How Retroreflectors Really Work

Retroreflectors, which reflect light from automobile headlamps back in the same direction from which the light originated, are invaluable safety devices. They are entirely passive, requiring no power supply or maintenance. They make street signs, lane dividers, bicyclists, joggers, and road crews highly visible. Although less than 100 years old, the devices are now ubiquitous and indispensable. Even so, most people do not know how they work, and those who think they do are probably wrong. Certainly the explanation I was given when I began my study of optics (and which I have heard from others as well) was demonstrably incorrect.

MOST PEOPLE DO NOT KNOW HOW THEY WORK . . .

There are two types of common retroreflectors—those consisting of arrays of corner cubes and those consisting of collections of "cat's eyes."[1] The former are probably the most common. They are easily manufactured in bulk out of a variety of plastics, and can be tinted in different colors. Because the cross-section is hexagonal or triangular, it is easy to completely cover the surface of a reflector with an array of such constructions (Fig. 1). The principle is straightforward and uncomplicated, and will not concern us further.

Corner cubes require a well-defined and oriented surface, however, and reflective tapes and paint often use a very different method. Glass or plastic beads are embedded into the material. Light that falls upon these beads ends up being reflected primarily back along its direction of origin. The phenomenon is the same one responsible for the "glow" from the eyes of animals caught in one's headlights. It is used in "beaded" projection screens, and was once used in a craft called "pastinella work," in which tiny glass spheres were scattered across painting while the paint was still damp. When light came from behind the viewer, such paintings seemed to light up themselves. The ultimate inspiration for most of this is the natural phenomenon called "heiligenschein," in which a person standing before a dew-covered field with the rising sun behind him sees his shadow surrounded by a bright glow.[2]

The usual explanation given for the strongly retroreflected light is that light follows a path similar to that in the case of a primary rainbow (Fig. 2). The ray is reflected upon entering the drop, strikes the rear surface, from which it suffers Fresnel reflection, then refracts upon striking the side of the drop again, exiting in the direction from which it came. There are a number of objections to this route. First, it can be shown that such a path only exists if the index of the drop lies between $\sqrt{2}$ and 2.0. Water (with an index of 1.33) will not support such a path, yet the effect is often seen in aqueous media, such as animal eyes and dewdrops. Second, light that is scattered from a spherical drop after undergoing a single internal reflection is concentrated along the rainbow angle, approximately 138° from the direction of incidence rather than being retroreflected along the direction 180° from the direction of incidence. This light is, in addition, broken up into its constituent spectral colors, while the light from "cat's eys" retroreflectors is white. Third, even where the index is sufficiently high to allow retroreflection, the resulting rays are restricted to near the edges of the drop. The center of the drop is dark.[3] In retroreflectors, heiligenschein, and animal eyes, the entire drop lights up uniformly bright.

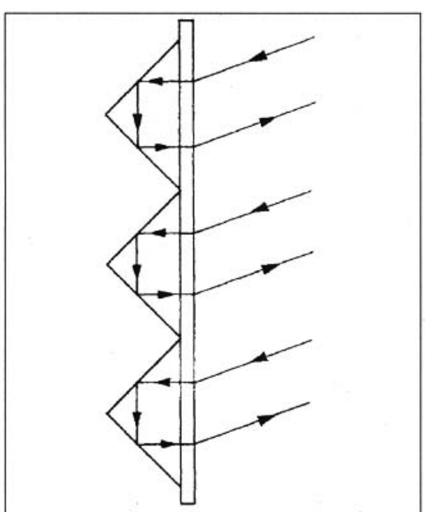

FIGURE 1. ARRAY OF CORNER CUBE RETROREFLECTORS (AFTER VAN LEAR).

