Little-known Rainbows

A Group of Neglected Optical Phenomena

By C. Fitzhugh Talman

LITTLE-KNOWN rainbows may be divided into two classes: (1) Those that, though common, are inconspicuous and generally escape the attention of the casual observer. The supernumerary bows belong to this class. (2) Those that are rare, because they occur only under more or less exceptional circumstances. This class includes bows of unusual coloration—especially the "white" rainbow—reflected bows of all kinds, and bows of a higher order than the secondary (viz., the tertiary, quaternary, quinary, etc.).

The ordinary primary and secondary rainbows are familiar to everybody, and their phenomena were so fully explained over two centuries ago, by Descartes and Newton, that for a long time the scientific world believed there was nothing further to be learned about them. These phenomena were assumed to be invariable; a rainbow was simply a rainbow, and the meteorologist who noted the occurrence of one in his log-book thought it unnecessary to add a detailed description. To the late J. M. Pernter, whose writings have done so much to rescue all branches of atmospheric optics from the neglect into which this branch of science had fallen, is especially due the credit for having brought to general attention the many variations to which the phenomena of ordinary rainbows are susceptible. These variations will be more fully considered below.

Supernumerary Bows.

Supernumerary bows—sometimes called *spurious bows*[1]—are the bands of prismatic colors often occurring just inside the lower, or primary rainbow, and less frequently outside the upper, or secondary, bow. Tait describes them as having the appearance of ripples. They repeat the colors of the spectrum—sometimes several times over—green and red being usually predominant; the other colors are often indistinguishable. As stated above, they are apt to be overlooked in a cursory observation; but as a rule they are easily seen by anyone who looks for them, especially those attending the primary bow, and they are sometimes quite conspicuous. Some of them are shown at *DD* in Fig. 3.

The Newtonian theory of the rainbow took no account of the supernumerary bows. They were first explained by Young, in 1803, and more fully by Airy, in 1836-38. They are interference phenomena, due to the fact that, in addition to the rays of light producing the colors of the ordinary bow, there are other mutually parallel rays emerging from a raindrop after traversing unlike paths within the drop. For the complete explanation the reader is referred to Preston's "Theory of Light," third edition, page 536 ffg. One result of Airy's investigations was the discovery that the supernumerary bows vary in appearance with variations in the size of the raindrops.

[1] In German, "secundäre Bogen"—"secondary bows"—a name that, in spite of Pernter's recommendation, cannot be adopted for this phenomenon in English, where it has long been appropriated to another use. The bow that we call, in English, the "secondary," is called in German "Nebenregenbogen," the primary bow being called "Hauptregenbogen." Anyone who has occasion to consult the German literature of the rainbow will do well to bear in mind these confusion-breeding discrepancies in the terminology.

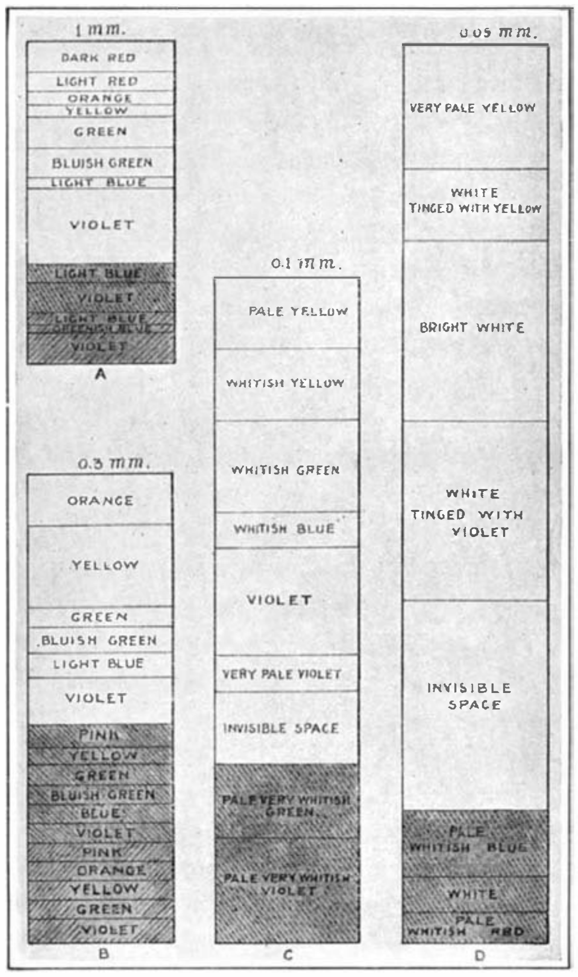

Fig. 1.—Relation of rainbow colors to the size of the raindrops (Pernter).

