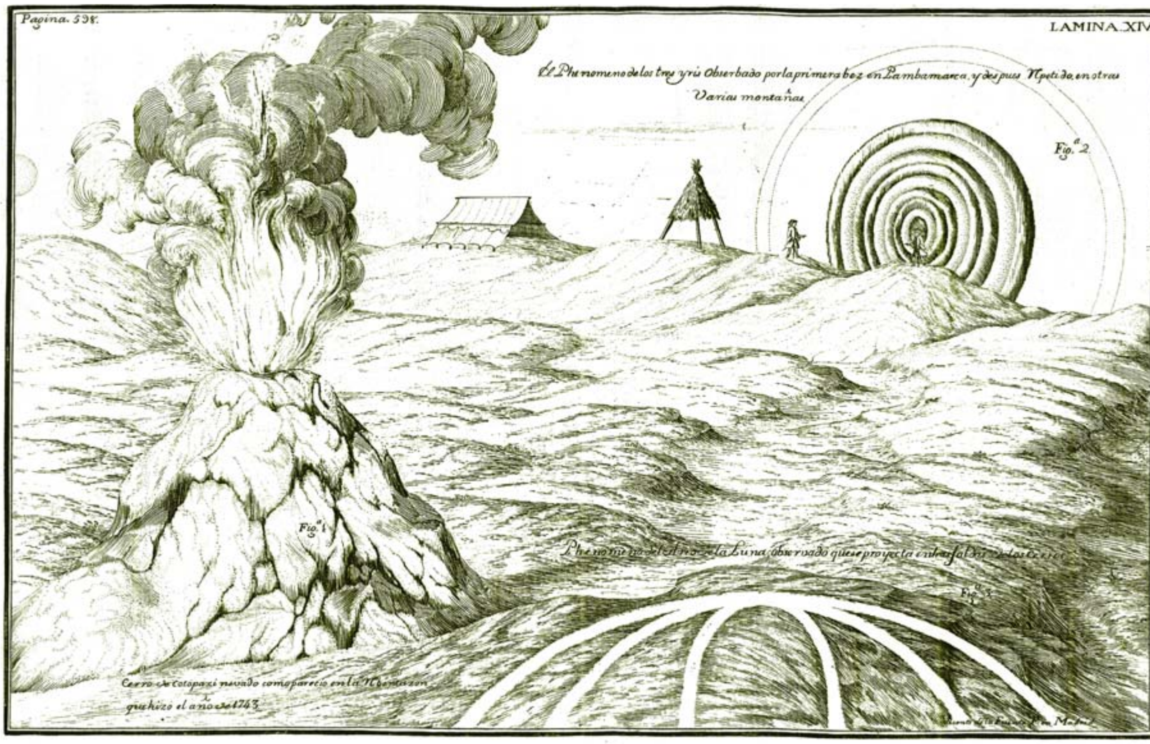

Figure 1. Illustration from A. de Ulloa and J. Juan, *Relación Histórica del Viaje a la América Meridional*. To save space, the illustrator has juxtaposed three independent events: a volcanic eruption, an observer (*upper right*) looking at a curiously three-dimensional glory and an unexplained optical phenomenon (*lower right*). [From Juan and Ulloa (1752). Courtesy of Library of Congress Rare Books Collection.]

Antonio de Ulloa's Mystery

Stephen R. Wilk

According to *Appleton's Cyclopedia of American Biography*, in 1779, Antonio de Ulloa y de la Torre Giral, rear admiral of Spain, lieutenant-general of the Spanish naval forces, one-time governor of present-day Peru and later of the Spanish territory of Louisiana, was sent in command of a fleet of ships to the Azores. He carried sealed orders, to be opened upon arrival, which directed him to proceed to Havana, Cuba, there to take charge of an expedition to reconquer Florida for Spain.*

De Ulloa was remarkable for being not only a naval officer and high-level official, but also one of the most renowned scientists of his day. He was a participant in the Spanish expedition to measure the arc of longitude in 1736, a student of the geology of South America (he authored the first description of platinum), a student of botany and an observer of optical phenomena. He was also a rare foreign member of the Royal Society of Britain.

