# 1
# Introduction and History

## 1.1
## General History

Stellar polarimetry appeared as a green shoot in astrophysical diagnostic practice some 60 years ago. Following the early nineteenth-century discoveries of polarimetric phenomena in the physics and chemistry laboratories, and the establishment of the understanding of the transverse nature of the oscillatory disturbances within electromagnetic radiation, polarimetry lay dormant for over 100 years in its application to stars. Its dawning on the stellar scene awaited the combination of a prediction by Chandrasekhar (1946) related to the outcome of radiative transfer studies for early-type stellar atmospheres, and the simultaneous development of detector technology sufficient to make an observational response to the challenge set by theory.

With a degree of interpretive licence, the introduction of polarimetry to Astronomy may be set to an earlier millennium. Much of the early history of astronomy is bound up with application of celestial observations to determinations of local time and geographical position. It has been suggested that a navigational tool, or medieval GPS, in the form of the natural crystal (*cordierite*) with polarization properties, was used as an astrolabe by the Vikings as early as AD 1000 (see Walker, 1978). With such a device the position of the Sun, hidden by a cloud, or below the horizon, could have been determined to within 3°. It might be claimed, therefore, that polarimetry was utilised within Astronomy well in advance of the more readily appreciated diagnostic tool of spectroscopy! The concept of polarimetry as applied to the pursuit of physical understanding of the heavens did not emerge, however, until the turn of the nineteenth century, with application particularly to the Solar System, running hand in hand with the development of the subject in the optical laboratory.

The history of polarimetry within the physical sciences can be followed in a variety of optical texts and will not be expounded in detail here. A benchmark in its study was the discovery in 1669 of the birefringence of Iceland Spar by Erasmus Bartholinus (1669).1) This phenomenon was investigated by Huyghens (1690)2) and

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1) An excerpt from this work, translated into English, can be found in Swindell (1975).

2) Again, relevant excerpts from Huygens' *Traité de la Lumière* can be found in Swindell (1975).

*Stellar Polarimetry.* David Clarke

ISBN: 978-3-527-40895-5

later by Malus, famous for his ‘$\cos^2 \theta$ law’, associated with the flux of light transmitted by two crystals or polarizers set with their principal axes at angle $\theta$ with respect to each other (see Malus, 1810a).

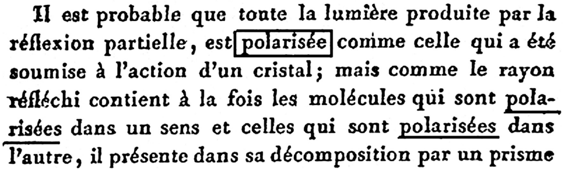
It was from an early description of the behaviour of the double refraction of Iceland Spar, and the orientational quality which appeared to be carried by light, that the connection with the root word ‘pole’, later to give rise to the word ‘polarization’, was made. In the writings of Sir Isaac Newton (see Newton, 1931), we find in ‘Question 29’ of Book III of his *Opticks*:

> . . . And lastly, the unusual Refraction of Island-Crystal looks very much as if it were perform’d by some kind of attractive virtue lodged in certain Sides both of the Rays and of the Particles of the Crystal . . . since the Crystal by this Disposition or Virtue does not act upon the Rays unless when one of their Sides of unusual Refraction look towards that Coast, this argues a Virtue or Disposition in those Sides of the Rays which answers to, and sympathizes with that Virtue or Disposition of the Crystal, as the poles of two Magnets answer to one another . . . I do not say that this Virtue is magnetical: It seems to be of another kind. I only say, that whatever it be, it’s difficult to conceive how the Rays of Light, unless they be Bodies, can have permanent Virtue in two of their sides which is not in their other Sides, and this without any regard to their Position to the Space or Medium through which they pass.

The essential point that Newton made was that light appeared to *interact* differently with the crystal according to the orientation with respect to the crystal of some direction at right angles to the ray. It may be noted that Newton’s use of the word ‘Bodies’ relates to his corpuscular theory for light. His reference to ‘poles’ was clearly an analogy to describe the observed behaviour.

In January 1808, the Paris Académie des Sciences promoted a prize for physics in 1810, the award being offered in response of a quest: ‘To furnish a mathematical theory of double refraction and to confirm it by experiment’. Among those who took up the challenge was Étienne Louis Malus (1775–1812), a French army officer and engineer, who had returned in ill-health to Paris following Napolean’s campaign in Egypt. The life and times of Malus have been graphically described in an essay by Kahr & Claborn (2008). With crystals of Iceland Spar to hand, Malus made a most momentous discovery related to the nature of light purely through simple curiosity.

One evening, in the autumn of 1808, while standing near a window in his home in the Rue d’Enfer in Paris, Malus looked through a crystal of Iceland Spar at the setting Sun, reflected in the windows of the Palais Luxembourg across the street. As he turned the crystal about the line of sight, the two images of the Sun seen through it became alternately darker and brighter, switching every 90° of rotation. After the Sun had set, Malus went indoors and pursued experiments with candle light reflected from the surface of water in a bowl and from a glass bottle. On that same night he was able to show that the strongest effect of intensity changes for the two refracted rays observed through the crystal occurred at particular angles of the reflecting surface, this property later being formulated by Sir David Brew-



Il est probable que toute la lumière produite par la réflexion partielle, est polarisée comme celle qui a été soumise à l'action d'un cristal; mais comme le rayon réfléchi contient à la fois les molécules qui sont polarisées dans un sens et celles qui sont polarisées dans l'autre, il présente dans sa décomposition par un prisme

**Fig. 1.1** The middle section of page 239 of the treatise of Malus published on 2nd January 1810 (see Malus, 1810a) records the introduction the word "polarisée" to language, three times within four consecutive lines.

ster. The fact that reflected light carried a similar property to beams produced by double refraction was presented by Malus at the Societé d'Arcueil on 12 December 1808 (see Malus, 1809a). After these preliminary discoveries, Malus investigated this peculiar orientational property associated with light by more substantial studies, including experiments on the behaviour of images seen through two crystals of Iceland Spar in sequence according to their relative orientation (Malus, 1809a, 1809b). Thus Malus had discovered the property of *polarization* associated with light, although in these early papers, use of words such as 'polarise' or 'polarisation' is absent.