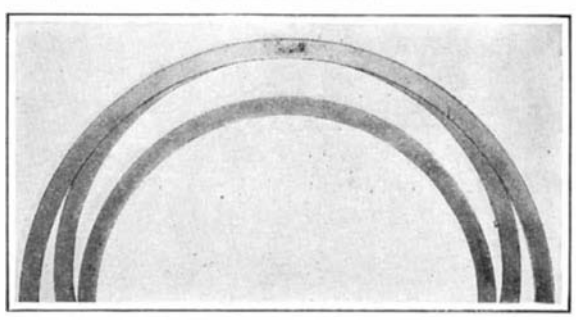

Fig. 2.—Intersecting rainbows. Seen by Halley, 1698.

The Colors of the Rainbow.

Formerly it was supposed that the primary rainbow was of a certain uniform breadth, and that the seven prismatic colors had a definite and invariable distribution therein. Turn to Brewster's "Optics," which was a standard work in the middle of the last century, and you will find the following statement: "The primary or inner rainbow consists of seven differently colored bows, viz., *violet*, which is the innermost, *indigo*, *blue*, *green*, *yellow*, *orange*, and *red*, which is the outermost. These colors have the same proportional breadth as the spaces in the prismatic spectrum." This is a good example of a class of ideas that gain acceptance by dint of reiteration in the textbooks, though unable to stand the test of even a small amount of careful observation.

As a matter of fact, all seven colors are rarely distinguishable in the rainbow, and the space occupied by each, when present, varies greatly from one bow to another.

Not until long after Airy's time was it generally understood that his explanation of the supernumerary bows has an important application to the ordinary bows. The latter, like the supernumeraries, vary greatly with the size of the raindrops. Small drops produce broad bows, and *vice versa*. Moreover, the smaller the drops the greater the superposition of the prismatic colors. Hence it is that the small drops constituting a fog, as distinguished from the larger drops that fall as rain, give us a bow in which the colors overlap to such an extent that they almost neutralize one another, and a so-called "white" rainbow is the result. This bow is not perfectly white; the lower border is more or less distinctly tinged with violet, and the upper is generally yellowish. As it is produced by fog, and not rain, it is often called a *fog-bow*.

White rainbows may, however, also be produced by rain, in the following manner: Since the luminous source of a rainbow is not a point, but a disk of finite magnitude (viz., the sun or moon) the light reaches the drop of rain from all points in this disk, and therefore at various angles. Hence there is a superposition of colors in all rainbows, and the colors never show the well-defined sequence of the pure spectrum. Now suppose in some way the luminous disk could be considerably increased in angular magnitude. There would result still more blending of the rainbow colors, and if the disk were large enough these would combine to produce white light. These conditions are fulfilled when the sun shines through thin clouds. Under these circumstances the sky for a degree or two around the sun becomes dazzlingly bright, and the luminous source is thus virtually

