1 Brief History of the Discovery of Phenomena Concerning Light Polarization

In this preliminary chapter the main landmarks in the evolution of ideas and the discovery of phenomena concerning the light polarization are summarized. The survey consists of data taken from Shurcliff (1962), Gehrels (1974), Können (1985), Coulson (1988) and Born and Wolf (1999). Many further important steps and discoveries in connection with polarization, not listed here, are mentioned and discussed in the appropriate chapters of this work. Generally, historical notes and references are given at the start of many of these chapters. It is a widespread belief that the history of light polarization began with the Vikings, who are supposed to have used certain enigmatic birefringent crystals to analyse the skylight polarization for navigational purposes. Since the alleged Viking navigation by skylight polarization has no any culture historical or archeological evidence, we start the history of polarization with 1669 when Bartholinus discovered the birefringence of the calc-spar.

- The history of light polarization began with the Danish physicist, physician and mathematician, Erasmus Bartholinus (1625-1698), who in **1669** discovered the phenomenon of double refraction of calc-spar (or Iceland spar, a variety of calcite), although he was not yet aware of the phenomenon of polarization.
- Christian Huygens (1629-1695) Dutch physicist and astronomer interpreted the double refraction by assuming that in the crystal there is, in addition to a primary spherical wave, a secondary ellipsoidal wave. It was in the course of this investigation that Huygens made the fundamental discovery of polarization in **1690**: each of the two rays arising from refraction by calcit may be extinguished by passing it through a second crystal of the same material if the latter crystal is rotated about the direction of the ray.[1] Isaac Newton (1642-1727) English physicist, astronomer and mathematician explained these phenomena by assuming that rays have "sides". Due to this "transversality" rejected Newton the wave theory of light – proposed by Robert Hooke (1635-1703) English physicist and chemist, and improved and extended later by Huygens –, since at that time scientists were familiar only with longitudinal waves from the propagation of sound.

[1] Huygens C (1690) Traité de la lumiére. Leyden (completed in 1678, published in 1690)

- Étienne Louis Malus (1775-1812) French engineer discovered the polarization of light by reflection[2]: One evening in **1808** he observed the reflection of direct sunlight from a window pane through a calcit crystal, and found that the two images obtained by double refraction varied in relative intensities as the crystal was rotated about the line of sight. However, Malus did not attempt to interpret this phenomenon. He formulated the Malus law, that is, the proportionality of the intensity of light transmitted by a polarizer to the square of the cosine of the angle of direction of the transmission axis for linearly polarized incident light. In fact, Malus applied as first the term "polarization" to light. He hypothesized that the light corpuscles were aligned after reflection in a manner similar to the way magnetic bodies are aligned by the poles of a magnet.
- In **1809** Dominique Francois Jean Arago (1786-1853) French physicist and astronomer discovered the polarization of light from the clear blue sky.[3] Later he established that the skylight polarization is maximal at 90^{o} from the sun and found the first neutral point of the firmament, later named after him.
- In **1811** Arago observed the optical activity of quartz, and Jean Baptiste Biot (1774-1862) French physicist discovered the high polarization of the rainbow.
- In **1812** Arago constructed a filter from a pile of glass sheets.
- In **1815** Biot established the optical activity of certain liquids (e.g. turpentine) and discovered the strong dichroism of tourmaline crystals. In the same year, David Brewster (1781-1868) Scottish physicist discovered the law giving the relationship between the refractive index of a medium and the angle of incidence at which reflected light is totally linearly polarized. However, in 1810 Malus was the first, who recognized the existence of such an angle in the reflection of light from the water surface.
- Together with Arago, Augustin Jean Fresnel (1788-1827) French physicist and engineer investigated the interference of polarized rays of light and found in **1816** that two rays polarized at right angles to each other never interfere.[4] This fact could not be reconciled with the assumption of longitudinal waves of light, which had hitherto been taken for granted. Thomas Young (1773-1829) English physicist and physician, who had heard of this discovery from Arago, found in **1817** the key to the solution when he assumed that the vibrations were transverse.
- In **1818** Biot observed the optical activity of gaseous turpentine, and Brewster discovered the coloured brush in pleochroic crystals, later named after him.
- In **1819** Arago discovered the polarization of light from comet tails.