According to the *Oxford English Dictionary – OED*[3] (1961), the introduction to the literature of the word *polarization* was by Malus. The etymological date provided by the 1961 Edition of *OED* is '11 March 1811', the citation taken from Malus (1811a, 1811b, 1811c), these three papers being commentaries on Malus' work. The date in the margin of the second and more important noted paper is '11 Mai 1811', later corrected to '11 Mars 1811' by an errata entry (see note in the Reference List relating to Malus, 1811b), this latter date being that referred to in the *OED*. General use of the word in the French scientific school appears prior to these dates, however. Arago had already used it and its derivatives on 18 February 1811, referring to Malus, in a paper delivered to "La Classe des Sciences Mathématiques et Physiques de L'Institut Impérial de France" (see Arago, 1858a).

The use of 'polar' as a stem word appears for the *first time* in Malus' treatise of *1810* published on *January 2nd* entitled: '*Théorie de la Double Réfraction de la Lumière dans les substances cristallisées*'. In this work, Malus (1810a) clearly describes the parallels of the properties of light reflected by optical surfaces at certain angles and the light beams produced by double refraction. The first use of the word 'polarisée' appears on page 239 of the treatise and the appropriate section is reproduced in Figure 1.1.

It is this coinage that introduces to language a term to describe the newly discovered property of light. Very shortly after, words such as 'polaris/zed' and 'polaris/zation' crossed the Channel into British scientific circles and journals. Now,

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[3] The Oxford English Dictionary intend to change the etymological details for the entry of polarization commencing with the online edition (Private Letter to the Author – 17 Dec. 2007).

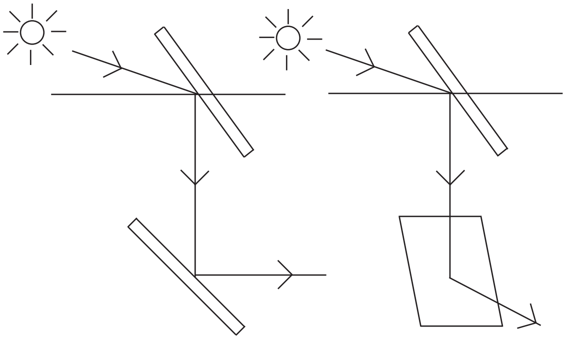

**Fig. 1.2** The observational arrangement used by Malus to demonstrate the polarization property associated with light, the intensity reflected by the second mirror being dependent on its orientation relative to the first.

of course, these words appear in more general everyday use beyond their esoteric association with optics.

The reasoning for choosing these terms is apparent from three papers read before before the *Institut de France* on 11 March, 27 May and 19 August, 1811 – these being the basis of the citations included in the *Oxford English Dictionary* – but appearing in the *Mémoires de l'Institut* under the year 1810 (see Malus, 1810b, 1810c, 1810d). In the first of the papers, Malus describes an experiment using two mirrors with polished glass surfaces in the form of a heliostat (see Figure 1.2). The phenomenon relating to the polarizing effects of the surfaces was described in the following manner (translation of Malus, 1810b (pp. 105–106) by Lowry, 1964):

> Let us direct, by means of a heliostat, a ray of sunlight in the plane of the meridian, in such a way that it makes an angle of 19°10′ with the horizon. Then let us fix an untinned mirror in such a way as to reflect the beam vertically downwards. If we place a second mirror below the first and parallel to it, it will make an angle of 35°25′ with the downward ray, which will be reflected again parallel to its first direction. In this case one will not observe anything remarkable; but if this second mirror is turned so that it faces East or West, without changing its inclination to the vertical ray, it will no longer reflect a single molecule of light, either at its first or at its second surface. If, whilst keeping its inclination to the vertical ray unchanged, its face is turned towards the South, it will begin anew to reflect the ordinary proportion of incident light. In intermediate positions, the reflection will be more or less complete, according as the reflected ray approaches more or less to the plane of the meridian. In these circumstances, in which the reflected ray behaves so differently, its inclination to the incident ray is kept constant. Thus, we see a vertical ray of light which, falling on a transparent body, behaves in the same way when the reflecting surface is turned to the North or South, and in a different way when this surface is turned to the East or West, although these

> surfaces are always inclined at an angle of 35°25′ to the vertical direction of the ray.
>
> These observations lead us to conclude that the light acquires in these circumstances properties which are independent of its inclination to the surface which reflects it, but are unique relatively to the sides of the vertical ray. These are the same for the South and North sides, and different from the East and West sides. Giving to the sides the names of poles, I will describe as *POLARISATION* the modification which gives to the light its properties relatively to these poles.

A translation and extension of the latter paragraph of the original article can also be found in Buchwald (1989):

> These observations lead us to conclude that light acquires in these circumstances properties that are independent of its direction with respect to the reflecting surface and that are the same for the south and north sides (of the ray), and different for the east and west sides. In calling these sides poles, I will call *polarization* the modification that gives light properties relative to these poles. I waited until now (two and a half years) before admitting this term in the description of the physical phenomena in question; I dared not introduce it in the *Mémoires* wherein I published my latest experiments; but their varieties presented by this new phenomenon and the difficulties in describing them force me to admit this new expression, which simply signifies the modification light is subject to on acquiring new properties that are related not to the direction of the ray, but only to its sides taken at right angles and a plane perpendicular to its direction.

The plane of the meridian, defined by the incident ray and the ray reflected from the first surface, was later selected to describe the 'plane of polarization'. Today we know that light has an electromagnetic nature and that the **E** component is usually the more important in general optical interactions rather than the **H** vector. According to Malus' experiments it turns out that the **E** vector oscillates *normal* to the plane of incidence and that the early definition of the *plane of polarization* corresponded to the **H** vector. Modern usage now has the *plane of polarization* at right angles to the plane of incidence as defined in Malus' experiment, although there are some texts, usually old ones, that carry the original definition.

In the second memoir, Malus (1810c) describes the partial polarization transmitted through glass being a mixture of unpolarized light and light polarized in a plane at right angles to the plane of polarization of the reflected ray. He also describes the use of a series of parallel plates, or pile-of-plates, to produce more complete polarization of the transmitted beam.

The third memoir (Malus, 1810d) describes the occurrence of double refraction in all crystals except those belonging to the cubic system, and in all vegetable and animal substances that were tested.

