Beyond the (visible) rainbow

By Robert Greenler

Sometimes science is a very personal activity. Ever since I was a small boy, I have been excited by the beauty and grandeur of the rainbow. This was my personal reaction long before I had acquired the tools of the scientist, with which to understand the origin of this marvelous arch of color.

Another, professional, interest in which I have invested a considerable amount of energy over the past three decades is the understanding of the structure of molecules that become attached (adsorbed) to the surface of a solid material. This understanding is important for such a diverse assortment of phenomena as the functioning of catalysts, the electrical properties of small integrated circuits, the separation of ores, and the processes that take place within a fusion reactor. It might seem that this interest would have nothing to do with rainbows, but not so. A contribution I have made to the understanding of molecules adsorbed on a metal surface is the development of a technique for deducing their structure using infrared radiation; so, some understanding of the nature of infrared radiation is one of the tools of my scientific trade.

These two different strands of my experience came together one day while I was sitting at my desk, woolgathering rather than addressing the task at hand. The question occurred to me: I wonder if there is an infrared rainbow in the sky? How does one explore such a question? Here is the process I went through.

For there to be an infrared rainbow:

1) The source of light must emit infrared radiation. The sun does emit in the infrared as well as the visible (and, in fact, over the entire electromagnetic spectrum from x-rays to radio waves).

2) The infrafed radiation must pass through the Earth's atmosphere. Water vapor and carbon dioxide in the atmosphere absorb some infrared wavelengths, but others pass through unimpeded.

> ***Yes, there should be an infrared rainbow in the sky and it should lie in a band just outside the red of the visible rainbow.***

3) The rainbow is caused by light rays that enter a droplet of water and are reflected internally before emerging from the drop. So the infrared rays would have to pass through a water droplet. This is a serious consideration. Just because a droplet of water appears transparent in visible light, we cannot assume that it is transparent to infrared "light" and, indeed, liquid water does absorb over a broad range of infrared wavelengths. However, the measured spectral transmittance[1] of water shows that water drops should be quite transparent from the visible region out to an infrared wavelength of about 1300 nm.

4) After emerging from the raindrop, the infrared rays that have survived all these losses must again pass through air to the unseeing eye of the would-be observer.

The search

This line of reasoning produced a tentative answer to the question that prompted the speculation: Yes, there should be an infrared rainbow in the sky and it should lie in a band just outside the red of the visible rainbow. I decided to try to photograph this invisible bow using a film that is sensitive to a portion of the infrared spectrum. Figure 1 shows the curve of the sensitivity of the film. The figure also shows a curve of the sensitivity of the human eye[2] as a way of defining the limits of the visible spectral region, extending from about 400 nm at the violet end of the spectrum to 700 nm at the red end.

We can see that the infrared film has a sensitivity extending out to about 930 nm. The problem in using this

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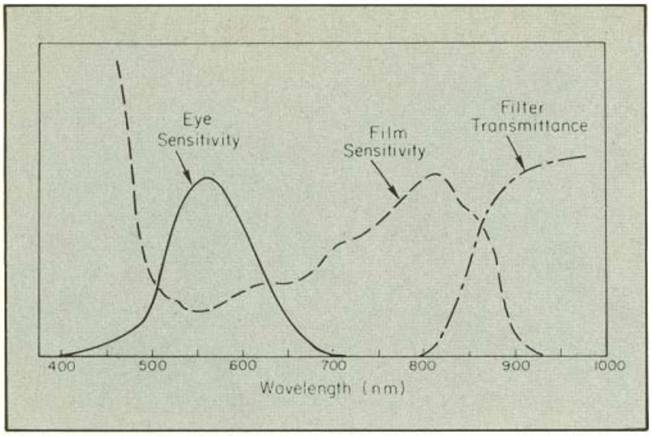

FIGURE 1. ***The infrared film (Eastman Kodak infrared film IR 135) has a sensitivity extending throughout the visible and into the near infrared region. The filter (Eastman Kodak 87C infrared transmitting filter) is opaque to visible light but transmits in the infrared for wavelengths longer than 800 nanometers. The combination of film and filter record an image with wavelengths between 800 and 930 nanometers, clearly outside the visible spectrum.***

film to record an infrared scene is that the film is not only sensitive to the infrared but throughout the visible region and, in fact, very sensitive to blue light. If we look at the black and white image produced by such a film, we have no way of knowing which parts of the image result from exposure to infrared and which parts to visible radiation. This problem was solved by using a filter that appears to be an opaque sheet of black plastic. The material is opaque to visible light and transmits only wavelengths longer than about 800 namometers. As can be seen from Fig. 1, this combination of film and filter will record only wavelengths in a band between 800 and 930 nm, well-removed from the visible spectral region.

The capture

Anyone who has tried to photograph rainbows knows that they usually occur when a camera is not at hand and fade before one is located. I decided to first try an easier subject—that of a rainbow in a water spray that I could turn on at my convenience in my backyard. Figure 2 shows one of the first photographic results. A garden hose with many holes is wrapped back and forth across a board resting on top of the ladder. And in the spray of the hose—the infrared rainbow! You can also see the fainter, secondary rainbow outside the brighter, primary bow. This corresponds to the secondary bow seen rather commonly in visible light and it results from rays that enter a water droplet and experience two internal reflections before leaving the drop.[3] There is another interesting feature in this infrared photograph: Immediately inside (to the right side of) the bright primary bow there is another bright band—or perhaps two bands. Such fringes, sometimes seen inside a visible bow, are called supernumerary bows and result from the interference of light waves.