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[2] Malus ÉL (1809) Sur une propriété de la lumiére réfléctie par les corps diaphanes. Nouveau Bull d Sci, par la Soc Philomatique (Paris) 1:266-269; Mém de la Soc d'Arcueil 2

[3] Barral MJA (1858) Oeuvres de Francois Arago I-V., Gide - Paris, Weigel - Leipzig

[4] Fresnel AJ (1866-1870) Oeuvres Complétes d'Augustin Fresnel (Paris) 1:767

- In **1824** Arago observed the polarization of light emitted by incandescent metals.[5] He discovered also the polarization of moonlight and found higher polarization on the maria than on the highlands.
- In **1825** Arago established the polarization of 22° haloes.
- In **1828** William Nicol (1768-1851) Scottish physicist invented a prism, which was the first easily usable polarizing filter.
- Dynamical models of the mechanism of aether[6] vibrations led Fresnel (**1832**, 1866-1870) to deduce the laws which now bear his name, governing the intensity and polarization of reflected and refracted light.
- In **1840** Jacques Babinet (1794-1872) French physicist and meteorologist discovered the second neutral point of the celestial hemisphere, bearing his name nowadays.[7] According to Coulson (1988, p. 5), the lateness of the discovery of the Babinet point is surprising in view of the previous interest in skylight polarization and the fact that this neutral point is not difficult to see with the Savart polariscope which was in use at that time.
- In **1842** Brewster discovered the third neutral point of skylight polarization, later named after him.[8]
- In **1844** Wilhelm Karl von Haidinger (1795-1871) Austrian physicist, geologist and mineralogist discovered that the human eye is able to perceive the linear polarization of light due to an entoptic phenomenon (Haidinger brushes).[9] Later he also discovered circular dichroism in crystals of amethyst and quartz.
- In **1845** Michael Faraday (1791-1867) English physicist and chemist discovered the rotation of the plane of linear polarization of light in magnetic fields.
- In **1848** Louis Pasteur (1822-1895) French physician and chemist described optically active hemihedral crystals.
- In **1852** W. B. Herapath English physician constructed a synthetic crystal (a drug combination of iodine and quinine) with very high dichroism and optical properties similar to those of tourmaline. This later became the basis of the manufacture of simple sheet polarizers. In the same year, George Gabriel

[5] Arago DFJ (1824) Ann Chem Phys (2) 27:89 [reference from Sandus O (1965) A review of emission polarization. Appl Opt 4:1634-1642]

[6] René Descartes (1596-1650) French scientist considered light to be essentially a pressure transmitted through a perfectly elastic solid medium, the aether filling all space. In that time scientists tried to explain all natural phenomena by mechanical laws: light was considered as the rapid vibration of aetherial particles. In spite of many difficulties, the theory of aether persisted for a long time and most of the great physicists of the 19th century contributed to it.

[7] Babinet J (1840) Sur un nouveau point neutre dans l'atmosphere. Compt Rend 11:618-620

[8] Brewster D (1842) On the existence of a new neutral point and two secondary neutral points. Rept British Assoc Adv Sci 2:13

[9] Haidinger W (1844) Über das direkte Erkennen des polarisierten Lichts und der Lage der Polarisationsebene. Annal Phys (Leipzig) 63:29-39

Stokes (1819-1903) Irish physicist described the four Stokes parameters of polarized light.[10]

- In **1858** Emmanuel Liais (1826-1900) French astronomer discovered the linear polarization of the solar corona.
- In **1860** Gustav Robert Kirchhoff (1824-1887) German physicist found that incandescent tourmaline emits polarized light due to dichroism.[11]
- In **1869** John Tyndall (1820-1893) Irish physicist established the fact that the polarization of light scattered by particles changes strongly with the dimensions of the particles, explaining earlier observations on smoke particles.
- In **1871** John William Strutt, alias Lord Rayleigh (1842-1919) English physicist explained theoretically the polarization of scattered skylight.[12]
- In **1872** William Parsons, alias Lord Rosse (1800-1867) Irish astronomer found that the light from the Venus is slightly polarized.
- In **1873**, according to theoretical considerations, James Clerk Maxwell (1831-1879) Scottish theoretical physicist has conjectured that light is an electromagnetic wave.[13]
- In **1874** A. W. Wright American astronomer discovered the polarization of zodiacal light.[14]
- In **1875** John Kerr (1824-1907) Scottish physicist discovered the birefringence of electrified media (Kerr effect). Later he also established changes in metallic reflection of polarized light in the presence of magnetic fields (Kerr magneto-optic effect).
- In **1884** J. Kiessling German physicist discovered the polarization of the glory.[15]
- In **1888** Heinrich Hertz (1857-1894) German physicist verified by direct experiments that light is an electromagnetic wave.[16]

