CHAPTER 12

Refraction Halos and Wedge Angle

Soon we will be looking at halos made by pyramidal crystals that are preferentially, rather than randomly, oriented. Crystals with plate orientations, Parry orientations, column orientations, and Lowitz orientations would all be examples of preferentially oriented crystals. When pyramidal crystals are preferentially oriented, many halos are possible—so many, in fact, that initially it may seem futile to come to grips with them. But the apparent complexity of the situation turns out to be a blessing in disguise, because it forces us to think more conceptually and systematically about halos in general. In the end it will turn out that the new halos are quite manageable. And what we learn will give insights into the old familiar halos as well.

Refraction halos are halos whose ray paths involve refraction only, with reflections playing no essential role. The 22° halo, the parhelia, and the tangent arc are examples of refraction halos, but the parhelic circle, the 120° parhelia, and the subparhelia are not, since their ray paths involve reflection.

Most of the common halos are refraction halos, and virtually all of the observed halos from pyramidal crystals are refraction halos. In subsequent chapters we will therefore concentrate on refraction halos. Even so, the situation may at first seem chaotic.

When the crystal orientations are not random

Let's try to get a sense of why preferentially oriented crystals might complicate matters. When crystals are randomly oriented they make circular halos, and that's all. But when the crystals are preferentially oriented, then for each circular halo that would have arisen in random orientations there is a whole family of related arcs. Perhaps this is already clear from Chapter 6, where we had 22° plate, Parry, column, and Lowitz arcs all related to the 22° circular halo, and where we had 46° plate, Parry, column, and Lowitz arcs all related to the 46° circular halo. Nevertheless, this idea is so fundamental that it can stand some elaboration.

With randomly oriented crystals, you get circular halos, with each circular halo being associated with a wedge angle α of a crystal. If, for example, the crystals are hexagonal prisms, then wedges with $\alpha = 60°$ make the 22° halo. If the same crystals are preferentially oriented rather than randomly oriented, then each wedge with $\alpha = 60°$ will again make a halo. But whereas for random orientations any two wedges with $\alpha = 60°$ would make the same halo (the 22° halo), those same two wedges may now make different halos. Suppose, for example, that the crystals are falling with plate orientations. With the faces numbered as usual (Figure 6.2), wedge 35 would make the left parhelion and wedge 37 would make the right. These two wedges, which made the same halo when randomly oriented, now make different halos.

If instead these same crystals fall with Parry orientations, then wedges 35, 46, 48, and 57, all having wedge angle $\alpha = 60°$, make four different halos (Figure 6.6). If the crystals fall with column orientations, then the wedges with $\alpha = 60°$ make the tangent arc. And if they fall with Lowitz orientations they make three additional arcs.

Thus there is a whole family of refraction halos that have wedge angle $\alpha = 60°$. Those that arise in preferentially oriented crystals we refer to as 22° arcs. (More generally, all halos that are "arcs" arise in preferentially oriented crystals.) In the classification scheme of Figure 12.1, the 22° arcs would be the 22° plate arcs, the 22° Parry arcs, the 22° column arcs, and the 22° Lowitz arcs. In the sky, all 22° arcs are necessarily subsets of the annular region that is the 22° circular halo. The arcs tend to be weak unless they are fairly close to the inner boundary of the circular halo, and therefore the 22° arcs do indeed appear at an angular distance of 22° or a bit more from the sun.

For wedge angle $\alpha = 90°$ there is an analogous family of arcs—the 46° arcs—that appear 46° or a bit more from the sun. Some 22° and 46° arcs are shown in Figure 12.2.

So there is one 22° halo but many 22° refraction arcs, and there is one 46° halo but many 46° refraction arcs. When you recall that the pyramidal crystals of Chapter 8 can make eight different circular halos, and when you realize that each of those circular halos must have a corresponding family of refraction arcs, you begin to sense the challenge of understanding the halos made by preferentially oriented pyramidal crystals.