With his simple, but fundamental, observation in a Paris street, followed up with some simple laboratory experiments, Malus, in these great 'eureka' moments, had discovered that light contained an orientational property that was common to beams emerging from what we now refer to as birefringent crystals and to beams being reflected by material surfaces. He discussed the exciting discovery of the similarities of such beams in terms of the wave theory of Huyghens and the corpuscular theory of Newton. No doubt he was aware of Newton's description of double refraction (see above), and it was therefore natural to describe the phenomena in terms of forces acting on the corpuscules of light and to describe light beams subject to such forces in their modification by refraction or reflection as being *polarized*.

In the paper presented to La Classe des Sciences Mathématiques de l'Institut Impérial de France on 18 February 1811, Arago (1858a) neatly sums up the discovery of Malus by saying:

> La lumière se polarise non-selement dans l'acte de la double réfraction, mais encore dans d'autres circonstances très-remarquable que Malus a découvertes.

The Count Rumford Medal for 1810 was awarded by the Royal Society to Malus for his work on double refraction, it being noteworthy that excellent scientific interchange was able to exist between two countries suffering strong political divides. The letter of announcement to Malus written by Thomas Young was dated 22 March 1811.

The first usage of the term and its extension within an article in English is in *Nicholson's Journal* (1811), Volume: XXX – page 192, with a letter from Paris saying:

> Mr Malus is still pursuing with success
> his inquiries concerning *polarised* light.

Also noted in *Nicholson's Journal* (1812), Volume: XXXIII – page 345, is the fact that Malus coined the word 'polarisation' with the comment:

> By giving to these sides (of the vertical ray) the names of poles, he calls the modification which imparts to light properties relative to these poles, *polarization* ... This new expression ... signifies simply the modification that light has undergone in acquiring new properties, relative not to the direction of the ray, but solely to its *sides*, considered at a right angle, and in a plane perpendicular to its direction.

In 1801, Thomas Young firmly established that light had a wave nature through his interpretation of the phenomenon of Newton's rings. He proposed that the observed colours exist within the incident light and that wavelengths could be assigned to them through the principle of the constructive interference of waves. His double-slit experiment, again related to the interference of light, still remains a classical experiment for physics undergraduates to perform.

In the immediate years following the discovery of polarization, a major problem was the reconciliation of the behaviour of polarized light and the principles of wave theory, particularly in respect of the propagation by longitudinal disturbances. Young had pondered the problem but remained baffled by it. In 1816, he received a visit from Arago who told him of a result obtained with Fresnel in connection with the double-slit experiment, but working with polarized light. They had found that if the slits were illuminated separately using beams of polarized light with their planes at right angles, the interference phenomena were not present. (The discovery of this behaviour was not published until 1819 – see Arago & Fresnel, 1819.)

Soon after Arago's return to France, Young reflected on this result and discovered the long-sought key to the mystery. The solution turned out to have been a proposal which Bernoulli (the younger) had considered and rejected 80 years ago, of supposing that the vibrations of light are executed at right angles to the direction of propagation. According to Whittaker (1958):

> Young's ideas were first embodied in a letter to Arago dated 12 January 1817. – 'I have been reflecting,' he wrote, 'on the possibility of giving an imperfect explanation of the affection of light which constitutes polarisation, without departing from the genuine doctrine of undulations. It is a principle in this theory, that all undulations are simply propagated through homogeneous mediums in concentric spherical surfaces like the undulations of sound, consisting simply into direct and retrograde motions of the particles in the direction of the radius, with their concomitant condensation and rarefractions. And yet it is possible to explain in this theory a transverse vibration, propagated also in the direction of the radius, and with equal velocity, the motions of the particles being in a certain constant direction with respect to that radius; and this is *polarisation*.'
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> In an article on 'Chromatics', which was written in September of the same year for the supplement to the *Encyclopaedia Britannica*, he says: 'If we assume as a mathematical postulate, on the undulating theory, without attempting to demonstrate its physical foundation, that a transverse motion may be propagated in a direct line, we may derive from this assumption a tolerable illustration of the subdivision of polarised light by reflection in an oblique plane,' by 'supposing the polar motion to be resolved' into two constituents, which fared differently at reflection.
>
> In a further letter to Arago, dated 29 April 1818, Young recurred to the subject of transverse vibrations, comparing light to the undulations of a cord agitated by one of its extremities. This letter was shown by Arago to Fresnel, who at once saw that it presented the true explanation of the non-interference of beams polarised in perpendicular planes, and that the latter effect could even be made the basis of a proof of the correctness of the Young's hypothesis; for if the vibration of each beam be supposed resolved into three components, one along the ray and the other two at right angles to it, it is obvious from the Arago–Fresnel experiment that the components in the direction of the ray must vanish; in other words, that the vibrations which constitute light are executed in the wave-front.

From thereon Fresnel took up the concept of transversality and wrote on it in very clear terms killing any idea that the vibrations could be longitudinal. Fresnel (1824a) later concluded that 'the vibrations of a polarized beam must be perpendicular to what is called its *plane of polarization*'. Fresnel's theory of the nature of polarized light was presented in *Mémoire sur la double Réfraction* and read before the *Académie des Sciences* on 26 November 1821, and 22 January and 22 April 1822 (see Fresnel, 1868). A most relevant passage to the advance in the understanding of the nature of polarized light is found in pages 265–266 of Fresnel (1825), and translated by Lowry (1964), reading as follows:

> . . . the luminous vibrations take place only in directions parallel to the surface of the waves . . . It suffices to admit in the ether a sufficient resistance to compression to understand the absence of longitudinal vibrations . . . Polarised light is that in which the transverse oscillations take place constantly in one direction, the ordinary light is bringing together and the rapid succession of an infinite number of systems of waves polarised in all directions. The act of polarisation does not consist in creating transverse vibrations, but in decomposing them along two fixed directions at right angles to one another, and separating the two systems of waves thus produced, either merely by their difference of velocity as in crystalline plates, or also by a difference of direction of the waves and of the rays, as in crystals cut into prisms or in thick plates of carbonate of lime; for, wherever there is a difference of velocity between the rays, refraction can make them diverge. Finally, according to the same theory, the plane of polarisation is the plane perpendicular to that in which the transverse vibrations take place.