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[10] Stokes GG (1852) On the composition and resolution of streams of polarized light from different sources. Trans Cambr Phil Soc 9:233-258

[11] Kirchhoff GR (1860) Pogg Ann 109:299 [reference from Pflüger A (1902) Prüfung des Kirchhoff'schen gesetzes an der Emission und Absorption glühenden Turmalins. Ann Phys 7:806-817]

[12] Strutt JW (Lord Rayleigh) (1871) On the light from the sky, its polarisation and colour. Phil Magaz 41:107-120, 274-279

[13] Maxwell JC (1873) A treatise on electricity and magnetism. Oxford, 2 vols

[14] Wright AW (1874) On the polarization of the zodiacal light. Am J Sci Arts (3rd ser) 7:451-459 [reference from Weinberg JL (1974) Polarization of the zodiacal light. In: Gehrels T (1974) pp 781-793]

[15] Kiessling J (1884) Abh Naturw Ver Hamburg-Altona III, abt 1; Kiessling J (1885) Zur Erklärung der ringförmigen Gegen-Dämmerung. Meteorol Z 2:70-72 [references from Meyer R (1942-1961) Optik der Tropfen I., Abschnitt 2: Kränze, Glorien und verwandte Erscheinungen, Handbuch der Geophysik, Kapitel 14, Band 8, Physik der Atmosphäre I., Linke F, Möller F (eds), Gebrüders Bornträger, Berlin, pp 898-942]

[16] Hertz H (1888) Wiedem Ann 34:551 (English translation in his Electric Waves, 1893, Macmillan, London, p. 107)

- In **1889** Marie Alfred Cornu (1841-1902) French physicist observed that artificial haloes in sodium nitrate crystals are highly polarized because of the double refraction of the crystals.
- In **1896** Pieter Zeeman (1865-1943) Dutch physicist found that spectral lines can be broadened when the radiating atoms are in the presence of an intense magnetic field. He observed later the splitting of spectral lines by magnetic fields and their associated polarization (Zeeman effect).
- In **1905** N. A. Umow (1846-1915) Russian physicist described the relationship between the degree of linear polarization of light reflected from rough surfaces and the albedo of the surface.[17]
- In **1908** George Ellery Hale (1868-1938) American astronomer showed the existence of strong magnetic fields in sunspots by means of polarization measurements of the Zeeman effect. In the same year, Gustav Mie (1868-1957) German physicist and Pieter Debye (1884-1966) Dutch-American physicochemist independently developed the theory of light scattering by spherical particles of arbitrary size.
- In **1911** Albert Abraham Michelson (1852-1931) American astronomer discovered the circular polarization of light reflected from the carapace of certain beetles.[18]
- In **1928** Edwin Herbert Land (1909-1991) American physicist constructed his first successful sheet-type dichroic linear polarizer (as an undergraduate student at the Harvard University).[19]
- In **1929** Bernard Lyot (1897-1952) French astronomer published his discoveries on the linear polarization of light from planets and terrestrial objects.
- In **1935** Richard Beth discovered that circularly polarized light exerts a slight mechanical torque on materials and thus proved directly the rotating character of the electric field vector of such light.
- In **1939** Y. LeGrand French and K. Kalle German physicists reported independently of each other that underwater scattered light is linearly polarized.[20]
- In **1940** J. Bricard French meteorologist observed that supernumerary fog-bows shift when one looks at them through a rotating linear polarizer.[21]
- In **1942** Yngve Öhman found polarized light emitted by the galaxy M31.
- In **1947** H. C. van de Hulst Dutch physicist gave a feasible explanation of the glory and explained its directions of polarization.

