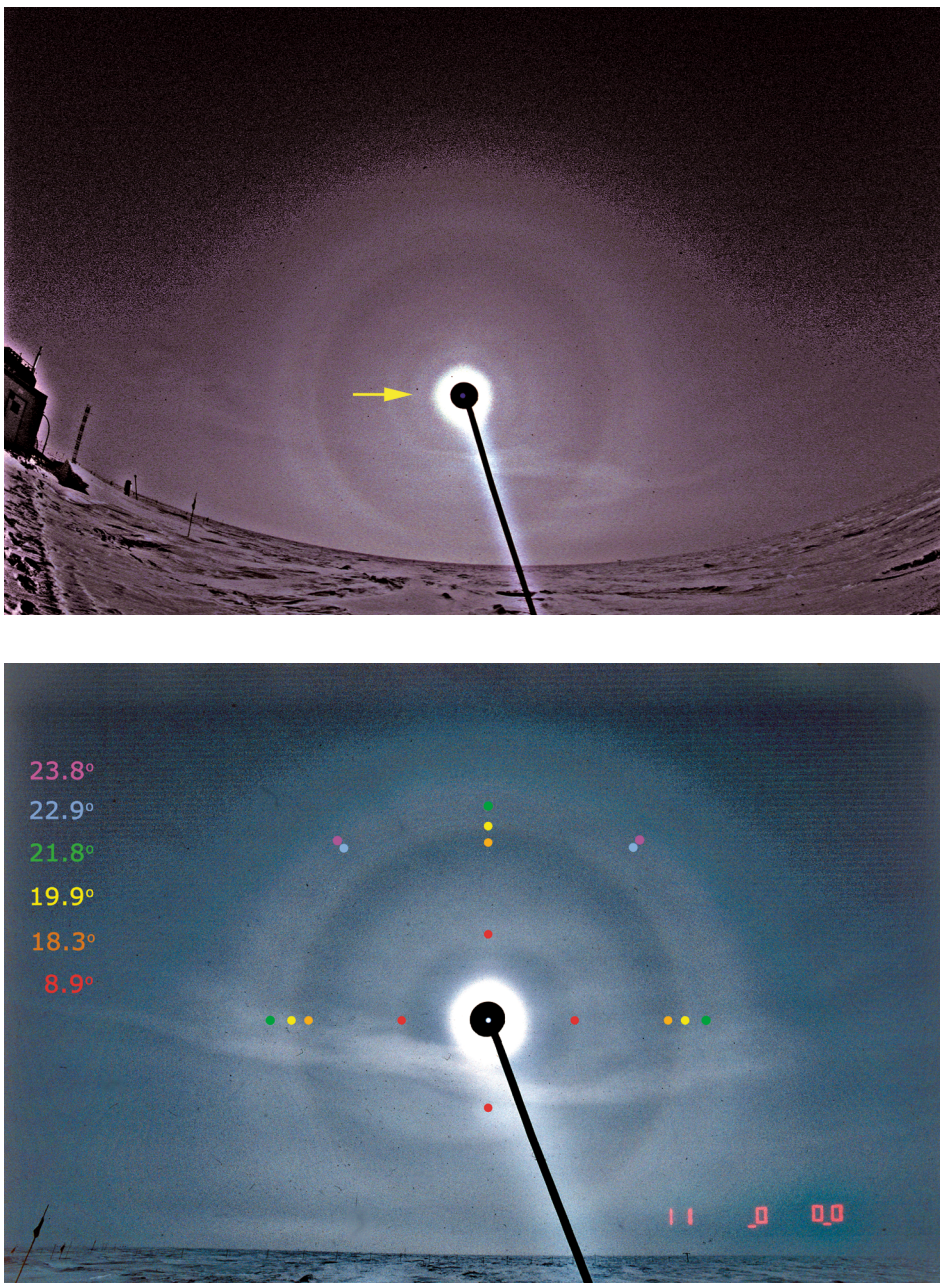


**FIGURE 18.4** Strongly enhanced photo of the Lascar halo display. Riikonen et al [62] believe the bright arcs here to be  $18^\circ$  and  $23^\circ$  plate arcs. The faint arc between the arrows is a “doubly odd radius” arc. Here it almost looks like an artifact of the enhancement, but it also appears clearly in the original slide. November 27, 1997. Photo © Marko Riikonen.

several reasons, but he does not have much in the way of concrete alternatives to offer. He is haunted by the seemingly outlandish possibility that the halo-making crystals might not be ice at all. In any case, regardless of who is right, the explanation of the Lascar display seems to require something other than our standard pyramidal crystal.

