POLARIZATION IN NATURE
(INVITED)

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ABSTRACT: In the open, we are surrounded not only by a mass of colour, but also by much polarization. The latter normally remains invisible to us, but with the aid of a simple polarizing sheet, like those in Polaroid sunglasses, one suddenly becomes aware how much polarization there is. In this article, a number of observations are described and the regularities in the natural polarization pattern are discussed.

Polarization

Light is characterized by three properties: intensity, colour, and polarization. The state of the light around us is thus completely defined only if these three characteristics are all known. Natural light displays not only strong variations in its intensity and colour, but also in its linear polarization. In other words, much of the light around us has a preferential plane of vibration, and the strength of this tendency (degree of polarization) and the position of this preferential plane (direction of polarization) may vary from place to place. Unfortunately, however, such variations remain almost entirely hidden from us, since the human eye is barely able to distinguish between unpolarized and polarized light: we are, so to say, "polarization-blind". Many animals share this handicap with us, but not all. Bees, for instance, can observe the polarization of light as easily as we can see colours, so that this particular aspect of light is vividly visible to them. If such animals were smart enough, they could use the additional information gained from their polarization observations to their advantage.

This happens, indeed, to be the case: in 1949 K. von Frisch showed that bees are able to infer the position of the Sun from the polarization pattern of the blue sky and use this to orient themselves. Since then, many other insects are found to do the same thing.

The Polarized World

With the aid of a simple polarizing filter, we can easily overcome our polarization-blindness. Such filters are easily accessible, since they are present in common Polaroid sunglasses. A polarizing filter

W.-M. Boerner et al. (eds.), Direct and Inverse Methods in Radar Polarimetry, Part 1, 33–44.

transmits only one direction of polarization. If this transmission direction corresponds to the polarization direction of light, it is transmitted by the filter; if the directions are perpendicular to each other, the light is weakened. The stronger the degree of polarization, the stronger the weakening.

Inspecting the world with a polarizing filter rotating before the eye, one suddenly becomes aware how much and how varied this polarization is in Nature: some objects change their appearance considerably during the rotation of the filter, others hardly at all, and the direction of polarization may vary from object to object. A typical example of strongly polarized light is the blue sky, particularly at about 90° from the Sun. Fig. 1 shows the sky observed with a polarizing filter directed in such a way that it maximally transmits its light; its appearance does not differ very much from that viewed with the naked eye. In Fig. 2, however, the filter has been rotated by a quarter of a turn and the aspect has changed drastically: in this case the contrast with the clouds is even entirely reversed. Watching a clear sky with a filter in the latter position, one perceives an impressing dark band at 90° from the Sun marking the area of maximal polarization. D.F.J. Arago was the first to report this remarkable polarization; his observation dates back to 1809.

As mentioned, some animals do see polarization clearly and even make use of it. But that does not mean that they see such a dark band in the sky as we see with the filter: they basically see "something different". Fortunately, it does not require very much imagination to know what they are actually seeing, since humans are still able to catch a feeble glimpse of the real appearance of the polarized world. This capability was recognized by K. Haidinger in 1844. The fact is, that in polarized light, we see in the centre of the retina a yellowish structure, which is absent in unpolarized light. Usually, however, some practice is needed to see it. The procedure is as follows: Take a filter for the eye to produce strongly polarized light, rotate it slowly, look to infinity, and relax. After a few seconds the yellow structure which co-rotates with the filter becomes visible. Once achieved, it becomes progressively easier to see this so-called Haidinger brush and it then may even reveal the polarization of the blue sky to our naked eyes.

Nevertheless, our sensitivity to polarization is only weak and we will restrict ourselves further to observations by filters, giving far more spectacular results, among them the "dark band" in the sky already mentioned. We have to realize, however, that the existence of this band is just a consequence of the specific properties of the filter, which is translating polarization shades into intensity shades for us. Through a filter, one thus perceives a very remarkable world, in which real intensity shades are intermixed with shades resulting from the translation of polarization into intensity. As the eye responds logarithmically to intensity, the most striking differences between Nature viewed with and without a filter occur when the filter is in a position close to maximal extinction. Moreover, in this position, the image is very sensitive to a small rotation of the filter. One may say that the filter then shows us at its best its translation of the "polarized world".

It is amazing that such a simple device as a polarizing filter suffices to give parts of our world such a dramatically different appearance. This is the consequence of two facts: our almost complete polarization blindness and the large amount of polarization around us. Since relatively few people seemed to be familiar with the polarized world and no guide for it existed, I recently wrote a book on the subject [1]. In this article I describe some major effects in a historical perspective and discuss the regularities in the natural polarization pattern.