Mention has already been made of Bernoulli (the younger) in relation to the notion that the transmission of light is accompanied by disturbances involving transverse vibrations. At the time, Bernoulli thought that all space was permeated by a fluid aether containing an immense number of excessively small whirlpools. According to Whittaker (1958), he thought that

> A source of light communicates to its surroundings a disturbance which condenses the nearest whirlpools; these by their condensation displace the contiguous corpuscles from their equilibrium position and these in turn produce condensations in the whirlpools next beyond them, so that vibrations are propagated in every direction from a luminous point. It is curious that Bernoulli speaks of these vibrations as *longitudinal*, and actually contrasts them with those of a stretched cord, which, 'when it is slightly displaced from its rectilinear form, and then let go, performs *transverse* vibrations in a direction at right angles to the direction of the cord.' When it is remembered that the objection to the longitudinal vibrations, on the score of polarisation, had already been clearly stated by Newton, and that Bernoulli's aether closely resembles that which Maxwell invented in 1861–62 for the express purpose of securing

> transversality of vibration, one feels that perhaps *no man ever so narrowly missed a great discovery*.

Even more remarkable is a statement made by Thomas Hooke, 100 years previous to Bernoulli, in which he appears to have recognised that light may consist of some kind of wave disturbance with associated transversality. In his celebrated book known as *Micrographia* Hooke (1655) writes

> . . . ; for since by that Hypothesis the undulating pulse is always carried perpendicular, or at right angles with the Ray or Line of direction, it follows, that the stroke of the pulse of light, after it has been once or twice refracted (through a Prisme, for example) must affect the eye with the same kind of stroke as if it had not been refracted at all.

The nature of the Fresnel–Arago interference laws with respect to polarization has been appreciated for some considerable time, but occasionally they are re-iterated with mathematical descriptions (e. g. see Collett, 1971). It is only recently that their understanding has been expressed in erudite form by Mujat, Dogariu & Wolf (2004). In this paper the laws have been summarized as follows:

1. Two rays of light polarized at right angles do not produce any effect on each other under the same circumstances in which two rays of ordinary light produce destructive interference.
2. Rays of light polarized in the same plane interfere as rays of ordinary light, so in these two kinds of light the phenomena of interference are identical.
3. Two rays that were originally polarized at right angles may be brought to the same plane of polarization without thereby acquiring the ability to interfere.
4. Two rays of light polarized at right angles and afterwards brought into the same plane of polarization interfere as ordinary light provided that they were originally polarized in the same plane.

As it turns out, appreciation of the behaviour according to these laws is of importance to the understanding of some of the interference problems which appear in modern instruments designed to undertake spectropolarimetry, as discussed by Semel (2003), for example.

With respect to transversality, mention has been made in a quotation above to the work of Maxwell. Based on the experimental works of Faraday on electrical and magnetic phenomena, James Clerk Maxwell was able to link them through a mathematical formulation that predicts electromagnetic waves which travel with a velocity calculable from electric and magnetic constants measured in the laboratory. The predicted velocity matched the measurements of the velocity of light. In addition, Maxwell's equations predict that the electric and magnetic oscillations associated with the progress of the waves are transverse to the direction of propagation. The nature of transversality was clearly described by Maxwell (1861) as follows:

> The velocity of transverse undulations in our hypothetical medium, calculated from the electro-magnetic experiments of MM Kohlrausch and Weber, agrees so exactly with the velocity of light calculated from the optical experiments of M. Fizeau, that we can

> scarcely avoid the inference that *light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena.*

Returning to the discoveries of Malus, Sir David Brewster in Edinburgh investigated reflection and refraction and, under the entry of polarization, the *Oxford English Dictionary* credits Brewster as being the first person to use the term 'polarisation' within a scientific paper (Brewster, 1814a). On page 188 of this paper he writes:

> A ray of light transmitted through a plate of agate cut by planes perpendicular to the laminae of which it is composed suffers *polarisation* like one of the pencils formed by double refraction.

The first scientific paper with the term 'polarisation' in its title also appears to have been written by Sir David Brewster (Brewster, 1814b), namely,

> 'On the Polarisation of Light by oblique transmission through all Bodies, whether crystallized or uncrystallized.

It is interesting to note that within this paper he says:

> The celebrated discovery made by MALUS, of the polarisation of light by oblique reflection, is perhaps the most important that optics has received since the discovery of achromatic telescopes;...

Of course, such a simile would not be used today, the latter instruments now being classed as technological dinosaurs, but the resonant sentiment remains with polarization being a very important and essential aspect to our understanding of radiation. The application of polarimetry is now a well-established diagnostic in astrophysics with an ever continuing expansion of its use in both theory and observation.

A mathematical expression relating the particular angle of incidence, $\theta_{\mathrm{B}}$, for which full polarization occurs in the reflected beam was established by Brewster (1815a, 1815b) 1 year later. For an air–material interface, Brewster's law may be expressed as $\theta_{\mathrm{B}} = \arctan(n)$, where $n$ is the refractive index of the reflecting material.

Observations of the colours produced when various substances were placed following a pile-of-plates polarizer and then viewed through an Iceland Spar crystal were presented at the Institut de France on 11 August 1811 by Arago (1811, 1858b). Most of the investigated materials were birefringent crystals and he was exploring the effects of differential phase delays that they introduce between the resolved components of polarized light, although he would not have appreciated this at the time. It is noteworthy that he found that the behaviour of a plate of quartz cut with surfaces perpendicular to the principal axis of the crystal behaved very differently to plates of mica or gypsum. What he had unknowingly discovered was the fact that polarized light is rotated by some materials, this later being referred to as *circular birefringence*, and becoming the basis of a very important diagnostic in the field of molecular chemistry; the laws governing this phenomenon were investigated and established by Biot a few years later (see chemistry texts such as Lowry, 1964). Of more direct relevance to radio astronomy, rather than in the optical domain, the rotation of polarized radiation caused by the presence of a magnetic field in the transmitting medium was discovered by Faraday (1846).

Fresnel's experiments related to total internal reflection, and the associated behaviour of polarization, led him to propose that orthogonal vibrations produce linear polarization when they are in phase, and circular polarization when they have a phase difference of $\pi/2$. In a paper (Fresnel, 1824b), he writes:

> . . . on aura une idée juste du genre de vibration lumineuse que j'ai proposé de nommer *polarisation circulaire*, en appelant *polarisation rectiligne* celle qui a été remarquée pour la première fois par Huygens dans la double réfraction du spath d'Islande, et que Malus a reproduite par la simple réflexion sur la surface des corps transparents.