In passing we mention Scheiner’s halo, a circular halo that is supposed to have a radius of  $28^\circ$ . Well before the Lascar display, Whalley [89] had suggested that cubic ice might be responsible for Scheiner’s halo. Whalley’s article lists half a dozen reported sightings of the halo, including the original sighting by the astronomer Christopher Scheiner at Rome in 1629.

We find these reports to be unconvincing. All of them are old. Several can easily be dismissed as sightings of incomplete tangent arcs. Scheiner’s observation itself seems to be lost, and what is usually cited instead is a description and drawing by Gassendi [19], with whom Scheiner had corresponded. Until the Lascar display, we ourselves did not believe in a  $28^\circ$  halo, and we are still not convinced that the Lascar display has any relation to these old and suspect reports.



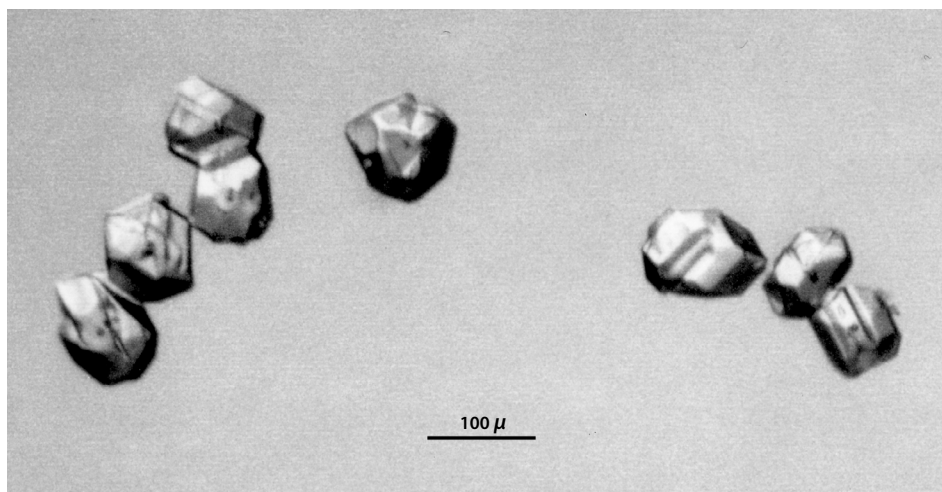
**FIGURE 18.5** Puzzling halo display, South Pole, December 10-11, 1998. The brightest halo is a  $20^\circ$  halo. Nearest the sun in the upper photo is a five or six degree halo (arrow), then next a  $9^\circ$  halo. The colored dots in the lower photo are at the indicated angular distances from the sun (the first six  $\Delta_{\min}$ -values from Table 8.1). The dots are reference points only; there may or may not be a halo nearby. The upper photo was taken with a 15 mm lens, the lower with a 20 mm. Both are strongly enhanced with digital unsharp masking. The apparent halo about  $28^\circ$  above the sun is largely an artifact of the enhancement.  $\Sigma=23^\circ$ .

## 5° Halo

In a murky overcast sky at the South Pole in December of 1998, we watched an odd radius display evolve over the course of a couple of hours. We photographed the halos, and we collected and photographed low level atmospheric crystals. However, due to the overcast conditions and the resulting absence of sparkles, we could not be sure that the halos were originating in low level crystals, and we therefore could not be sure that the crystals that we collected were representative of those making the halos. Some of the halos are shown in Figures 18.5 and 18.7, and some of the crystals are shown in Figures 10.8 and 18.6.