Gloss, Reflections, and Umov's Rule

Although the blue sky is a nice example of strong polarization in Nature, it is certainly not the best known one which is provided by the gloss of smooth surfaces like water or window panes. Its polarization was discovered in 1808 by E. Malus, when he was looking at glass through a calcite crystal. In such a crystal, light is split into two rays of opposite polarization. This effect had already been observed by C. Huygens in 1690, although he did not know the reason of the intrinsic difference of the two rays. Malus found that the two images produced by calcite (sometimes called "drunkard's-glass") were extinguished alternately when he rotated the crystal. This discovery marks the start of the exploration of polarized light in Nature.

Figs. 3 and 4 show the polarization of the gloss at a water surface of a pond. Again, the appearance changes drastically: when the gloss is maximally extinguished by the filter, even plants at the bottom of the pond become visible as the glare is eliminated. Apparently, at the angle at which we are observing the water surface in this picture, the polarization is almost complete. If one looks at a steeper or a more grazing angle, the polarization is less: this also can be seen in the pictures. Indeed, as was pointed out by D. Brewster in 1812, there is one particular angle of reflection at which unpolarized light is converted completely into polarized light. For most natural substances this Brewster angle of reflection is about 50°. As a consequence, the completely polarized image of the Sun, reflected at this Brewster angle, is at an angular distance of about 80° from the real Sun.

The direction of polarization of gloss is parallel to the reflecting surface. Polaroid sunglasses make use of this, the sheet polarizers being set in the frames with their transmission direction vertically. Consequently, they reduce the glare from horizontal smooth surfaces without greatly affecting the appearance of other objects. Of course, for vertical surfaces like window panes, such sunglasses do not confer this advantage: on the contrary, they make the situation more unfavourable.

Many objects in Nature are not smooth enough to have a gloss: they scatter light in all directions. But coloured, diffusely reflected light is also polarized, although the degree of polarization is by no means as strong as that of a glossy surface. Interestingly, the degree of polarization of rough objects is governed by a simple rule, given by N. Umov in 1905: the darker the surface, the stronger the polarization. Hence, the light reflected from concrete is less polarized than that from dark asphalt. Likewise, the diffusely reflected light of wet bricks is more strongly polarized than that from dry bricks. An interesting consequence of this rule is that colours of objects in Nature are more pronounced if the intensity is maximally extinguished with a polarizer. The direction of polarization of diffusely reflected light is perpendicular to the plane of scattering (that is, the plane containing the Sun, the reflecting particle and the observer); this holds also for the blue sky. Again, maximum polarization occurs if the reflecting object is at about 90° from the Sun. Thus, the polarization pattern of scattered light (the blue sky), diffusely reflected light, and light reflected by smooth objects are similar, differing only in the degree of polarization [1].

By far the greater part of the light encountered in Nature is scattered or (diffusely) reflected sunlight: consequently, the polarization pattern in Nature is very uniform. In this respect, the polarization pattern differs markedly from the colour pattern around us.

A Uniform Polarization Pattern

The simplicity of this overall polarization pattern (direction of polarization perpendicular to the scattering plane, maximum polarization at about 90° from the Sun) suggests that the explanation of it is simple too, and this is, indeed, the case. The reason is that light waves are transverse. This means that if they progress in the z-direction, their vibrations take place in the x-y plane only. If such a wave conceals a small scatterer, the latter starts to oscillate also and to emit light. But since oscillations in the z-direction are lacking, light emitted perpendicularly to this z-direction vibrates only in one direction: for example, light radiating in the x-direction has left vibrations only in the y-direction. Thus, this light should be completely polarized; light scattered in another angle with the z-axis partially polarized; and backward or forward scattered light unpolarized. Hence, the overall polarization pattern is caused simply by the anisotropic structure of light waves, which always lacks one of the three vibration modes. In practice, however, the maximal polarization is often weaker than this qualitative description suggests. The anisotropy of waves also explains immediately why the direction of polarization in the case of scattering by small particles, or in case of reflection, is perpendicular to the plane of scattering. This implies, that in the event the Sun is obscured but its resulting polarization pattern is still present in the sky, the solar position can be easily inferred from polarization observations. This is in fact what bees do. Interestingly, some ten years ago, the archaeologist T. Ramskou found indications that our Viking ancestors had adopted the same technique, using a cordierite crystal as polarizing filter. Such a navigation tool would have been very useful, as it works even under a cloud deck or in fog if their vertical dimensions are not too large.