In referring to polarization forms, the term '*circular*' remains to this day but the word '*rectilinear*' is normally reduced simply to '*linear*'.

In the above text, it may already have been noted that there is an alternative in spelling of the theme word and its derivatives, with both 's' and 'z' being used. At its birth in the French language, Malus used the terms 'polarisée' and 'polarisation', the words incorporating 's'. Its introduction to papers written in English shows immediate spelling ambiguity. In two of Brewster's papers (1814a, 1814b), the root word is spelled with 's' whereas in a contemporaneous paper by Brewster (1814c), it employs an inconsistent mixture of both 's' and 'z'. In a paper by Faraday (1846), both the words 'polarized' and 'polarising' are used. Modern texts continue to use the alternative spellings – though usually more self-consistent. The *Oxford English Dictionary* refers only to the alternative with 'z'; the *Collins English Dictionary* (1992) lists the use of 'z' with the alternative of 's'. Throughout this text, the 'z' spelling is preferred, except in verbatim quotations, and in titles of papers within the reference lists, originally using 's'.

More important than the arcane detail of the 'correct' spelling of *polarisation* is the fact that the word itself seems inapt for describing what are now known to be the statistical fluctuations of the electric vector in a beam of electromagnetic radiation. Again according to the *Oxford English Dictionary*, under the entry on the origin of the word *polarize*, it says:

> But this unfortunately assumed a sense of *pole*, quite different from its use in astronomy, geography, and magnetism with the consequence that *polarization* as applied to light and radiant heat has nothing in common with magnetic or electric polarization.

As already mentioned, the term 'pole' in relation to optical phenomena originates from Newton. Apart from not describing the underlying behaviour accurately, some of its derivatives such as *plane of polarization* are open to alternative interpretations. In Figure 1.3, two scenarios are depicted which cannot simply be differentiated by using the term 'plane of polarization'. Lord Kelvin made pertinent comment on the terminology in 1884 in his Baltimore Lectures (see Lord Kelvin, 1904). In his discussions he referred to a confusing remark of Jamin's as follows:

> . . . 'vibrations polarisé dans le plan de l'incidence' may have signified not that the plane of polarization but that the line of vibration, was in the plane of incidence.

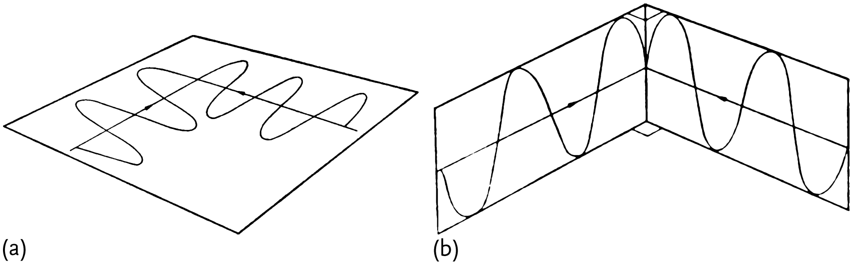

**Fig. 1.3** Origins for confusion over the use of the term 'plane of polarization'. (a) depicts two light waves with the same plane of polarization, but perpendicular directions of vibration; (b) depicts two light waves with the same direction of vibration but perpendicular planes of polarization.

Lord Kelvin asterisked 'plane of polarization' and made the following comment in a footnote:

> Considering the inevitable liability to ambiguity of this kind, I have abandoned the designation 'plane of polarization' and resolved always to specify or describe with reference to vibrational lines. Abundant examples may be found . . . illustrating the inconvenience of the designation 'plane of polarization' were, as is now generally admitted, in the very beginning unhappily chosen words for differences of action in different directions around a ray of light. These differences are essentially not according to what we now understand by 'polar quality'.

The term 'polarization' is deemed to stay in the literature, however, there being little point in displacing it as there is no obvious alternative. It is perhaps ironic that the word associated with phenomena related to the wave nature of light should find its origin in Newton's now abandoned corpuscular theory. As for the usage of 'plane of polarization', alternatives such as *direction of vibration* appear in the literature. In astronomy the use of *position angle of the vibration*, *azimuth of the vibration* or *direction of vibration* is an attractive alternative, especially when measurements are being referred to projections against celestial coordinate systems. In addition to waves which vibrate in a particular plane (linear polarization) set at a given position angle relative to some preferred axial frame, the form of the polarization may be *elliptical* and the term 'position angle' or 'azimuth' may also be applied to the orientation of the major axis with respect to the reference frame.

## 1.2
## Early Astronomical Polarimetry

It is interesting to note that running hand in hand with the development of the basic understanding of laboratory polarization phenomena, the light from celestial bodies was also investigated for the attribute. As it turns out, the eye by itself is virtually insensitive to polarized light, although under favourable circumstances, the effects of high levels of polarization can be apparent through the phenomenon of Haidinger's Brush – see Haidinger (1844). If the eye perceives a wide uniform field of strongly polarized light such as the sky viewed at 90° from the Sun, some people are able to detect a yellowish figure of eight, about 3° across, at the centre of the field. The figure has its long axis at right angles to the direction of polarization. Its origin results from the yellow pigment of the eye being dichroic. Details of how the appearance of Haidinger's Brush behaves according to both linear and circular polarization, and how the perception is induced in the eye are provided by Fairbairn (2001). Experiments on the eye's response to linear and circular polarization have been conducted by de Vries, Jielof & Spoor (1950). In order to make any polarization of a light beam more generally detectable by eye, some simple optical pieces are required. Such devices are, of course, also required to make the modern detectors used on telescopes sensitive to polarized light, their combinations comprising a polarimeter.

The first polarimetric observations in Astronomy were made by Arago in 1811 when he directed his visual instrument to the Moon to see if the reflected sunlight carried similar properties to those seen by Malus in reflections by glass surfaces (see Arago, 1855a, 1858c). Arago's equipment (see Arago, 1855b) comprised a quartz plate, cut to give a wavelength-dependent rotation of the direction of vibration of any linearly polarized light, and a Wollaston prism to resolve the orthogonal polarizations. Two images of differing colour were seen for incident polarized light. The original instrument has been restored and tested by Dougherty & Dollfus (1989).