The challenge can be met, however, and in fact we have already begun to do so. It is clear from the preceding discussion that the wedge angle itself, or,

	$\alpha = 60°$ $\Delta_{min} = 22°$	$\alpha = 90°$ $\Delta_{min} = 46°$
plate orientations	22° plate arcs	46° plate arcs
Parry orientations	22° Parry arcs	46° Parry arcs
column orientations	22° column arcs	46° column arcs
Lowitz orientations	22° Lowitz arcs	46° Lowitz arcs
random orientations	22° halo	46° halo

FIGURE 12.1 Halo classification matrix. Each column is determined by a wedge angle α (60° or 90°), each row by a crystal orientation class (plate, Parry, column, Lowitz, or random). This matrix is for halos made by prismatic crystals; for pyramidal crystals the matrix would require eight columns instead of two. The matrix includes only refraction halos, that is, halos whose ray paths do not involve reflection.

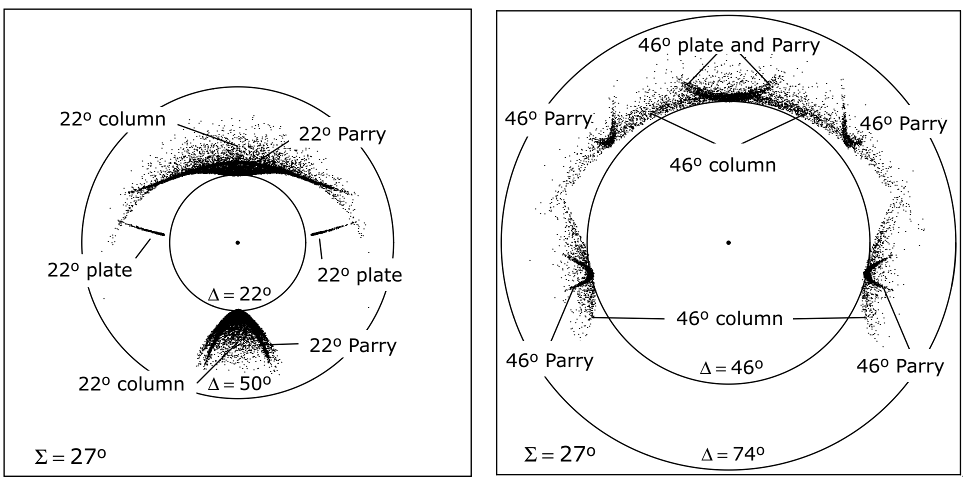


FIGURE 12.2 (*Left*) Some 22° arcs, that is, refraction halos that have wedge angle $\alpha = 60°$ and that arise in preferentially oriented crystals. All 22° arcs are subsets of the 22° circular halo, which is here indicated only by its inner and outer boundaries $\Delta = 22°$ and $\Delta = 50°$. (*Right*) Some 46° arcs. This diagram is the $\alpha = 90°$ analogue of the one at left. See the tables of Chapter 6 for names of the individual arcs.

equivalently, the radius $\Delta_{\min}$ of the associated circular halo, provides a preliminary classification of refraction arcs. Just as there is a family of 22° arcs and a family of 46° arcs, there is also a family of 9° arcs, a family of 18° arcs, and so forth, one family for each of the circular halos from Chapter 8. The 9° arcs are 9° or a bit more from the sun, the 18° arcs are 18° or a bit more from the sun, and so forth.

Thus if you know the wedge angle that gives rise to a halo (assumed to be a refraction arc), then you know about how far from the sun to look for the halo. So the wedge angle is a fundamental entity, and indeed it has been recognized as such for centuries. But if you only know the wedge angle of the halo, there is obviously a lot that you still do not know about the halo. You do not know the shape of the halo, and you do not even know its location, since, although you know its approximate angular distance from the sun, you do not know its direction from the sun. Is there a fundamental entity of a halo that contains the information about shape and about direction from the sun, much as the wedge angle contains the information about angular distance from the sun? Yes, but it took a long time to see just what it was. In principle the missing information is contained in the wedge orientations that give rise to the halo. But how are you supposed to cope with wedge orientations? The beautiful and surprising answer is that you can do so in a simple and rather mindless way, without ever really focusing on the wedge orientations themselves. What is needed is the spin vector.

CHAPTER 13

The Spin Vector

In spite of its esoteric name, the spin vector is simple. It will be the key to managing wedge orientations without actually having to think about them.