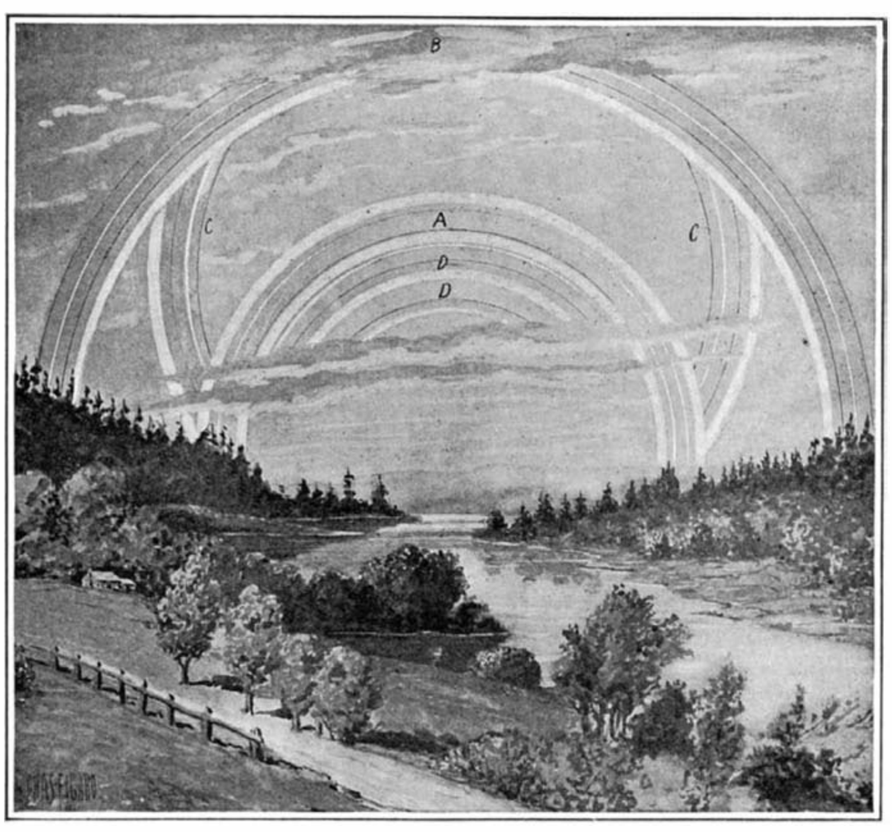

Fig. 3.—Intersecting rainbows observed at Nya Kopparberg, Sweden, by Gumœlius. (After Tissandier.)

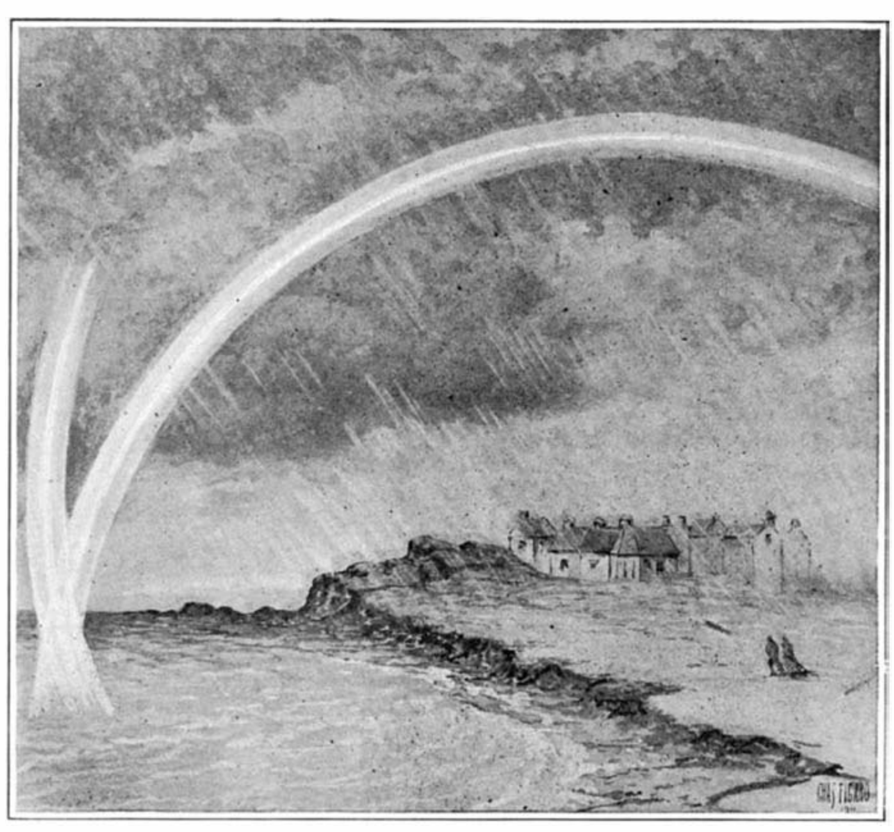

Fig. 4.—Intersecting rainbows observed at St. Andrews, Scotland, 1874. (After a sketch by T. Hodge.)