At about the same time, Arago discovered that the light of the daytime sky was polarized, finding that the polarization maximum occurred at approximately 90° from the Sun. He also found that the light from a direction of about 25° above the antisolar direction was unpolarized. This point is referred to as Arago's neutral point. Two other neutral points were later found to be present in the sunlit sky. The Babinet point and the Brewster point were discovered in 1840 and 1842 respectively, both lying within 10° to 20° along the vertical circle through the Sun; the Brewster neutral point occurs below the Sun and the Babinet point occurs above it. Although it is very apparent to anyone who wears 'Polaroid' sunglasses that the light of the sky is generally polarized, it is difficult to detect the neutral points by eye because of the solar glare. They occur as a result of multiple scattering within the atmosphere and their position relative to the Sun is sensitive to the local turbidity.

In 1828, Arago (see Arago, 1855b) made measurements of solar light and, from his null result, concluded that the Sun was wholly gaseous, since, if solid or liquid, its surface would give rise to partial polarization near the limb. This conclusion was accepted by some later workers, but was criticised by Sir John Herschel (1869) who suggested that such a notion was only applicable to a smooth surface with observations showing that this latter condition did not apply. With the advance of modern technology and improved detectivity, measurements of limb polarization, particularly within spectral lines, have opened up a new exciting avenue of solar research. Records of spectropolarimetry of the Sun are referred as the '*second*' solar spectrum (see Stenflo, 1996 and Stenflo & Keller, 1997). Arago (see Arago, 1855c and Grant, 1852) is also credited with the discovery that cometary light (namely the comets of 1819 and 1835 (Comet Halley)) is polarized.

Unlike astrometry, photometry and spectroscopy, the advances of polarimetry in the nineteenth century were relatively slow being limited to the Moon, this being of interest only because of its extreme brightness accompanied with high levels of polarization. Notable contributions in the nineteenth century were by Secchi (1860) and Lord Rosse (see Parsons 1878). The key works related to lunar polarimetry from this period and the early part of the twentieth century have been referenced by Fielder (1961) and also described by Turner (1957, 1958). It may also be mentioned that the Moon's light, particularly from the dark maria at a phase $\sim 110^\circ$, provides a simple, but delicate, opportunity to observe polarization directly by eye by rotating a polarizer before it, with, or without, the use of a telescope.

Planetary work was also initiated at the turn of the century by Lyot (1929) through the ingenious design of a sensitive visual polarimeter. His observations were seminal, acting as reference for a whole range of later measurements of the Moon, planets, asteroids and rough scattering by laboratory samples. One of the highlights resulting from a development of this work is the determination of asteroid diameters by polarimetry. According to Umov (1912), the albedo of a rough surface is inversely proportional to the amount of polarization in the scattered light. With good calibration, partly obtained by laboratory measurements, and partly through telescope observations, polarimetry of asteroids over their phase angle range provides albedo values. For any asteroid, photometric measurement of its absolute magnitude, together with its 'polarimetric' albedo, then allows a cross-sectional area to be determined, from which a diameter is obtained. Early work in this area was undertaken by Bowell & Zellner (1974).

## 1.3
## The Dawning of Stellar Polarimetry

The first attempt to measure polarization in the light from stars appears to have been made by Öhman (1934) when he used a photographic technique to investigate possible polarimetric variations within spectral lines of the famous eclipsing binary, $\beta$ Lyr. At the time, tentative claims were made for positive results, but on reflection, some 30 years later, Öhman (1965) commented that he was now more cautious about his earlier detection levels and that the photographic method was probably not sufficiently sensitive to give conclusive answers in every respect. Encouragement to publish his results was offered by the Editor of the scientific journal *Nature*, following a visit by him and his wife to Stockholm Observatory.

The key paper which triggered observational activity in stellar polarimetry was that of Chandrasekhar (1946) who predicted that the continuous radiation of early-type stars should be polarized. By considering the opacity of the atmospheres of such stars to be the result of electron scattering, he demonstrated that the radiation emerging from the stellar limb would have a polarization of just over 11%, with the azimuth of vibrations tangential to the limb, the polarization becoming zero for radiation emerging from the centre of the disc. Quoting from his paper, he says:

> It is not impossible that this predicted polarization of the radiation of the early-type stars (in which scattering by free electrons is believed to play an important part in the transfer of radiation) would be detected under suitably favourable conditions.

Radial symmetry rules out there being a net polarization in the global radiation, but for an eclipsing binary in which a larger late-type companion partially masks the disc of the early-type star, the symmetry is broken and a polarization modulation is to be expected during the eclipse phase. It is of interest to note that, at about the same time as Chandrasekhar's work on radiative transfer, Kopal & Shapley (1946) suggested that polarization modulations might be expected in such stars as V 444 Cyg, comprising a Wolf–Rayet and O star eclipsing system, embedded in an extended dissociated atmosphere of free electrons.

As well as potentially revealing polarization by breaking the symmetry as consequence of eclipses, Öhman (1946) demonstrated by qualitative argument that, for stars with high values of $v \sin i$, a variation of polarization might be seen at all times across the Doppler rotationally broadened profiles, with the wings of the lines being weighted by radiation from the equatorial limb and the line core being weighted by light from the centre of the stellar disc. At the time of this proposal, measurement techniques were insufficient to explore the proposition.

## 1.4
## The Discovery of Interstellar Polarization

The history of the serendipitous discovery that interstellar dust imposes polarization on starlight passing through it has been sketched out by Struve & Zebergs (1962). They comment that:

> The detection of interstellar polarization always will remain one of the most striking examples of purely accidental discovery, such as Wilhelm Röntgen's discovery of X-rays in 1885.

In response to Chandrasekhar's theoretical paper on the production of polarization by electron scattering in the atmospheres of early-type stars, the challenge of detecting polarimetric variability in eclipsing binaries was taken up, the first chosen star for investigation by Jansenn (1946) being U Sag. The exploratory technique employed a Wollaston prism placed before the photographic camera attached to the Yerkes 40″ refractor. In order to improve the detectivity, the resolved beams were spread over a large area of the plate by focussing the objective on the emulsion, rather than obtaining pin-point sharp stellar images. With this system, Hiltner (1947) investigated the eclipsing binary RY Per and suggested that a systematic change in polarization had been detected through the light-curve minimum.

