7.9 Imaging Polarimetry of the Rainbow

The rainbow, a coloured circular band visible at about 42° from the antisolar point if sunlight falls onto water droplets underneath clouds, is one of the most spectacular phenomena in nature. It is not mere chance that many artists drew inspirations from rainbows (Lee and Fraser 2001). One of the peculiar characteristics of the rainbow is, that rainbow light is strongly polarized with the direction of polarization tangential to the bow, as discovered by the French physicist, Jean Baptiste Biot in 1811.

The light-scattering properties of large water spheres have been studied in great depth to explain the intensity and colouration of the rainbow light (Minnaert 1940; Tricker 1970; Greenler 1980; Coulson 1988). The polarizational characteristics of the rainbow have also been investigated theoretically. Assuming unpolarized incident light on water droplets of various sizes, Dave (1969) computed the intensity I and degree p of linear polarization of the scattered light. He concluded that there is a strong oscillation of p between the primary and secondary rainbows as well as in the areas of the supernumeraries of the primary rainbow. Khare and Nussenzveig (1974) proposed a theory of the rainbow and compared it with the exact Mie solution. Their improvement was particularly remarkable for electric polarization. Können and de Boer (1979) extended the Airy theory of the rainbow to polarized incident light with the direction of polarization perpendicular or parallel to the scattering plane, which is tangential or radial to the bow at any point along the rainbow. Nussenzveig (1979) developed a complex angular momentum theory of the rainbow including parallel and perpendicular polarization components. Mobbs (1979) gave a rainbow theory based on Huygens's principle and compared it with the complex angular momentum theory. He found a good agreement over a large range of scattering angles and size parameters for both the magnetic and electric polarizations. Using Mie theory for monodisperse water drops, Lynch and Schwartz (1991) calculated p of rainbow light without background contribution. They obtained that the maximum polarization p_{max} (occurring at the peak brightness of the bows) of both primary ($p_{max} < 90\%$) and secondary ($p_{max} < 50\%$) bows varies with drop size. Wang and van de Hulst (1991) compared the results of Mie computations with those of the Airy approximation. Lee (1998b) compared the differences in the perceptible colour and luminance as well as in the angular positions of luminance extrema between the Mie and Airy rainbow theories.

The rainbow is a relatively exceptional atmospheric phenomenon, the polarimetric study of which is made more difficult by the fact that its appearance cannot be predicted. It occurs by chance when generally there is no polarimeter at hand, and if there is a polarimeter, one may wait usually a long time for the possible occurrence of a rainbow. Due to the difficulties in observing rainbows, the experimental research of the rainbow's polarizational characteristics is scarce. Using a polar nephelometer employing a monochromatic linearly polarized laser source, Sassen (1979) performed angular scattering measurements with vertically and horizontally polarized incident light to examine the rainbow generation of pendant water drops, a type of artificial near-spherical, vertically elongated particle, which models the distorted shape of larger (diameter > 0.3-1 mm) raindrops with circular cross section in the horizontal plane during fall. He measured linear polarization ratios as a function of scattering angle and compared the experimental data with theoretical predictions. Können (1986, 1992) published a pair of colour photographs taken by A. B. Fraser about a rainbow viewed through a linearly polarizing filter: on the left and right photograph the rainbow light was maximally transmitted and extinguished, respectively. In the 1991 "Light and colour in the open air" feature issue of Applied Optics (Lock 1991) also some rainbow photographs taken by A. B. Fraser through linear polarizers were presented. Lee (1991) used these photographs to isolate the rainbow's intrinsic colours exploiting the fact that rainbow light is highly linearly polarized compared with light from the background: The rainbow's perpendicular polarization component is defined as that seen through a linear polarizer when its transmission axis is perpendicular to the scattering plane determined by the sun, a raindrop contributing to the bow, and the observer. At this polarizer orientation, the rainbow is the brightest. If the polarizer is rotated by 90°, the bow's much weaker parallel polarization component is practically invisible. Light from the backround (landscape and cloudy sky) is usually almost unpolarized. Thus an estimate of the rainbow's intrinsic colours (without background) can be obtained if the digitized image of a rainbow's perpendicularly polarized component is colourimetrically subtracted pixel by pixel from its parallelly polarized counterpart.