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[17] Umow N (1905) Chromatische Depolarisation durch Lichtzerstreuung. Phys Z 6:674-676

[18] Michelson AA (1911) On the metallic colour of birds and insects. Phil Magaz 21:554

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[20] LeGrand Y (1939) Ann Inst Océanolog Monaco 19:393; Kalle K (1939) Die Farbe des Meeres. Rapports et procès-verbaux des Reunions. Conseil permanent international pour exploration de la mer 109(3):98-105 [references from Waterman TH (1954) Polarization patterns in submarine illumination. Science 120:927-932]

[21] Bricard J (1940) Contribution a l'étude des brouillards naturels. Ann Phys 14:148-236

- In **1948** Hans Mueller German physicist developed a phenomenological calculus to problems involving wide-band partially polarized light, using 4×4 matrices (Mueller matrix and Mueller calculus).[22]
- In **1949** Karl von Frisch (1886-1982) Austrian zoologist discovered the polarization sensitivity of honeybees.[23] In the same year, J. S. Hall and W. A. Hiltner found that the light from stars is polarized.
- In **1950** Subrahmanyan Chandrasekhar (1910-1995) Indian-American physicist and astronomer gave a solution of radiative transfer in a sunlit plane-parallel planetary atmosphere with Rayleigh scattering.[24] In **1960** the solutions were tabulated in convenient form by Kinsell L. Coulson, J. V. Dave and Zdenek Sekera.[25]
- In **1954** V. A. Dombrovskij Russian astronomer discovered the strong polarization of the Crab Nebula predicted with synchrotron radiation by the Russian astronomer I. S. Shklovskij. In the same year, Talbot H. Waterman American biologist rediscovered the underwater polarization.[26]
- In **1955** William A. Shurcliff discovered that the human eye is also capable of perceiving circularly polarized light (Shurcliff brushes).[27]
- In **1956** Lionel Jaffe American biologist discovered that, when certain algae cells are illuminated by linearly polarized light, they tend to develop in the direction of vibration.[28]
- In **1959** R. A. Duncan Australian meteorologist reported on the polarization of the aurora.[29] However, in later correspondence between Duncan and Günther P. Können (personal communication) this claim was disputed. Thus, the claim of Duncan is probably untrue, so the auroral light may be unpolarized.
- In **1960** Georg Witt Swedish meteorologist established the polarization of noctilucent clouds.[30]
- In **1974** the first comprehensive monograph, edited by T. Gehrels American astronomer, was published about planets, stars and nebulae studied with photopolarimetry.[31]

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[26] Waterman TH (1954) Polarization patterns in submarine illumination. Science 120:927-932

[27] Shurcliff WA (1955) Haidinger's brushes and circularly polarized light. J Opt Soc Am 45:399

[28] Jaffe L (1956) Effect of polarized light on polarity of Fucus. Science 123:1081-1082

[29] Duncan RA (1959) Polarization of the red oxygen auroral line. Planet Space Sci 1:112-120

[30] Witt G (1960) Polarization of noctilucent clouds. J Geophys Res 65:925-933 (1960)

- In **1977** Günther P. Können Dutch meteorologist discovered the strong polarization of the inner-edges of refraction halos.[32]
- In **1985** G. P. Können published his famous book about polarized light in nature.[33] In the same year appeared the monograph of the American physicist Walter G. Egan about photometry and polarization in remote sensing.[34]
- In **1988** appeared the comprehensive monograph of the American meteorologist, Kinsell L. Coulson on polarization and intensity of light in the atmosphere.[35]
- In **1989** R. M A. Azzam and N. M. Bashara American physicists published their book dealing with ellipsometry and polarized light.[36]
- In **1990** the comprehensive book edited by Jin Au Kong was published about polarimetric remote sensing.[37]
- In **1993** was published the book of the American physicist Edward Collett on the fundamentals and applications of polarized light.[38]
- In **1999** Gábor Horváth, István Pomozi and József Gál Hungarian physicists discovered several neutral points of skylight polarization during the totality of a solar eclipse.[39]
- In **2001** G. Horváth and his students (András Barta, Balázs Bernáth and Bence Suhai) observed as first the fourth (the last) neutral point of atmospheric polarization from a hot air balloon.[40]
- In **2003** G. Horváth and Dezső Varjú published their monograph about polarized light in animal vision and polarization patterns in nature.[41]

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[31] Gehrels T (ed) (1974) Planets, stars and nebulae studied with photopolarimetry. Univ Arizona Press, Tucson, Arizona

[32] Können GP (1977) Polarisation of haloes and double refraction. Weather 32:467-468

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