The real breakthrough to the detection of stellar polarizations came with the application of the photomultiplier tube which, following World War II, fortuitously appeared on the scene at the right time to provide sufficient photometric sensitivity for the remarkable, but serendipitous, discovery of *interstellar polarization*. Rather than detecting the predicted intrinsic effects generated within stellar atmospheres, the new technology discovered a very unexpected phenomenon.

From two adjacent papers in the journal *Science*, it is apparent that William A. Hiltner (1949a) and John S. Hall (1949) originally had collaborated on stellar polarimetric observations, but that instrumental problems and other difficulties had prevented the completion of their joint study. These two papers describing the early results of independent work serve as a benchmark for the establishment that starlight becomes polarized by its passage through the interstellar medium.

Responding to Chandrasekhar's prediction, Hall designed a photoelectric polarimeter (see Hall, 1948 and Hall & Mikesell, 1950) in 1946 and independently measured the constant interstellar polarizations in the summer of 1948.

The description of how the phenomenon of interstellar polarization became established is clearly related by Hiltner (1949b). His photoelectric measurements of CQ Cep, also made in the summer of 1948, revealed a polarization of some 10% which was independent of the stellar phase. Other stars such as Z Lac and HD 211853 also provided substantial levels of polarization. Hiltner concluded:

> . . . that this polarization is not associated with the individual stars but is introduced to the stellar radiation in its passage through interstellar space.

In the penultimate paragraph of the paper, Hiltner listed a number of conditions that must be met to explain the presence of polarization in distant stars, namely

1. the mechanism must be independent of wavelength,
2. the mechanism must be operating over a large distance – stars within a small area on the sky exhibit polarization of different amounts but with the same position angle,
3. a positive colour excess is necessary but not sufficient and
4. the plane of polarization is associated with the galactic plane, i. e., stars of low galactic latitude tend to provide the electric vector maximum which is approximately parallel to the galactic plane.

Finally, Hiltner surmised:

> . . . if the polarization is a consequence of scattering by interstellar particles, it follows that these particles must be unsymmetrical, that is, elongated, and that these particles are subject to some alignment force. This force may take the form of magnetic fields,. . .

Hiltner and Hall continued to make measurements, both producing catalogues (Hiltner, 1951, 1954; Hall, 1958) which mapped the variations of interstellar polarization around the Galaxy, a task which was made more complete by Mathewson & Ford (1970) (see Figure 1.4).

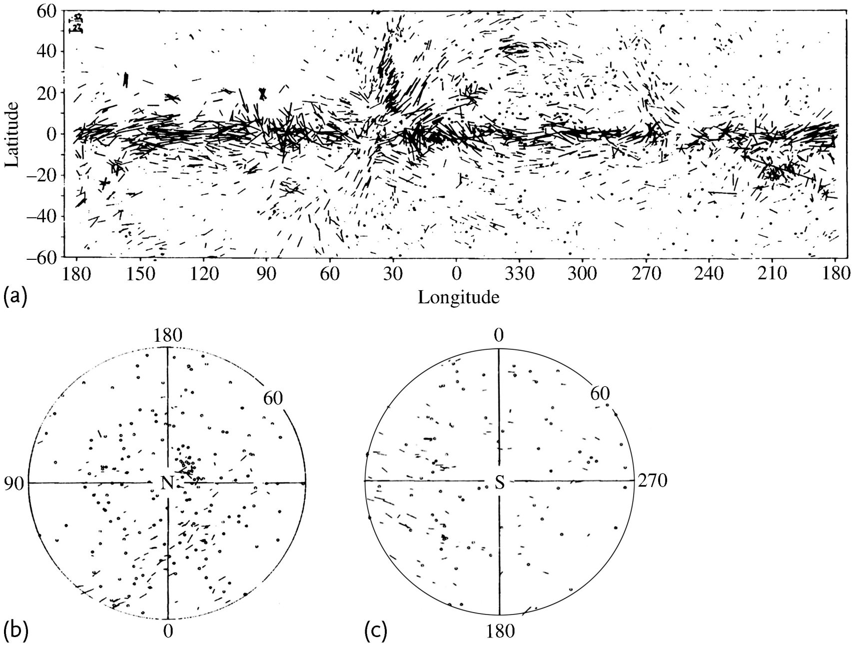

**Fig. 1.4** Polarization vectors corresponding to measurements of individual stars set on a galactic map. (a) plots values for stars along the galactic equator covering a galactic latitude range of ±60°, while the circles (b,c) correspond to the galactic poles. The similarity of patterns akin to those of iron filings scattered on paper with a magnet placed on the underside is not fortuitous. (From Mathewson & Ford, 1970.)

It is perhaps of interest to note that Öhman (1949) also discovered interstellar polarization without realising it. One of the photometric instruments he developed involved the use of quartz plates following a rotating polarizer such that the modulated signal provided information on the stellar colour. For some reddened stars the photomultiplier produced a greater 'dark current' than expected. The excess was considered to result from the presence of polarization effects but was rejected as being improbable and was attributed to accidental variations in the dark signal. In this instance, the hand of serendipity was not grasped.

Photoelectric instruments immediately lent themselves to investigations of the wavelength dependence of polarization. Indeed early observations by Hiltner and Hall of the newly discovered interstellar polarization suggested that there was little or no wavelength dependence. Ten years later, as instrumental techniques and sensitivities improved, broadband spectropolarimetry became firmly established. Initial work on the wavelength dependence of the interstellar polarization was undertaken by Behr (1958) and Gehrels (1960). Adjacent to Behr's paper is a discussion by Davis (1958) on the nature of interstellar dust and the form of the wavelength dependence of the generated polarization. It is of interest to note though that the majority of the stars measured by Behr have subsequently been proven to display intrinsic polarizations.

In the early 1960s, Gehrels & Teska (1963) were promoting the application of spectropolarimetry to a wide variety of astronomical sources. A series of papers under the running heading of 'Wavelength Dependence of Polarization' also began to appear at this time in *Astronomical Journal*; a full listing of these is given in Appendix B.

An important conclusion emerged around 1970 in respect of the wavelength dependence of interstellar polarization. By normalizing both the polarization measurements and the wavelength points of the observations, a unique curve emerged, this being independent of the galactic position of any star (see Chapter 10). This behaviour was established by Serkowski (1973), although formulated earlier by Serkowski (1971), but with an erroneous value for a constant term which the later paper confirmed as being a misprint. This algebraic representation of the behaviour of interstellar dust above is now referred to as *Serkowski's Law*.