An expedition to conquer Florida for Spain at that time would have had profound implications for the history of North America and for the American colonies, then struggling to gain their freedom from England. It would have, at any rate, had it taken place. *Appleton's Cyclopedia* reports that "… entirely occupied with scientific observations, de Ulloa forgot to open his sealed orders, and, returning to Cadiz after a cruise of two months, was arrested and tried by a court-martial in December, 1780, which acquitted him, but recommended him for land duty."[1]

It's a great story, one that combines geopolitics and history with the ever-popular saga of the absent-minded professor. Unfortunately, like most such stories, it apparently isn't true. No biography of de Ulloa published since 1900 reports him guilty of such negligence. An entry in the *National American Biography*, for instance, attributes the "… charges of neglect of duty growing out of the loss of a Spanish ship [to] his failure to capture eight British merchantmen."[2,3]

The reasons the multitalented, posthumously maligned de Ulloa has made an appearance on these pages include his participation in the expedition to measure the arc of longitude in South America in 1735 and the fact that, while in what is now Ecuador, he made a series of interesting optical observations. He is credited with the first report of a white rainbow, or "fog-bow"(also known as the "circle of Ulloa" in his honor). Such a colorless rainbow usually occurs when the droplets of water suspended in the air are smaller than about 25 micrometers. De Ulloa also observed the glory in a cloud bank that surrounded his shadow in the valley below Mount Pambamarca. Both observations were reported in *Relación Histórica del Viaje a la América*

* Florida had been under the control of the British since the Seven Years' War (1756-63). The Spanish eventually recaptured portions of it, beginning in 1781 with Pensacola. In 1784, Spain ultimately regained control of the entire peninsula as a result of the treaty that ended the American Revolution.

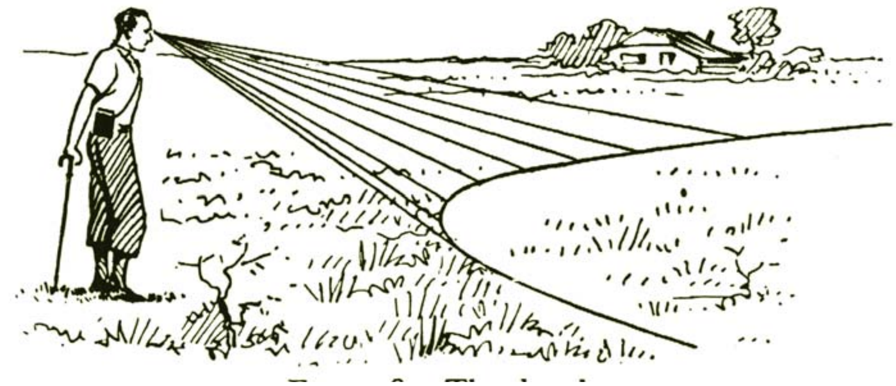

Figure 2. The dew-bow, or horizontal rainbow, is formed by droplets of water suspended on blades of grass. The observer interprets the 42-degree cone as a hyperbola on the ground rather than as a circle suspended in the air. [From Minnaert's *The Nature of Light and Color in the Open Air*. Courtesy of Dover Publications.]

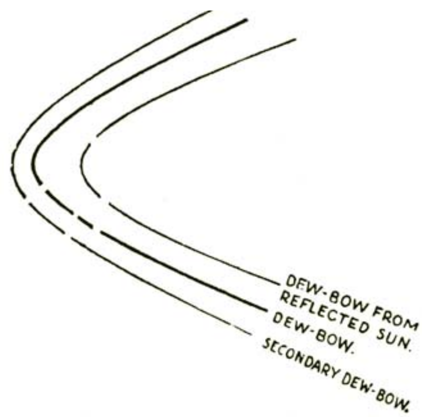

Figure 3. If the dew-bow, the reflected dew-bow and the secondary dew-bow were all present and "painted" on the ground (as they seem to be to the observer), this is how they would appear when viewed directly from above. Compare this to the figure in the lower right in the engraving from de Ulloa and Juan. [From Minnaert's *The Nature of Light and Color in the Open Air*. Courtesy of Dover Publications.]

Meridional, written with a collaborator, Jorge Juan, and published in Madrid in 1748.

It was during the expedition to measure the arc of longitude in 1735 that de Ulloa, along with Don Jorge Juan, visited the Paramos of present-day Ecuador and made a number of interesting optical observations. From the top of Mount Pambamarca, de Ulloa observed the glory, a series of tight, rainbow-like circles that can be seen around a shadow. The phenomenon is frequently seen by today's airline passengers around the shadow of a plane, but in those pre-flight days one of the few opportunities to observe it was looking down into a cloud bank at one's own shadow from the top of a mountain.