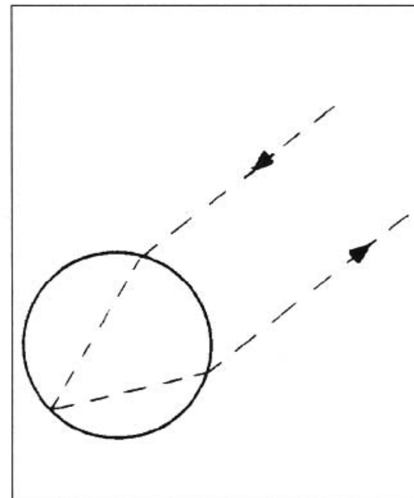

FIGURE 2. PATH OF LIGHT IN THE COMMON EXPLANATION OF RETROREFLECTION FROM WATER DROPLETS AND "CAT'S EYES" (AFTER TRICKER). NOTE THAT NO LIGHT IS REFLECTED FROM THE CENTRAL PORTION OF THE SPHERE.

The "cats eye" effect is thus rather remarkable—it occurs for drops of all indices and sizes, providing very close to exact retroreflection. The mechanism is somewhat unexpected (Fig. 3). Light from some distant source is focused by the drop onto a surface very close to the drop, perhaps even the rear surface of the drop. The focusing is not complete, since the surface lies closer than the focal point of the crude lens, but does result in a more constrained circle

STEPHEN R. WILK *is senior optical systems engineer with Optikos Corp., Cambridge, Mass.*

of light. Since the light paths are reversible, the drop also acts to direct light reflected from this surface back along its original direction. Put another way, a viewer looking nearly along the direction of the incidence is in precisely the correct location to see the drop act as a magnifier for the spot of light. In his *Introduction to Meteorological Optics,* Tricker shows very effectively that this is the operating mechanism by use of flasks filled with water and a white card. If the card is placed very close to the flask, the flask is seen to light up, while if the card is moved far away from the flask there is no notable retroreflection.

The result is very desirable from the point of view of manufacturing—there are no tight tolerances on indices, reflectivities, sizes, or distances. All one nèeds is to suspend glass or plastic spheres in such a way that they become partly uncovered as the paint dries.

It is interesting to note that the natural retroreflector effect of heiligenschein is probably responsible for an almost universal symbol of holiness—the halo, or aureole. Anyone observing the effect with a light source behind them will see the head of their shadow surrounded by the bright retroreflected light. If others are present, each will see the head of his or her shadow surrounded by this burst of illumination (but they will not see this halo around the shadows of their companions.) The Renaissance artist and goldsmith (and egotist) Benvenuto Cellini was said to have seen in this evidence of his own magnificence. The more prosaic explanation that only one's own head's shadow lies near the position from which the incident light is retroreflected into the eye is illustrated by photographs of the effect taken with a tripod-mounted camera. Here it is the shadow of the unattended camera, which is surrounded by a saintly halo.[4] A more epigrammatic call to humility was issued a century ago in the pages of *Nature*: "Nature naturally takes no account of moral analogies, of which Nature herself is full. Else one might note that a man never sees a halo round his own head unless he turns his back to the light."[5]

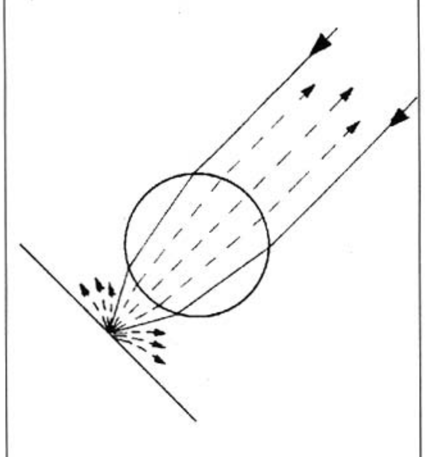

Figure 3. True light path in "cat's eye" type retroreflectors. The scattering surface may be the rear surface of the sphere, rather than a surface close to the sphere.

References

1. G.A. Van Lear, Jr. "Reflectors used in highway signs and warning signals, parts I, II, and III," Journal of the Optical Society of America **30**, 1940, 462.
2. R.A.R. Tricker, *Introduction to Meteorological Optics*, American Elsevier Publ., New York, N.Y. 1970, 24-42.; M. Minnaert, *The Nature of Light and Colour in the Open Air*, Dover Publications **350**, New York, N.Y. 1954, 230-234.
3. See Plate II, Tricker **6**, 37.
4. Ibid., p. 26.
5. "B.W.S." Nature **38**, 1888, 589.