Exotic Sky Phenomena

Not all the light around us emerges from direct reflection or from scattering by very small particles. Sometimes remarkable structures appear in the sky; among them the rainbow is a familiar example. These phenomena are caused by scattering of light by larger objects: in the case of the rainbow these are water drops. Such a phenomenon may have a striking appearance and display its own specific polarization. This polarization usually differs markedly from the general polarization pattern outlined above. For these reasons, such exotic phenomena are among the most delightful objects to be observed in Nature. Their complete description, however, could easily fill a full chapter in a book [1,7-10] and will not be attempted here. In this article we restrict ourselves to a brief discussion of three typical examples of this group: the rainbow, the 22° ice-crystal halo, and the glory.

The polarization of the rainbow was first observed by J.B. Biot in 1811. It was found to be extremely strong, as can be seen from Figs. 5-6. Indeed, with a polarizing filter the rainbow can be completely "rotated away". The direction of polarization is perpendicular to the scattering plane, thus tangent to the bow. As the bow appears at about 140° from the Sun, this strong polarization manifests itself at a very unusual place in the sky, hence disturbing the usual polarization pattern completely. The polarization is caused by the fact that the rainbow-generating light-path through the drop consists of the sequence: refraction-internal reflection-refraction, and that the reflection happens to occur very close to the Brewster angle. The rainbow is without doubt one of the most spectacular examples of polarized light in Nature.

The second exotic phenomenon is the group of the 22° ice crystal haloes, which often appear in cirrus clouds. A prominent member of this group is the parhelion, which shows up at 22° at the left or the right of the Sun. Such a halo is shown in Fig. 7. It is caused by refraction of sunlight by tiny, oriented hexagonal ice crystals, which act as prisms. Unlike the rainbow, a parhelion cannot be extinguished with a polarizing filter. In 1977, however, I found that something else happens: it shifts its position to and fro as the filter rotates. The distance at which the shift occurs corresponds to about one quarter of the apparent diameter of the Moon. As the angular width of the halo itself is much larger, this means that its inner, red edge is completely polarized. So, again, strong polarization is produced at an unusual place in the sky, albeit only in a small angular range. The direction of polarization of the halo-edge is in the plane of scattering, hence opposite to what one normally encounters. Although this halo-edge polarization has been known for only about ten years, it is very easy to observe with a filter. It arises from the birefringence of ice, which causes the halo to consist of two completely polarized components, which appear at a slightly different angular distance from the Sun.

The last example of our list of exotic phenomena is the glory, which is a kind of aureole around our shadow (Fig. 8). It is often visible from aircraft if the shadow point falls on clouds of small water drops. Normally, hardly any polarization is to be expected near one's shadow point, but the glory is an exception. Its polarization, first reported by J. Kiessling in 1884, is found to display to remarkable structure: its direction at the coloured ring is in the plane of scattering, but that of the bright area within this ring, close to the shadow point, is perpendicular to this. As the glory is concentrated in a small solid angle, this polarization causes a regular structure to appear in the glory if viewed through a filter. Obviously, this structure co-rotates with the filter. The strongest polarization appears when the glory is relatively large, which means that the generating drops are small. The mechanism causing the glory polarization will not be discussed here, as it is rather complex and outside the scope of this paper. Suffice it to say that the first step toward a correct explanation was given in 1947 by H.C. van de Hulst, and that the complete description by H.M. Nussenzveig dates from 1977.

From this discussion the following conclusion may be drawn. Although it is true that there is a large variation in the polarization, there is also clearly a system in it. All cases display a cylindrical symmetry in the polarization with respect to the primary light source. This means on the one hand that the magnitude of the polarization depends only on the angular distance to the Sun, and on the other hand, that the direction of polarization is either in the plane of scattering or perpendicular to it, but not in between. Apparently, this cylindrical symmetry is a basic feature of our polarized world if dominated by single scattering or single reflection.

Hierarchy and Exceptions

However, this symmetry is not valid for all light in Nature, for part of it reaches us via more than one object. Its polarization then differs from that of singly scattered or singly reflected light.

For simplicity we may divide light in Nature into three groups. Group 1 consists of the direct light sources; group 2 of light reaching us via one object; and group 3 of light reaching us via more than one object. The main characteristics of the light and its polarization of the subsequent groups are the following.

