Probable photographic detection of the natural seventh-order rainbow

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Received 8 September 2014; revised 25 October 2014; accepted 25 October 2014; posted 28 October 2014 (Doc. ID 216753); published 21 November 2014

We present a stacked and contrast-enhanced image comprised of 12 digital photographs that shows a series of color hues in the correct order and location to be part of the seventh-order rainbow. The observation was made on September 22, 2013, near Magdalena in New Mexico (USA). The seventh-order rainbow is located at 64° from the Sun in a region of the sky with little interference from the zero-order glow. The color hues in the image range from red to blue-violet, spanning about 12° in total extent; their locations generally agree with a numerical Debye-series simulation of the seventh-order rainbow. Despite the low color contrast of the seventh-order rainbow, the current observation indicates that it is feasible with current digital-imaging technology to detect this higher-order rainbow in near-ideal atmospheric conditions. © 2014 Optical Society of America

OCIS codes: (010.1290) Atmospheric optics; (010.1310) Atmospheric scattering; (010.1690) Color; (010.7295) Visibility and imaging; (100.2000) Digital image processing; (110.5200) Photography.

http://dx.doi.org/10.1364/AO.54.000B93

1. Introduction

The recent photographic observation of the third-order (tertiary) rainbow [1], followed by those of the fourth-order (quaternary) rainbow [2] and the fifth-order (quinary) rainbow [3], has renewed interest in the study and search for natural higher-order rainbows. These observations motivated a recent study to investigate the degree of polarization and visibility of higher-order rainbows [4,5]. This study suggested the possibility of imaging the natural seventh-order (septenary) rainbow, if photographed in polarized light and near-optimal atmospheric conditions.

As with the tertiary and quaternary rainbows, the seventh-order rainbow is located in the sunward region of the sky, its red band appearing at 64° from the Sun. The rainbow is produced by light that has undergone seven internal reflections within a drop (Fig. 1). Although the seventh-order rainbow has lower intensity than the nearby tertiary and quaternary rainbows, which appear at ~40° from the Sun, its loss in contrast with the background is mitigated by the fact that the zero-order glow at ~65° from the Sun is one order of magnitude weaker than at ~40°.

Upon the suggestion of possible detection of the natural seventh-order rainbow, a search spanning one year was undertaken for this rainbow, resulting in one observation in which traces of the seventh-order bow seem present. The observation was made in light rain from a receding thunderstorm in the late afternoon of September 22, 2013, near the village of Magdalena in New Mexico, USA.

2. Observation

Aside from the candidate seventh-order rainbow, several previously documented [1–3] higher-order rainbows appeared in the late afternoon of September 22, 2013. Between 23:32 and 23:40 UTC (17:32 and 17:40 local time) bright primary and secondary rainbows

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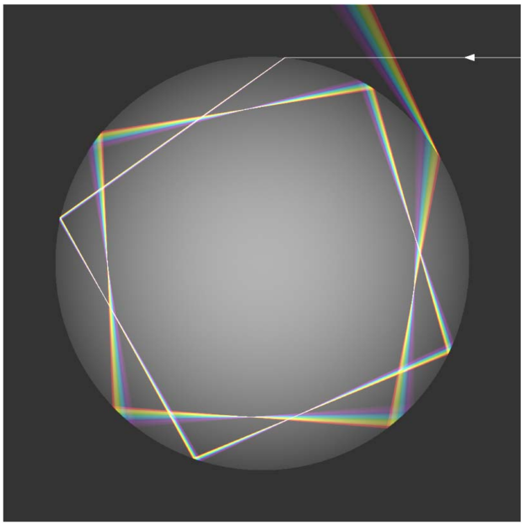

Fig. 1. Schematic diagram of the ray path producing the seventh-order rainbow. The incoming ray undergoes seven internal reflections within the drop before exiting. (All rays are rendered at the same intensity.)

appeared in the east. Contrast-enhanced versions of the individual photographs obtained during this time interval show the tertiary and quaternary rainbows on the opposite side of the sky, and the green and blue-violet color bands of the quinary rainbow [6] in Alexander's dark band between the primary and secondary rainbows.

At 23:36 UTC, with the Sun at an elevation of 17.4° and azimuth of 257.7°, a series of 12 photographs were taken in a south-southwest direction within a timespan of 3 s. The photographs were processed in Adobe Lightroom 4 and then stacked in Adobe Photoshop CS5 using the median stacking method to reduce image noise and increase the dynamic range. The unenhanced stacked image is shown in Fig. 2, in which the tertiary rainbow is just above the limit of detectability.

At the time of the observation, none of the tertiary, quaternary, and seventh-order rainbows were visually seen. The tertiary rainbow was briefly visually sought, but in a wrong direction, namely, in a region higher up in the sky where it does not appear in the photographs, instead of in the region immediately above the horizon (Fig. 2).