On the same trip during which he made these observations, de Ulloa made a third, more mysterious one, this time by the light of the moon. He described a series of three colorless arcs that intersected at a single point (see Fig. 1). Lynch and Futterman[4] translate the relevant passage: "On several occasions we noticed that in these Mountains the Arches were formed by the light of the Moon. I saw a quite singular one the fourth of April 1738, in the Plain of Turubamba at 8 o'clock in the evening; but the most extraordinary of all was observed by Don George Juan on the Mountain of Quinoa-Loma on the 22nd of May, 1739 at eight o'clock in the evening. These Arches were composed of no other color than white, and formed themselves in the slope at the top of a Mountain. The one which we saw was composed of three Arches meeting at a single point. The diameter of that in the middle was 60 degrees, and the thickness of the color white occupied a space of five degrees. The two other Arches were similar to that one."

Since De Ulloa and Juan oversaw the preparation of the engraving that illustrated their work (they refer to it in the text), the peculiar white arcs depicted are clearly meant to convey what they saw. The fog-bow and the glory are clear enough, and represent well-understood phenomena. But what is the third effect? As Lynch and Futterman properly note, "Apart from the difficulty in assigning a diameter to any of the arcs shown in [our] Fig. 3, because they do not appear circular and therefore do not have a constant radius, it is unclear which arc is being measured."

That seems an unanswerable objection. But all the same, the illustration looked familiar to me, and I was finally able to place it. It resembles the drawing in Minnaert's *The Nature of Light and Color in the Open Air*[5] that illustrates reflected dew-bows (see Fig. 2). A dew-bow is a rainbow formed by drops suspended on the hairs of blades of grass (or presumably by some other mechanism). Rather than being suspended in air, such drops, still very nearly spherical in shape, are located approximately in the plane of the ground. What's more, the eye and the mind clearly perceive them as being on the ground, so that when one tries to account for the shape of the phenomenon, one does not perceive it as a suspended arc (the conic section generated by cutting the 42-degree cone with a plane perpendicular to its axis), but rather as a hyperbola (the conic section generated by the intersection of the cone with a plane parallel to, but not containing, the axis); see Fig. 2. It's interesting that when Minnaert presented reflected dew-bows, he drew them as if they *really were* hyperbolas or, in other words, as if the dew-bows formed real marks on the ground; in his rendition the hyperbolas represent what a viewer floating directly overhead would see (Fig. 3). Of course, such an overhead viewer would see nothing at all, because only a viewer with his back to the sun would see a series of illuminated points 42 degrees from the anti-solar point, which he would interpret (unless he made an effort to see the arcs as parts of a circle) as hyperbolas.

This is exactly the way the illustrator for de Ulloa and Juan has rendered the scene. If we assume that the location of the observer looking at the dew-bow is identical to that of the observer who earlier observed the fog-bow and the glory, then the perspective is looking down the mountain at arcs that would appear to him to lie at the same angle from the anti-solar point, but which look to us, the floating observers, like hyperbolas, or at least like a family of some sort of curves. That would also explain why de Ulloa and Juan talk about such apparently non-circular arcs as having set diameters. As seen by *their* observer, each curve does in fact have a well-defined angular diameter.

The explanation seemed correct in many ways; it is a well-known fact, for example, that a rainbow seen by moonlight appears white.[6] If the dew-bow, its secondary, and a reflected dew-bow were seen on a downward slope by moonlight, they would appear—just as illustrated by de Ulloa—as three white hyperbolas. I wrote to *Applied Optics,* which forwarded my correspondence to David Lynch. He replied that such an explanation, for all its apparent aptness, still has difficulties. The observed angular diameter of the phenomenon was 60 degrees, not 84 degrees as a dew-bow would have been. Moreover, the angular width of 5 degrees that de Ulloa and Juan reported is too wide for either a rainbow or a dew-bow. And secondary moonbows are normally too dim to be seen.

If the dew-bow, its secondary, and a reflected dew-bow were seen on a downward slope by moonlight, they would appear—just as illustrated by de Ulloa—as three white hyperbolas.

It was a long time before a better explanation came to mind. It seemed to me that my original hypothesis had not been far off. The other two phenomena de Ulloa and Juan had reported were observed in fog banks; why not this one as well? If the observed phenomenon had consisted of a series of low-lying fog-bows, then they would appear to be white in sunlight as well as in moonlight. It would have a definite angular diameter and yet appear hyperbolic in shape, so as to match the engraving. But in this case the angular diameter of the bow would be smaller; fog-bows are very peculiar forms of rainbows, formed when the size of the droplet is approximately that of the wavelength of light. Typical fog-bow diameters are about 60 degrees. Moreover, the angular width of a fog-bow is wider than that of a conventional rainbow—about 5 degrees, just as de Ulloa and Juan had reported in this case.