LITTLE-KNOWN RAINBOWS

spread over a large spherical angle. The effect is the same as if the disk of the sun, instead of spanning an angle of half a degree, had a diameter of two or three degrees. Parenthetically, it may be remarked that since the apparent diameter of the sun is greater at the earth's perihelion than at aphelion, the appearance of the rainbow varies slightly with the season; while on other planets than the earth, if rainbows occur at all, they must differ in appearance from those with which we are familiar.

The lunar rainbow is often described as "white," but here the apparent absence of color is simply the effect of feeble illumination. Bright lunar rainbows usually show the rainbow colors distinctly.

Lastly, a white circle, a little smaller than the rainbow, is sometimes seen from a mountain summit, or in the polar regions, on a bank of fog opposite the sun. This was long supposed to be a true rainbow, and was regarded as *the* white rainbow, *par excellence*; but Pernter has shown it to be a halo, produced by the reflection and refraction of light from crystals of ice. He calls it the *Halo of Bouguer*.

People who ought to know better sometimes report having seen a "white rainbow around the moon." This is, of course, a halo, and not a rainbow; and like the true lunar rainbow, seen in the part of the sky opposite the moon, it is not truly white, but appears so on account of its feeble lustre. A rainbow *around* the moon, or the sun, would be as much out of place as a palm tree at the North Pole.[2]

The way in which the colors of the rainbow vary with the size of the water drops producing it is illustrated in the accompanying diagram (Fig. 1) by Pernter, which shows sections of the bows resulting from drops having uniform diameters of 1 millimeter, 0.03 millimeter, 0.1 millimeter, and 0.05 millimeter, respectively. Diagrams *A* and *B* include, in each case, segments of two supernumerary bows (the shaded portions of the figures); in *C* and *D* only one supernumerary is shown in each. Although in nature the drops are never of quite uniform size, they are often so nearly so that these figures represent substantially bows that actually occur. At any rate they illustrate the fact that the appearance of the rainbow is by no means invariable. When the drops are about 1 millimeter in diameter (*A*) the colors are rich and intense; when they are smaller—say from 0.15 to 0.4 millimeter in diameter (*B*)—the colors are more numerous and distinct. Still smaller drops (*C*) produce a whitish bow, which is further distinguished by the fact that there is an unilluminated space between the primary and the supernumerary bows. The smallest drops (*D*) —those that occur in a fog, and are too small to fall rapidly as rain—give us a bow the middle of which is pure white; and here there is a still broader interval between the primary and the supernumerary bows.

Red rainbows have occasionally been observed. They occur when the sun is low and when its disk appears red, owing to selective scattering of its light.

Reflected Rainbows.

Reflected bows are among the striking phenomena of nature. They are of two kinds: (1) those produced by an image of the sun reflected in a body of water, or other horizontal surface, and (2) those that are themselves reflected from such a surface.

An example of the first kind is shown in Fig. 3. The sheet of water extends back of the observer, who is facing the rainbow. *A* and *B* are, respectively, the ordinary primary and secondary bows. *D*, *D* are supernumerary bows. *C*, *C*, which intersect the primary and secondary bows, are arcs of a circle whose center lies as far above the horizon as the center of the primary and secondary bows lies below it. This *extraordinary* or *intersecting* bow, as it is called, is formed by an image of the sun in the water behind the observer. The reader is, of course, familiar with the fact that in the case of the ordinary rainbow the higher the sun stands in the heavens the lower the bow, and *vice versa*. In the case of the extraordinary bow, the luminous source is, in effect, below the horizon; hence the center of the bow lies above the latter. If the angular altitude of the sun exceeds the radius of the bow the latter will be lifted entirely above the horizon, and if the curtain of rain extends high enough the bow will form a complete circle. Usually, however, only the lower part of such a bow is visible, and we have the phenomenon of the *inverted rainbow*.