Figure 3 shows a cropped version of Fig. 2, which is enhanced in contrast and saturation and has an unsharp-mask filter applied. Four regions are identified and marked in the figure, corresponding to red, green, blue, and blue-violet hues, respectively (in order from left to right in the image, toward the Sun). The tertiary and quaternary rainbows are conspicuous, appearing farther to the right and ~20° closer to the Sun.

The camera was a Nikon D700 digital camera fitted with a Nikon Nikkor 24–70 mm 1:2.8G ED lens set at a focal length $f = 24$ mm and aperture of $f/5.6$ and fitted with a photographic circular polarizing filter (a linear polarizer combined with a quarter-wavelength retarder on the lens side of the filter).

Fig. 2. Median-stack of 12 photographs from September 22, 2013, at 23:36 UTC. In this unenhanced image the third-order (tertiary) rainbow is visually detectable just above the horizon near the center of the frame. In the original image, hints of the adjacent fourth-order (quaternary) rainbow are also discernible. The Sun is to the right just outside the frame. The horizontal field of view is 75°. A TIFF version of the image is available in the online multimedia content accompanying this paper (Media 1).

The camera was set to ISO 400 and an exposure time of 1/500 s. The polarization filter was oriented with its polarization axis vertical. At the location where the seventh-order rainbow appears, this corresponds within ~10° to the orientation that is perpendicular to the scattering plane.

3. Image Processing and Numerical Simulation

The imaging parameters of the stacked image were obtained following the same calibration method described in [3]. In this case, two landmarks (hilltops on the horizon) were identified and the corresponding azimuth and elevation coordinates calculated

Fig. 3. Top: Cropped section of Fig. 2 at increased contrast and saturation and an unsharp-mask filter applied. The third-order (tertiary) and fourth-order (quaternary) rainbows appear at right. Bottom: The same image with annotated regions of color hues at the location of the seventh-order rainbow (R = red; G = green; B = blue; BV = blue-violet). The horizontal bar represents 12° in azimuth; the total horizontal field of view spans ~40°. A TIFF version of the image is available in the online multimedia content accompanying this paper (Media 2).

Table 1. Camera Calibration Parameters

Sun azimuth	257.7°
Sun elevation	17.4°
Camera azimuth	216.4°
Camera elevation	18.1°
Frame rotation	1.1° counterclockwise
Focal length	23.8 mm
Sensor resolution	118.222 pixels/mm

from their global positioning system (GPS) coordinates. The coordinates were converted to pixel coordinates and drawn on the image. By adjusting the estimated values for the camera attitude and other imaging parameters, a good match could be obtained. The estimated accuracy of the calibration method is 10′ in clock and scattering angles. The calibration parameters are listed in Table 1.

To visualize the theoretically expected appearance of the seventh-order rainbow, a numerical simulation using the Debye series expansion was carried out, using the same software and workflow as described in [3]. The Debye orders $p = 0$ (external reflection), $p = 1$ (zero-order glow), $p = 4$ and $p = 5$ (tertiary and quaternary rainbows), and $p = 8$ (seventh-order rainbow) were calculated for a nominal and monodisperse droplet radius [3] of 0.5 mm. As there are no significant contributions from the orders $p = 2$ (primary rainbow) and $p = 3$ (secondary rainbow), these orders were not included. The simulated rainbows were overplotted on the photograph (with reduced intensities of $p = 0$ and $p = 1$) using the same parameters for image calibration and polarization (Fig. 4).

4. Discussion

The contrast-enhanced stacked photograph in Figs. 3 and 4 shows red, green, blue, and blue–violet hues at locations closely matching the position of the simulated seventh-order rainbow. The four color hues span a total angular width of ~12° in scattering angle (from ~53° to ~65°), which is consistent with the large angular width of the seventh-order rainbow. The red and green hues are the most conspicuous in the image.

The candidate seventh-order rainbow only appears close to the local horizon in front of cloud. The same is true for the tertiary and quaternary rainbows, even though rain was falling at the location where the photographs were taken. The blue sky background at higher-elevation angles prevents visual identification of any of the three rainbows in the image.

Due to the limited dynamic range of the digital image, the extremely low color contrast of the seventh-order rainbow, as well as the nonuniform background, it is not feasible to extract RGB light curves from the photograph for either the tertiary, quaternary, or seventh-order rainbow. A quantitative