The spatially extended polarization patterns of rainbows existing only for short periods would be difficult to study by point-source scanning polarimeters; these patterns can be measured only with wide field-of-view imaging polarimetry. Barta et al. (2003) have performed the first imaging polarimetric investigation of the rainbow. Figure 7.9.1 shows the polarization patterns of a rainbow above the sea surface measured at 450, 550 and 650 nm. The primary rainbow was as usual red outside and blue inside and the innermost colours were paler than the red. At about 11° outside the primary rainbow, a secondary rainbow with a reversed sequence of colours appeared, which was much fainter than the primary one and a few supernumerary rainbows were also visible below the primary one. These are unfortunately not recognisable in the prints. The plots in Fig. 7.9.2 represent the p- and α-values measured at 450, 550 and 650 nm as a function of the angle of elevation θ along the vertical arrows in Fig. 7.9.1 after subtracting the contribution of light from the sky background.

In the p-patterns, the rainbow shows up most strikingly at 650 nm (red), while at 450 nm (blue) it is hardly visible. In the red also the arc of the secondary bow is discernible. Crossing the primary rainbow upward, there is an abrupt decrease of p: at 650 nm, for example, p decreases from about 50% of the primary rainbow to about 5% of Alexander's dark band between the primary and secondary rainbows. The light in Alexander's dark band is unpolarized, because the background skylight is unpolarized. Lee (1991) and Gedzelman (1982) discussed the role of the background skylight in observations of the rainbow. Moving off downward from the primary rainbow, p gradually decreases with some oscillations (Fig. 7.9.2. These oscillations are due to the supernumerary rainbows. At all three wavelengths, in the α-patterns (Fig. 7.9.1) and α-plots (Fig. 7.9.2) the rainbow does not show up, which demonstrates that there is no contrast in α between the rainbow and its celestial background.

According to Können and de Boer (1979) as well as Können (1985), the strong polarization of the rainbow is the consequence of the path that the beams of light generating the rainbow follow in the drops: In the primary or secondary rainbow, the beams suffer one or two reflections in the drop, respectively. Since these reflections happen at angles very near the Brewster angle, the reflected light is highly polarized, and the direction of polarization is always perpendicular to the scattering plane, that is, tangential to the arc of the bow. Since the light below the primary rainbow and above the secondary one rises in the same way as the light of the rainbow itself, its direction of polarization is also tangential to the bow. Though the scant light from the Alexander's band between the primary and secondary rainbow arises from reflections from the outside surface of the water droplets, background skylight plays a large role also. This light is also tangentially polarized with respect to the bows.

Hence, the direction of polarization of sunlight returned by the primary and secondary rainbows, as well as by the celestial regions below the primary rainbow, between the primary and secondary bows and above the secondary bow is always perpendicular to the scattering plane, that is, tangential to the bows. Thus, there is no contrast in α between the rainbows and their sunlit celestial surroundings, which usually is also characterized by E-vectors perpendicular to the scattering plane. This is why the rainbow does not show up in the α-patterns and α-plots.

The explanation of the observation, that in the p-patterns the investigated rainbow showed up best in the red, but was hardly visible in the blue, is that the background light was unpolarized or only very weakly polarized due to multiple scattering, and it was most intensive in the blue due to Rayleigh scattering, therefore it could most strongly desaturate and depolarize the coloured and polarized rainbow light in the blue. Furthermore, the partially polarized light scattered in the air column between the observer and the rainbow, and being most intense in the blue, partly overwhelms the rainbow light, especially in the blue. This is clearly seen in Fig. 7.9.2: p of blue light from the surrounding of the rainbow is much higher than p of green and red light.