There is surprisingly little work on fog-bows in the literature. One very useful report appears in the *London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science.*[7] The author, James C. M'Connel, cites a series of observations made at the observatory atop Ben Nevis between May 1886 and

October 1887. The angular widths and diameters were measured with a special instrument devised there, the stephanome.[8]

Double fog-bows were reported on Nov. 12 and Dec. 26 in 1886, and then on Feb. 13, July 21 and Oct. 15 in 1887, but no measurements were taken. On Dec. 30, 1886, a double fog-bow was carefully measured. The inner bow had an inner angular radius of 32 degrees 20 minutes and an outer angular radius of 34 degrees 44 minutes. The outer fog-bow, which was quite noticeable, had an inner radius of 36 degrees 36 minutes and an outer radius of 41 degrees 22 minutes, which gave it an angular width of almost 5 degrees. The observers also reported lunar fog-bows on at least five occasions.

M'Connel notes that double fog-bows are very common, far more so than one might expect. He writes that "Out of eighteen bows no fewer than ten were double." The reason seems to be that fog-bows, given the greater uniformity of droplet size and the smaller separation between peaks at different wavelengths, don't generally "average out" the first supernumerary bow the way larger raindrops do.[9]

As for the third bow, there are two possibilities. It might be a secondary fog-bow, caused by two internal reflections rather than by one. A secondary fog-bow, like a secondary rainbow, is much dimmer than a primary, and especially so for a lunar bow, so this hypothesis seems very unlikely. The other possibility is that it is a reflected fog-bow. As in the case of a reflected rainbow, this sort of bow is caused by light reflected from fog droplets, light that comes not from the moon itself but from the reflection of the moon behind the observer. Such a bow has the same angular radius as the original bow, but a different center. For this reason, the reflected bow deceptively appears to have a different radius. When only a portion of the bow is visible, in fact, it is often interpreted as a straight segment. Segments of such reflected rainbows are responsible for reports of "rainbow pillars."[10]

A reflected bow can be quite bright, almost as bright as the primary bow, if the reflection itself is bright and nearly specular. A reflection from ice or from a plain of snow near glancing incidence would fit this requirement nicely and is not unlikely atop a 3,500 meter mountain at a temperature that might be near freezing.[11]

I suggest, then, that the unidentified phenomena reported by de Ulloa and Juan consists in fact of a lunar fog-bow accompanied by a primary reflected lunar fog-bow. The bows are observed on a snow- or ice-covered slope from which very low lying fog is being emitted, so that the bow appears to be lying on the mountainside. The mind therefore interprets these lunar fog-bows as ground-hugging hyperbolas instead of as circles suspended in the fog. The bows would not actually meet at the "closest" point, but they might easily give that impression. One of the brightest bows could have an angular diameter of 60 degrees and a width of 5 degrees, as in the case reported by M'Connell.

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Notes

1. The entry in *Appleton's Cyclopedia* (1887-89) is online at www.famousamericans.net/antoniodeulloa/.
2. On the history of Florida, see dhr.dos.state.fl.us/flafacts/shorthis.html.
3. Biographies of de Ulloa appear in Scribner's *Dictionary of American Biography* (1964) **X**, 107-8; the Oxford University Press *American National Biography* (1999) **22**, 95-6; and Scribner's *Dictionary of Scientific Biography* (1970) **XIII**, 530-1. See also references therein.
4. David K. Lynch and Susan N. Futterman, Appl. Opt. **30** (24), 3538-41 (1991). Lynch and Futterman appear to be the first to cite de Ulloa and Juan's original book. Unlike previous writers, they give the correct dates for the observations and they are the first to bring the complete illustration reproduced here as Fig. 1 to the attention of a wide audience.
5. M. Minnaert *The Nature of Light and Color in the Open Air*, Dover, 1954.
6. On lunar rainbows see Jearl D. Walker's *The Flying Circus of Physics*, Wiley, 1975 and 1977, sect. 5.37 and references therein.
7. James C. M'Connell, London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 5th series, 453-61 (June 1890).
8. The top of Ben Nevis was apparently a good place for making observations of the optical phenomena associated with fog. C.T.R. Wilson observed several glories while stationed there. It was the desire to examine glories in the laboratory that led to his invention of the Wilson cloud chamber, which would come to play such an important role in particle physics. See James Burke *Connections* (Little, Brown, 1978), 39, or see the second episode of his PBS series of the same name, "The Road to Alexandria."
9. For a good photograph of a fog-bow and a comparison to theory see www.sundog.clara.co.uk/droplets/fogbow.htm. For excellent pictures of fog-bows, see www.meteoros.de/nebel/nebel_b.htm
10. On rainbow pillars, see Walker, sect. 5.39 and references therein.
11. See page 3541 of the work by Lynch and Futterman cited at ref. 4.