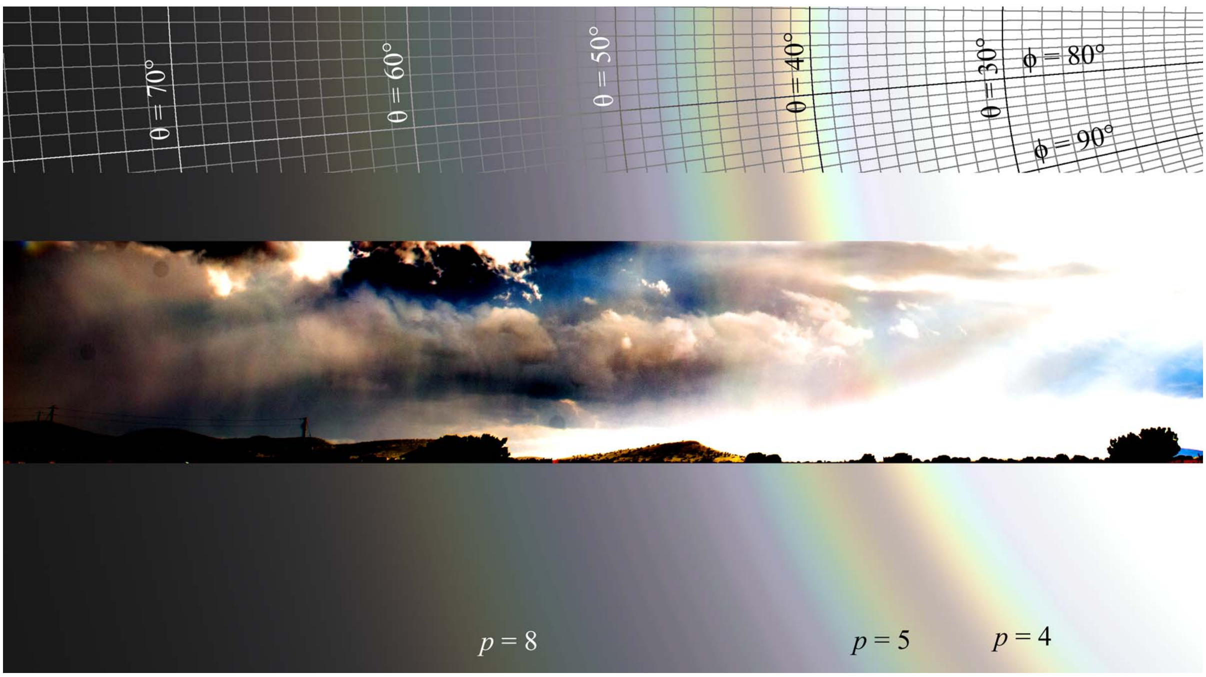

Fig. 4. Simulation of Debye orders $p = 0$, $p = 1$, $p = 4$, $p = 5$, and $p = 8$ overlaid on the contrast-enhanced image (Fig. 3). In the simulation, the calculated intensities of the tertiary, quaternary, and seventh-order rainbows (Debye orders $p = 4$, $p = 5$, and $p = 8$, respectively) are in mutual proportionality to each other; those of the $p = 0$ and $p = 1$ orders (external reflection and zero-order glow) are reduced by a factor of 30 in order to visualize the three rainbows. Convolution by the solar disc (smearing) is taken into account. In plotting the Debye orders, a polarization filter was simulated with vertical axis of polarization. The color hues in the photograph at ~60° from the Sun (indicated in Fig. 3) match the positions of the color bands of the simulated seventh-order rainbow ($p = 8$). The scattering coordinate frame (scattering angle θ and clock angle ϕ) is overlaid at the top of the figure. The horizontal field of view is 56°. A TIFF version of the image is available in the online multimedia content accompanying this paper (Media 3).

comparison between the photograph and Debye-series simulations (such as performed in [3]) is therefore not possible.

The low color contrast of the seventh-order rainbow, even in the contrast-enhanced image, may render it undetectable on some computer displays. The same is true for the visibility of the tertiary rainbow in the original, unenhanced image in Fig. 2. We (the two authors) identified the candidate seventh-order rainbow in the contrast-enhanced image independently from each other by indicating the locations of observed color hues, which were found to be in mutual agreement. After this initial possible detection, simulations of the seventh-order rainbow were run and overlaid on the image. Agreement was found with the locations of the color hues seen in the image (Figs. 3 and 4).

We have found that the tertiary (and hints of the quaternary) rainbow is readily detectable in Fig. 2 on good-quality computer displays, e.g., of the super-in-plane-switching (S-IPS) type, but to a lesser degree or not at all on other types of displays. The same may hold for the color hues that we attribute to the seventh-order rainbow. Furthermore, image compression reduces or eliminates areas of low color contrast from digital images. For these reasons, Figs. 2–4 are also available as TIFF files in the online multimedia content accompanying this publication (see also [7]).

The positive identification of the quinary rainbow on a large number of occasions (12 cases as of September 4, 2014 [6]), all in the same geographic region of New Mexico, reinforces the notion that higher-order rainbows are not rare [3] and do occur on a regular basis in regions where the atmosphere is very clean. The same may well be true of the seventh-order rainbow; the main difficulty in documenting additional cases may simply be in waiting for the opportune moment in which the Sun, rainfall, and observer are all positioned in an optimal viewing geometry, with a dark and featureless background.

In this observation, the color hues indicative of the seventh-order rainbow appeared in a localized region of the sky in a nonuniform background. More photographic observations are required to obtain a better sense for the general appearance of the seventh-order rainbow and to gain a better understanding of the characteristics of the rainfall and other atmospheric conditions in which the rainbow may appear.

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