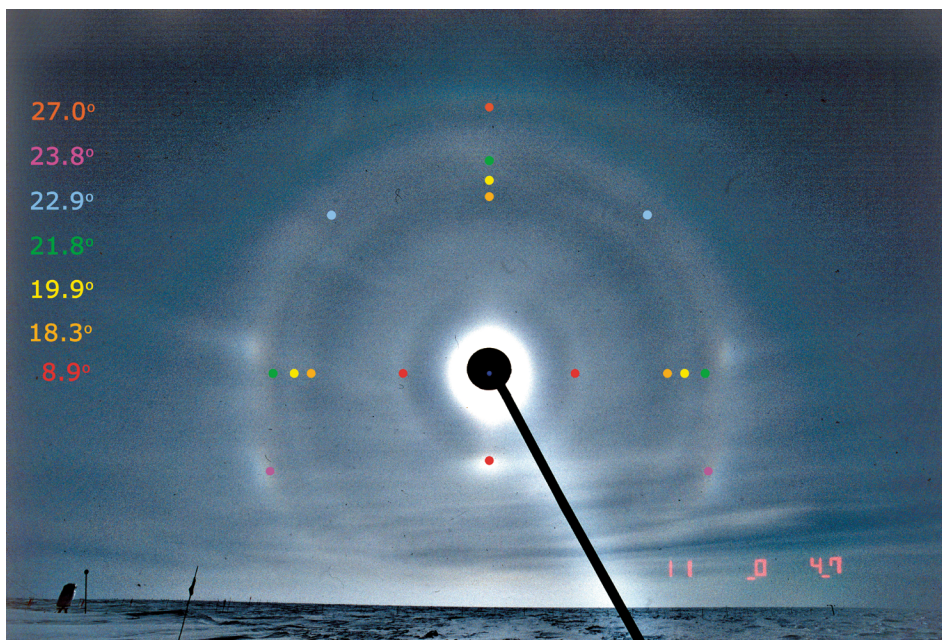
At the time of the display we thought we knew what we were seeing, but upon returning home and developing the film, one of us—Moilanen—noticed in many of the slides a 5° halo and perhaps a 12° halo, neither of which we had recognized earlier. These halos would of course be further examples of doubly odd radius halos. The 5° halo is quite clear in many of the original slides, being thin and sharply defined, and we hope that it will survive reproduction in Figure 18.5. The 12° halo is much fainter and more diffuse, if indeed it exists at all. Perhaps Figure 18.7 has a suggestion of it?

More surprises were yet to come. We had assumed that the brightest and most conspicuous circular halo in the display was the 18° halo, but measurements of the halo radius from the photos proved otherwise. This is clear from the lower photo in Figure 18.5, where the colored dots are at the indicated angular distances from the sun. The sunward edge of the halo in question is nearly at the yellow dots, which are about 20°, not 18°, from the sun. (Our 15 mm lens is not calibrated for



**FIGURE 18.6** Some crystals that fell during the halo display of Figure 18.5.





**FIGURE 18.7** A later stage of the display shown in Figure 18.5. The lower 9° plate arc, the 22° plate arcs, the upper 23° plate arc, and the infralateral 24° plate arcs seem clear. The circular halos, except for the 9° halo, are difficult to identify. The photo is strongly enhanced.

making angular measurements, which is why colored dots were not put on the upper photo.)

Using only our standard pyramidal crystal, we do not see how to make a 20° halo without making either a strong 18° or a strong 22° halo. But there is no 18° halo present in the display, and we are not convinced that the 22° halo is there either—if it is, it is not strong. So even without the 5° and 12° halos, this display is a mystery.

The crystal photos may well contain the key to the display, but the crystals are complex, and so far we have not been able to decipher them. Perhaps there is some sort of twinning going on.

Figure 18.7 shows a later stage of the same display. By that time, what appear to be standard odd radius plate arcs had become conspicuous. Some, at least, of the responsible crystals seem therefore to have been ordinary pyramids. But the circular halos are still hard to identify with any certainty, other than perhaps the 9° halo.

## Parheliion flares

In the halo display shown in Figure 18.8 a tall column of light, bending ever so slightly outward, seems to emanate from each parheliion. We do not understand



**FIGURE 18.8** Parhelion “flares”—the two tall columns of light seemingly emanating from the parhelia. Odd radius arcs are present as well. The origin of the parhelion flares is not known. Fairbanks, December 30, 2002.

these halos. Until we do, we propose to call them parhelion “flares.” Parhelion flares as tall and bright as these are rare, but we fairly often see rudimentary and shorter parhelion flares in low level displays in Fairbanks. They tend to be accompanied by unusually tall and bright sun pillars, as here.

Parhelion flares may or may not turn out to involve novel wedge angles; we just do not know. And they may or may not be related to the parhelia.

## Elliptical halos

On rare occasions one or more small rings, vertically elongated and often incomplete, appear around the sun or moon (Figure 18.9). These “elliptical halos” can be passably simulated using thin pyramidal crystals with angle  $x$  very large—something more than  $80^\circ$ , depending on the size of the halo. The crystals would thus be something like the pyramidal crystal of Galle in Figure 11.1, but thinner, with the pyramidal faces sloping much more gently and with the prism faces being smaller or absent.

A glance at Table E.2 shows that pyramid faces with large  $x$  are completely unreasonable from a crystallographic point of view; in the entire table the largest entry for  $x$  is only  $72.6^\circ$ . The  $\{1\ 0\ \bar{1}\ 11\}$  pyramid faces would give  $x = 80^\circ$ , from Eq. (9.6), but, again, these faces are ridiculous crystallographically. So we do not know how elliptical halos form.

A recent article by Sillanpää et al [68] contains much more information on elliptical halos, including an analysis of the display in Figure 18.9, as well as references to other work. The article also discusses Bottlinger's rings, a phenomenon resembling elliptical halos but surrounding the subsun rather than the sun.