The direct light sources, group 1, are at night the most conspicuous part of our world; our eyes are inevitably drawn to them. As the light emerges from particles at high temperatures in chaotic motion, it is usually unpolarized. Examples of this group are stars and artificial lights. The Sun also belongs in this group, but as its intensity is so dazzling we take care not to look straight at it. So during the day the most striking feature is not the light source itself, but the many objects around us which it illuminates. These provide light belonging to the next groups.

Group 2, light that reaches us via one object, is the next brightest after the sources. As indicated above, it basically has a cylindrical symmetrical polarization with respect to the original light source, in which the direction of polarization is predominantly perpendicular to the scattering plane.

Group 3, light that reaches us via more than one object, is the least intense contribution. In its complicated route to our eyes its polarization may have changed drastically, so that the polarization pattern bears no obvious relationship to the position of the last object with respect to the original source. Nevertheless, strong polarization can be present if the light path is favourable. In this case, during its light path, polarized light may even become circularly polarized. This has to be observed with other types of filters than those suitable for linearly polarized light. Obviously circularly polarized light is rare in Nature.

Although the polarization of most light in the groups fits this description, there are still some exceptions. For there is light which definitely must be included within groups 1 or 2, but yet shows a polarization belonging to the next group. Indeed, there are some strongly polarized light sources in Nature. One example, the glow of clean, incandescent metals was discovered by D.J.F. Arago in 1824; a second example, discovered by V.A. Dombrovski in 1954, is the synchrotron radiation from the crab nebula. But perhaps the most outstanding example of exceptional polarization concerns a certain family of beetles, to which, for example, the rose chafer (**Cetonia aurata**) belongs. These beetles display a metallic gloss, which turns out to be completely circularly polarized! This unique feature was discovered in 1911 by A.A. Michelson. Although liquid crystals were later found to have the same property, no further examples of this particular characteristic outside this family of beetles have been found to exist in Nature. Its biological function, if any, is completely obscure [11].

Some Applications of Optical Polarization

As said at the beginning of this article, polarization is as important a property as colour in light. But since the state of polarization is determined by other factors, it often contains information which cannot easily be inferred from spectral analysis. Today very sensitive polarimeters exist, which have been successfully applied in, for example, astronomy; also interplanetary spacecrafts are often equipped with sensitive polarimeters. A further important use is in the quality control of materials: from the way they alter the state of polarization of light passing through, information can be obtained about their crystalline structure while weaknesses (mechanical tensions) in them can be detected. In daily life we are sometimes directly confronted with this latter application when we drive a car: the coloured spots which often appear in the windscreen when we wear Polaroid sunglasses are caused by this very effect. Applications of polarized light like the ones mentioned are very widespread in research, technology, and industry. It is all the more surprising that so few people seem to be aware that in the open field there is so much polarized light, in which gloss, the blue sky, and the rainbow are only just a few of many spectacular examples.

Acknowledgements

This paper is an updated version of a review paper recently published by the author on "Viewing our world with polarizing glasses" in Endeavour, New Series, Vol.10, No.3, pp.121-124, 1986.

The bibliography, below, includes key references for further reading. References [1] to [6] are primarily focussed on polarization and scattering; references [7] - [10] on rainbows, halos and other atmospheric optical phenomena.

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Figs. 1 and 2 The blue sky at 90° from the Sun viewed through a polarizing filter in two positions. Above, the filter transmits the light maximally; the aspect of the sky is similar to that viewed with the naked eye. Below, the polarized light is maximally extinguished, causing a drastic change in its appearance and, in this case, also a contrast reversal with respects to the weaker polarized clouds.

Figs. 3 and 4 A pond viewed through a polarizing filter. Above, the filter transmits its gloss maximally; below, the light is maximally extinguished. In the latter case the gloss disappears and the bottom of the pond becomes visible.

Figs. 5 and 6 A rainbow viewed through a polarizing filter. Above, its light is maximally transmitted and the rainbow is markedly brighter than when viewed with the naked eye. Below, the polarized light is maximally extinguished with the filter and the bow disappears completely.

Fig. 7 A parhelion, member of the 22° halo group. Its position in the sky shifts by .1° to and fro if viewed through a polarizing filter which is rotated; the inner red edge of the halo being completely polarized.

Fig. 8 The glory, around the shadow of the basket of a balloon. Despite it being located near the shadow point, it still produces strong polarization. (Photograph by A.F.G. Kip)