Fig. 4 shows a fragment of an intersecting bow, together with an ordinary primary bow. It was observed by no less a person that P. G. Tait. (See *Nature*, vol. 10, 1874, p. 437.)

A celebrated case of a reflected bow was that seen by Halley, over the River Dee, in 1698. In this case the primary and secondary bows were both visible, and the reflected bow was between them. (See Fig. 2.) The reflected bow was observed to rise and the ordinary bows to sink (with the increasing altitude of the sun) until the upper part of the reflected bow mingled with the secondary for a certain distance, and this portion of the combined bows became white. This resulted from the fact that the order of the colors in the reflected bow was the reverse of that in the secondary; the red of the one coincided with the violet of the other, etc., producing white light.

Reflected rainbows of the second class are seen, not in the sky, but in the reflecting surface; i. e., usually a sheet of water. In this case the bow seen in the water is not the reflection of the *same* bow that is seen in the sky; in other words, the bow in the water does not exactly correspond to the reflection that would be cast by a wooden framework set up in the position of the series of drops producing the ordinary bow, and painted to imitate its colors. This will be clear from Fig. 5. The observer at *O* sees an ordinary rainbow produced by a series of raindrops, one of which is *R*. Another series of drops, of which R^1 is one, forms a bow that cannot be seen directly by the observer; the ray of light emerging from R^1 strikes the water surface at *W*, and is reflected upward to the observer *O*, to whom the corresponding point in the bow appears to lie in water at *B*. This bow in the water is, in fact, the reflection of the one that would be seen by an eye vertically below that of the observer, and as much below the surface as his eye is above it.

Nearly all works on optics that mention bows of this class (a majority ignore them altogether) convey a rather misleading impression as to the appearance of the bow resulting from the process above described. Unless the observer stands at a considerable elevation above the water the reflected rainbow due to distant raindrops does not differ sensibly from that which would be produced if the rainbow in the sky were an objective reality. An inverted bow is seen in the water, and its ends are continuous with those of the aerial bow. If, however, the observer stands far above the water, then the reflected bow will be a conspicuously smaller arc of a circle than is the ordinary bow, and the ends of the former will no longer "join on" to those of the latter.

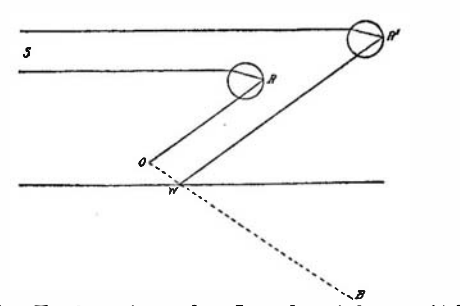

Fig. 5.—Explanation of reflected rainbow. (After Pernter.)

Tertiary Bows, Etc.

The primary rainbow is due to one reflection and two refractions of light in the raindrops; the secondary bow to two reflections and two refractions. (See any encyclopædia or book on optics.) These deviations of the light determine the angular size and the position of each bow. Both are central at the antisolar point, and their radii are, respectively, 42 degrees and 50 degrees (measuring from the red border in both cases). Three reflections and two refractions would give us the *tertiary bow*, and geometrical optics shows that it would lie between the observer and the sun—i. e., it would encircle the latter, after the manner of a halo. Four reflections within the drop would give us the *quaternary bow*, and it, also, encircles the sun. The *quinary bow*, due to five reflections, would lie opposite the sun, its radius being a little greater than that of the secondary bow, which it would partly overlap. More reflections within the drop would give us bows of still higher order; in fact there is no limit to the number that may exist, theoretically.

Have bows of higher order than the secondary ever been seen? Some writers, including Pernter, say no (except in the laboratory). Others are non-committal; "rarely, if ever," is the usual verdict. The observation of the tertiary and the quaternary would certainly be most exceptional; the sun would need to be shining brightly *through* a curtain of rain, and the direct illumination of the sky about it would generally eclipse the relatively feeble light of the rainbow. The quinary, although in a much more favorable position, would be exceedingly faint on account of the many reflections undergone by the light rays, and could, at best, be seen only as a fringe above the secondary.