**FIGURE 18.9** Elliptical halo display, Kokkola, Finland, February 13, 1997. Photo © Martti Penttinen.

## Hevel's halo

Hevel's halo is supposed to be a circular halo of radius  $90^\circ$ . It has been treated by many authors, including one of us [76], and we have all come up empty. That is, nobody understands how such a halo could occur. We have little to add here, so we will be brief.

The halo was reported by Johannes Hevelius in his famous Danzig display of 1661. His original Latin description is in the rare *Mercurius in Sole visus Gedani* ... [26], but most of it can also be found in Smith's *Opticks* [69], in English translation.<sup>2</sup> Hevelius was quite explicit about the size and shape of the halo; it was circular, though incomplete, and its radius was  $90^\circ$ . Hevelius was one of the premier astronomers of his time and was superbly equipped to make observations of angular distances in the sky, so it is hard to believe that he got the description wrong by much.

<sup>2</sup> The *Opticks* version has some weaknesses, the most serious being the omission of Hevelius' explicit statement that the halo in question crossed the ecliptic at right angles, as a  $90^\circ$  sun-centered halo must. If Hevelius was correct on this point, then the halo in question could not have been the subhelic arc. A French translation of Hevelius' description of the display, as well as his original Latin description, can be found in the complete works of Huygens [33, pp 424–429].

Hevel's halo is too big to be a circular halo in the conventional sense of Chapter 8. A halo whose ray path enters and then directly exits the crystal, as we assumed there, can have radius no larger than  $80.5^\circ$  (page 77). So if Hevel's halo is a truly circular  $90^\circ$  halo, then some new mechanism is needed for its explanation. No such mechanism has been forthcoming.

In 1980 Greenler [21] suggested that perhaps Hevelius was not seeing a circular halo at all, but was seeing the subhelic arc instead. At first, Greenler's suggestion seems unlikely, almost preposterous. The subhelic arc is just not close to being a  $90^\circ$  circular halo, and Hevelius, as we said, should have been too good an observer to confuse the two. But is the alternative any more likely? The alternative is that Hevelius in 1661 saw a halo that has been neither seen nor explained since.

If we absolutely had to bet, we would probably go with the subhelic arc hypothesis. One objection to it has recently been removed, namely, that a subhelic arc should have been accompanied by a Wegener arc, and that Hevelius did not see any Wegener arc. Recent halo displays like that in Figure 5.9 have shown that the subhelic arc can occur without the Wegener arc. But the removal of this objection does not change things much. Until somebody gets a photograph of a  $90^\circ$  halo, Hevel's halo will continue to fuel late night pub conversations at halo conferences.

## 44/46° parhelia

The orange arrow in the photograph in Figure 18.10 points to a halo that might easily be misidentified as a “46° parhelion,” were it not for presence of the 46° halo.<sup>3</sup> But the halo in question is clearly closer to the sun than is the 46° halo; it cannot be a true 46° parhelion.

We believe the halo is a secondary halo, a parhelion of a parhelion. That is, the ordinary  $22^\circ$  parhelion is acting as a light source and creating its own  $22^\circ$  parhelia. One of them would be at the sun and would of course be overpowered by the sun. The other is about  $44^\circ$  from the sun and is the halo of interest here. The blinding intensity of the ordinary  $22^\circ$  parhelion in the photo is just what we would expect, if the parhelion is to be able to make its own halos.

The idea of secondary halos goes back at least as far as Bravais [9] in 1847. Secondary halos were added to halo simulations by Tränkle and Greenler [78] in 1987. We mention secondary halos here mostly to caution that an odd radius does not automatically imply an odd wedge angle. In the photo we seem to have a halo with  $\Delta_{\min} \approx 44^\circ$ , but its explanation does not lie in a wedge angle  $\alpha \approx 89^\circ$ , as would follow from Eq. (8.1).

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<sup>3</sup> One can argue about whether the apparent 46° halo here might in fact be the supralateral arc, but it does not matter much, since for this sun elevation the two halos would nearly coincide in this part of the sky.





**FIGURE 18.10** Bright 22° parhelia at left, 44° parhelia (orange arrow), and 46° halo (green arrow). The sun is out of the photo at the left. Teuva, Finland, November 21, 2004. Photo © Heikki Mahlamäki.

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It is a mistake to think that because halo theory is old, it is also complete. There are halos, like the parhelia flares, whose existence is indisputable but whose origin is obscure. Moreover, there will be new halos, new in the sense that they are being recognized for the first time. Some of them will have been anticipated, as would be the 9° Parry arcs if they were to turn up. Others will be completely new, as was the M-arc when it was first seen. The fun is not over.