Close inspection of the negative of Fig. 2 reveals yet another feature, which is difficult to reproduce in a printed picture. There is a faint fringe just outside the secondary bow. A process similar to the one that produces supernumerary bows inside the primary should, in theory, produce a similar set of fringes outside the secondary. I have never seen any of those fringes associated with any rainbow or with any rainbow photograph, but they are visible in the original of this photograph. In fact, they are even visible to audiences before whom I project the slide. For the first attempt, that was quite an exciting collection of effects.

Other effects in the infrared photos

Some other features of these infrared photographs are worth considering. If the only radiation that produced these photographic images is invisible, infrared radiation, is it surprising that we can see the ladder, trees, and grass? One should not be too surprised. These objects absorb some wavelengths and reflect or scatter others. Objects that absorb the infrared appear dark in the photos and those that scatter it strongly appear bright. To make it clear just what these photos show, we need to understand the difference between reflected (or scattered) radiation and emitted radiation.

Normally when you look at objects in your landscape, you see them only by the light they scatter. However, if the temperature of an object is high enough, it emits light. If it is very hot—you may call it "white hot"—it emits a broad

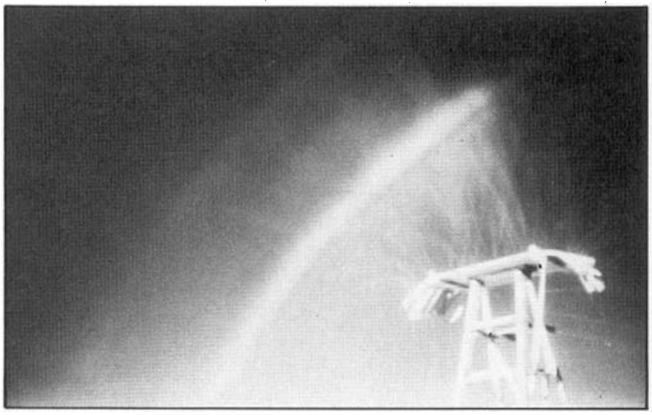

FIGURE 2. ***An infrared rainbow photographed in the water spray of a garden hose. The fainter secondary bow is shown to the left of the primary bow. The fringes seen inside the primary bow are caused by interference effects. A rare interference fringe outside the secondary bow is visible on the original photo but may be difficult to pick out on the reproduction.***

spectrum of wavelengths with the peak of the emission curve in the visible spectrum. If the object cools down a bit, the peak in the emission curve moves to longer wavelength. The result is that there is more red than blue light being emitted, and the appropriate description for its temperature is "red hot." At a lower temperature you may see a dull red glow. At this point, the peak of the emission curve is in the infrared with just a small amount of emission in the red end of the visible region. At a slightly lower temperature, the object appears dark; the emission peak has moved farther into the infrared and no visible radiation can be seen. If the object cools to where it is warm to the touch, its emission peak is far out in the infrared—perhaps at 10,000 nm—and it is emitting almost nothing in the visible or in the near infrared region to which photographic films are sensitive.

If, however, you could produce a picture with 10,000 nm radiation, objects slightly warmer than their surroundings would appear to be bright—they would be glowing with emitted infrared radiation. There are ways to produce such pictures and they are used to show sources of heat loss in homes, or to record warmer spots on a human body that may indicate the site of some physical disorder. These pictures are usually described as infrared pictures, but they are quite different from the photographs taken with infrared-sensitive film. The film is sensitive only to the near infrared, but the "heat pictures" result from emitted radiation in the far infrared. So the infrared photographs shown here show only the infrared radiation from the sun that is scattered by the leaves or ladder, or transformed by raindrop spheres into an invisible rainbow.

Another interesting feature of the photographs is the darkness of the clear sky background. We see light in the clear, clean sky, away from the sun, by scattering from the molecules of gases in the air. Such small scattering particles (much smaller than the wavelength of the light) scatter the shorter waves more effectively than the longer waves. Thus, more blue light is scattered than red light, giving the sky its blue color. This same effect, which makes the sky darker in red light than in blue, makes it even darker in the infrared light sampled by these photographs.

FIGURE 3. ***A natural infrared rainbow. This photograph shows the clouds to be brighter inside the bow than outside, a common feature of visible rainbows (see references).***

FIGURE 4. ***A photograph of Nature's own invisible rainbow, showing the primary bow, secondary bow, and a series of interference fringes (supernumerary bows) inside the primary.***

After taking the initial photographs, made with the leaky hose, I waited to capture Nature's own, natural, infrared rainbow. It was four years before I saw a natural rainbow when I had, at hand, my camera, infrared film, the filter, and time enough to put them together for the photographs shown here.

Public response

I received an interesting collection of letters in response to a brief published note describing the infrared rainbow.[4] Some were from people who had a "scientific interest" in the matter; others from friends, with whom ties had been stretched by distance and neglect, saying: I'm glad to see you're still at it. Other letters represented unique interests, such as the psychologist studying color blindness, wondering whether such a disability might be a reason for a person named Greenler to be interested in invisible light—or the person from Belgium Television wanting photographs of the infrared rainbow for a show they were producing, insisting that they be in color. But most of the letters were from people who shared with me the fascination of "seeing" for the first time this bow, whose undetected presence in the sky predated that of a human consciousness on this planet.

REFERENCES

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3. A general discussion of the formation of the rainbow can be found (among other places) in *Rainbows, Halos and Glories*, Robert Greenler, (Cambridge Univ. Press, 1980).
4. R. Greenler, Science **173**, 1231 (1971).