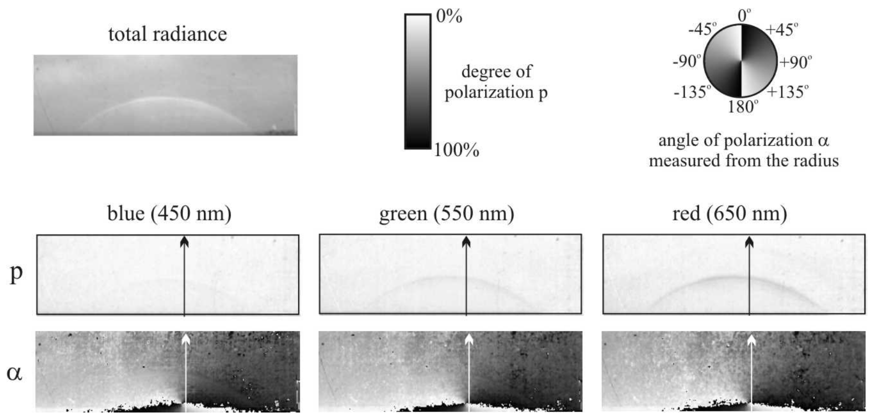

Fig. 7.9.1. Patterns of the total radiance, the degree of linear polarization p and the angle of polarization α of a rainbow above the sea surface at the shore of Oulu (65°0'N, 25°26'E, Finland) measured at 450, 550 and 650 nm by 180° field-of-view imaging polarimetry on 18 July 2001, at 17:42 (local summer time = UTC+3) when the solar elevation was 29°41'. Time of exposure = 1/250 s, aperture = 5.6, detector = Fujichrome Sensia II, 100 ASA colour reversal film. At a given point of the α-patterns, α is measured clockwise from the radius of the bow. (After Fig. 3 of Barta et al., 2003, p. 403).

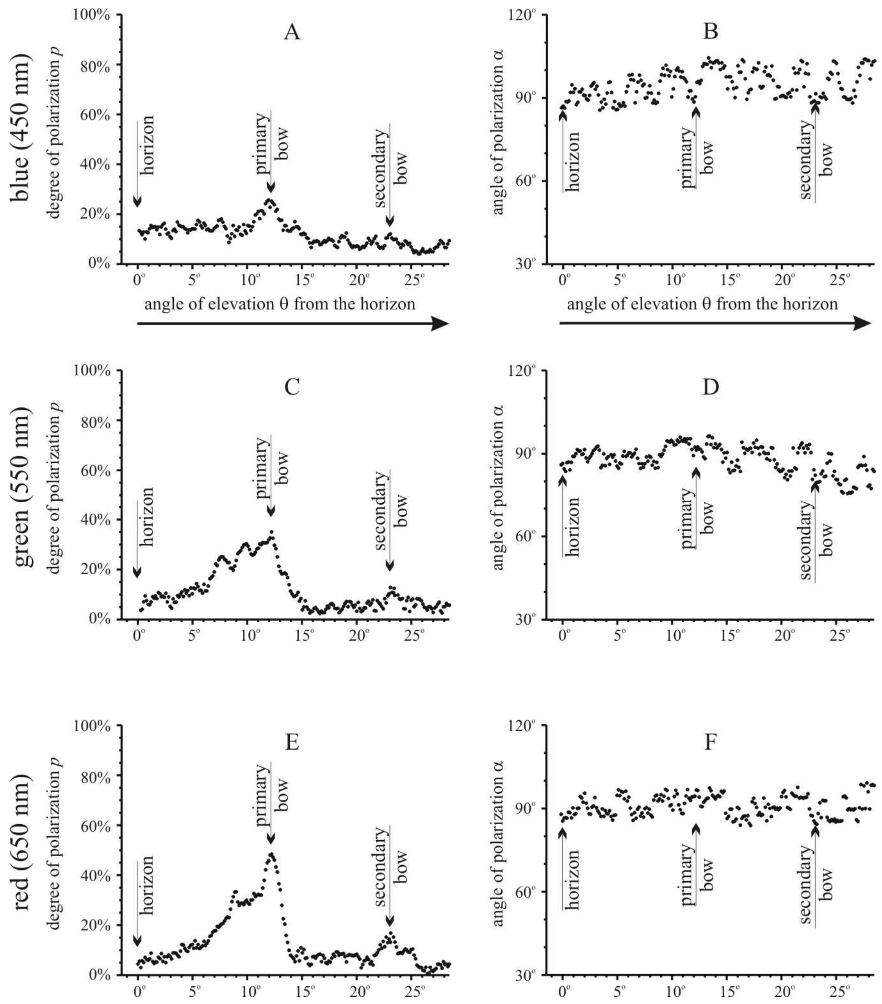

Fig. 7.9.2. Degree of linear polarization p and angle of polarization α at 450, 550 and 650 nm as a function of the angle of elevation θ along the vertical arrows shown in Fig. 7.9.1 (pointing from down $\theta = 0^\circ$ to up $\theta = 28^\circ$) after subtracting the contribution of the weakly polarized light from the sky background. (After Fig. 4 of Barta et al., 2003, p. 404).