In view of the fact that no recent writer on optics appears able to refer to a specific instance of the occurrence of these necessarily rare phenomena, it is worth while to call attention to a paper published by Charles Hartwell in the *American Journal of Science*, second series, vol. 17, pp. 56-57, describing fragments of a tertiary bow observed by him at South Windsor, Connecticut, in 1851.

As to the quinary bow, Mascart, in his "Traité d'Optique," says that "it appears to have been sometimes observed," but he cites no specific instances.

Miscellaneous Phenomena.

The foregoing brief list of the vagaries of our familiar friend the rainbow is by no means exhaustive. The ancients were wise in regard to the sex of Iris—for she is infinitely various. It remained for a modern poet (Keats) to complain that we know all about her; but his famous plaint paid an undeserved compliment to the scion of his generation.

The rainbow is occasionally distorted by refraction. Pernter, in his "Meteorologische Optik" (p. 498), describes a case in which a streak of cloud between the observer and the bow caused such a distortion.

Sometimes from a mountain peak, or other elevation, when rain is falling at a lower level, a bow is observed apparently lying on the ground. Such a bow was seen on April 9th, 1908, from the observatory of Rocca di Papa, near Rome, stretching over the green vineyards of the Campagna; and a few days earlier a similar bow was observed from the Eiffel Tower, in Paris. These two observations were widely quoted, at the time, in the scientific journals, and not the least interesting circumstance in connection with them was the difficulty of naming them correctly in French. *Arc-en-ciel?* or *arc-en-terre?* Scientific terminology is frequently upset in this way by the whims of nature. We have seen above that we have similar problems in English. Rainbows may occur without rain; viz., on a bank of fog. Shall we still call them "rainbows"?

[2] The excessively rare tertiary and quaternary bows, described later in the article, as well as theoretical bows of still higher order, are ignored in making this statement.

The Abnormal Summer of 1911

ALTHOUGH, so far as the public at large is concerned, the remarkable heat, drought and continuous sunshine experienced in Europe, and to some extent in North America, during the summer of 1911, has ceased to be a topic of current interest, meteorologists are just now assembling the results of accurate observation of this subject, and it has already been discovered that during the period in question more or less unusual weather prevailed throughout the world.

While Europe and the United States were abnormally warm, the greater part of South America was experiencing an exceptionally cold winter. While the drought in our country and Europe was most severe, South America was treated to a drenching probably unprecedented in that part of the world.

From the meteorological log books of a number of vessels it appears that the trade winds over the North Atlantic were exceptionally strong during the summer of 1911. During the same period the meteorological station at Punta Arenas, at the southern extremity of South America, a location well within the "roaring forties," or zone of the "brave west winds," noted the highest average wind velocities for fifteen years, September being the stormiest month on record. These observations from two of the most definitely marked wind zones of the earth indicate that, as might be expected, the general circulation of the atmosphere was strongly affected by the unusual thermal conditions.

It remains to be seen just what disturbance in the great "centers of action" of the atmosphere were responsible for the weather anomalies of 1911, and whether these disturbances can be traced to any extraterrestrial cause.

Political and Economic Aspects of the Mawson Expedition

IN the many recent notes and articles published in the scientific journals regarding the antarctic expeditions now or lately in the field certain unique features of the Australian venture under Dr. Mawson appear to have been overlooked.

In the first place this party, before leaving home, received official authority to take possession of the coast of the antarctic continent facing Australia on behalf of the commonwealth of Australia. This action is explained by the fact that the antarctic shores are believed to be not without economic value. It is said that there is some prospect of discovering coal deposits near accessible harbors. A more definite project, however, appears to be that of establishing a profitable fishing industry in these regions; especially whaling, which has had, of late, a revival in polar and sub-polar waters.

The wireless stations which Dr. Mawson was to establish at Macquarie Island and on the shore of Antarctica itself might, if the expectations of the explorers are realized, be made permanent, and we should then have a southern parallel to Spitzbergen, which has been put into wireless communication with the world on account of its coal mines and fisheries.