There is a spin vector associated with each of our four classes of non-random crystal orientations:

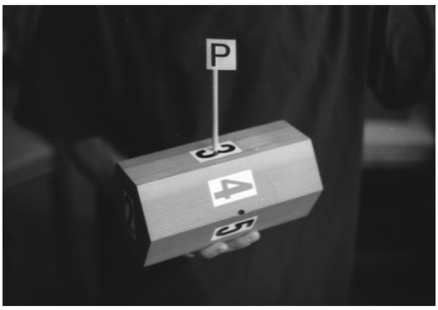
Plate orientations Recall that a hexagonal prismatic crystal is in plate orientation when face 1 is horizontal and on top (Figure 6.1). Thus the crystal is in plate orientation if $\mathbf{N}_1$, the outward normal vector to face 1, is vertical (and pointing up rather than down). The vector $\mathbf{N}_1$ is the spin vector for plate orientations. It is a vector which is fixed in the crystal and which characterizes plate orientations: The crystal is in plate orientation exactly when the spin vector is vertical.

The spin vector is illustrated with a wooden crystal model in Figure 13.1. The spin vector is the dowel, inserted in face 1. The crystal model is in plate orientation when the dowel points up.

Parry orientations A crystal is in Parry orientation when face 3 is horizontal and on top. Thus the crystal is in Parry orientation when $\mathbf{N}_3$, the normal vector to face 3, is vertical. The vector $\mathbf{N}_3$ is the spin vector for Parry orientations. It is a vector which is fixed in the crystal and which characterizes Parry orientations: The crystal is in Parry orientation exactly when the spin vector is vertical.

Column orientations A crystal is in column orientation when the crystal axis is horizontal, that is, when the vector $\mathbf{N}_1$ is horizontal. The vector $\mathbf{N}_1$ is the spin vector for column orientations. It is the same as the spin vector for plate orientations, but for column orientations the spin vector is horizontal, whereas

Wooden crystal model in plate orientation. The spin vector **P** (the dowel) is $\mathbf{N}_1$, the normal vector to face 1. In plate orientation the spin vector is vertical.



Crystal model in Parry orientation. The spin vector is $\mathbf{N}_3$ and is vertical.

Crystal model in column orientation. The spin vector is $\mathbf{N}_1$ and is horizontal

Crystal model in Lowitz orientation. The spin vector is $\mathbf{N}_1 \times \mathbf{N}_3$ and is horizontal.

FIGURE 13.1 Compare these photographs with Figure 6.1.

TABLE 13.1 Crystal orientation classes and spin vector.

Crystal orientation class	Spin vector **P**	Direction of **P**
plate orientations	$\mathbf{N}_1$	vertical
Parry orientations	$\mathbf{N}_3$	vertical
column orientations	$\mathbf{N}_1$	horizontal
Lowitz orientations	$\mathbf{N}_1 \times \mathbf{N}_3$	horizontal

for plate orientations it is vertical. That is, the crystal is in column orientation exactly when the spin vector is horizontal.

Lowitz orientations Lowitz orientations are rare, and we mention them here mainly to illustrate further the concept of spin vector. A crystal is in Lowitz orientation when $\mathbf{N}_1 \times \mathbf{N}_3$ (a vector parallel to face 1 and face 3) is horizontal. Hence the spin vector for Lowitz orientations is $\mathbf{N}_1 \times \mathbf{N}_3$, and the crystal is in Lowitz orientation exactly when the spin vector is horizontal.

Thus for each of the above four classes of crystal orientations there is a vector **P**—*the spin vector*—which is fixed in the crystal and which characterizes the class of orientations: A crystal has the orientation in question exactly when the spin vector is vertical (plate and Parry orientations) or horizontal (column and Lowitz orientations).

Contact arcs and non-contact arcs

We said that the spin vector **P** is always horizontal or always vertical. Refraction arcs that arise in crystal orientations with **P** horizontal are called *contact arcs,* those that arise in crystal orientations with **P** vertical are called *non-contact arcs.* The middle diagram in Figure 5.5 can be thought of as showing the distribution of the spin vector for a contact arc, and the left-hand diagram as showing the same for a non-contact arc. In Figure 12.1 halos associated with the first and second rows—plate arcs and Parry arcs—are non-contact arcs, and those associated with the third and fourth rows—column arcs and Lowitz arcs—are contact arcs. The terminology of contact and non-contact has to do with whether the arc normally makes contact with the associated circular halo (Chapters 14 and 16).

Contact arcs behave quite differently from non-contact arcs. More importantly: In spite of our initial impression of chaos, all contact arcs behave alike, and all non-contact arcs behave alike. In the next chapter we will look at the non-contact arcs, then in Chapter 16 the contact arcs.