Not only has Serkowski's Law been important in investigating the nature of interstellar dust grains within the Galaxy, it provides a useful diagnostic for decoupling intrinsic and interstellar contributions within individual stellar measurements. By the mid-1970s there was independent evidence – time-dependent variability and peculiar wavelength dependences – which confirmed that some stars have polarigenic4) mechanisms operating within their atmospheres. Understanding the nature of these mechanisms and of their presence in astrophysical situations has grown as more and more measurements have accrued.

## 1.5
## Intrinsic Polarization

Although the observational investigations had taken a completely different tack from the direction set by Chandrasekhar's theoretical work, it was only a few years later when variability of polarizations was reported, confirming that some stars exhibit intrinsic effects generated within their atmospheres. Indeed, hints of the presence of intrinsic polarization were indicated in the early catalogues of measurements. For example, Hall & Mikesell (1950) noted that ζ Tau displayed a polarization greater than expected according to its small colour excess. Later measurements of this star revealed a wavelength dependence very different from the curve associated with interstellar polarization (e. g. see Capps, Coyne & Dyck , 1973), and also a temporal variability (e. g. see Clarke & McLean, 1976).

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4) Some etymological purists might object to the use of such an engineered word, but 'polarigenic' describes very well the concept of the generation of polarized light by some physical mechanism. Its origin is uncertain, but the author became conscious of its use in the PhD thesis of Schwarz (1984). (Dr. Hugo E. Schwarz died tragically on 20 October 2006.)

In Behr's (1959) catalogue, $\gamma$ Cas was highlighted as displaying variable polarization. Both $\zeta$ Tau and $\gamma$ Cas are Be stars and, as it has since turned out, this spectral class has provided targets for one of the most fruitful fields of stellar polarimetric research. Serkowski (1970) demonstrated that measurements made with standard *UBV* filters were sufficient to reveal that Be stars behave differently from stars exhibiting polarization simply as a result of the interstellar medium.

The acceptance and establishment that some stars do indeed display intrinsic polarization was not without problems. An interpretation of measurements made by Thiessen (1961) was of a correlation existing between the amount of polarization and stellar luminosity, the notion that synchrotron radiation might occur in stellar atmospheres being mooted. Behr (1961) dismissed this suggestion, demonstrating the influence of observational selection; brighter supergiants are observed more readily, despite effects of interstellar absorption – but with increased interstellar polarization. Later, however, through the discovery of variable intrinsic polarization of OB supergiants (see, e. g. Coyne, 1971), the notion of polarization/luminosity relationships re-emerged, but not to the extent originally proposed by Thiessen.

At the other end of the spectral range, red supergiant stars such as $\mu$ Cep were reported as displaying variable polarization (e.g. see Grigoryan, 1958). Even in the late 1960s, however, Lodén (1967a, 1967b) suggested that such claims of intrinsic variations should be treated with some caution. Again, observations of both temporal fluctuation and spectral variation of the polarizations of this type of star have since become a profitable study.

Investigations of eclipsing binary stars which initiated the first stellar polarimetric observations were continued and have become productive as detection sensitivities have improved. Early notable work was by Shakhovskoi (1963) who observed the famous supergiant eclipsing binary, $\beta$ Lyrae. Changes in polarization during the eclipse phase in about 12 other binary systems were discovered by Shakhovskoi (1965, 1969) and by Shulov (1967), with most of the examples displaying spectra indicating the presence of gas streams and rings, the polarigenic mechanism being scattering from detached material and not from the Chandrasekhar (1946) effect.

By the early 1970s the usefulness of studying polarization associated with circumstellar material gained significant momentum. A benchmark paper was presented by Zellner & Serkowski (1972) which highlighted situations whereby intrinsic polarization might be generated and also decrying the fact that very little work had been done on modelling the temporal or spectral behaviour of a plethora of observations. Nearly all of the various categories of stars known to be photometric and/or spectroscopic variables (e. g. T Tauri, RV Tauri stars, etc.) have now been detected as displaying polarimetric variability. It is not profitable here to cite all the early observations and to assign names of researchers associated with the discovery of intrinsic polarization for each kind of star, but a seminal paper describing such pioneering investigations was presented by Serkowski (1971). The latter chapters of Part II of the text are dedicated to presenting the polarimetry of the various kinds of variable star.

## 1.6
## Circular Polarization

All the discussion above is essentially related to ‘linear polarization’. In the early 1970s James C. Kemp introduced a photoelastic modulator to the telescope, the system being ideally suited to the measurement of circular polarization (see Kemp & Barbour, 1981). With this instrument he detected circular polarization in the light of white dwarfs (Kemp, 1970a) and at the same time described (Kemp, 1970b) a new physical process of gray-body magneto-emissivity to explain the observed phenomena.

As interstellar grains are birefringent, on entering a dust cloud, any initial linear polarization will be modified by differential phase changes to produce a circular component. Thus, circular polarization may be generated by the interstellar medium if the stellar line of sight contains complex dusty regions. Linear polarization might be produced by the early part of an interstellar cloud and, if its alignment axis is set at an angle to the later part of the cloud, the twist produces a circular component. In addition, there may also be an intrinsic linear polarization from the star itself, prior to the light passing through a cloud. An effect of the handedness having opposite senses either side of the wavelength, $\lambda_{\max}$, at which the linear polarization has its maximum value, was discovered by Kemp & Wolstencroft (1972).

Following the interest in the optical identification of newly discovered X-ray sources, Tapia (1977) investigated the star AM Her and found remarkably large changes in both linear and circular polarization on a period of 0.128918 days. The source of the polarization was suggested as cyclotron emission by hot electrons in a magnetic field of the order of $10^8$ G. These systems are perhaps the most exciting stellar objects in terms of their polarimetric behaviour. Several more have since been discovered and stars of this genre are sometimes referred to as *polars*.

Although not measuring polarization directly, Babcock (1958) used the diagnostic of spectral line splitting by the Zeeman effect to undertake a survey of magnetic fields associated with Ap stars. By forming two spectra comprising orthogonal circular polarizations, the longitudinal component of the magnetic field was measured from the line pair displacements in the photographic spectral records. His catalogue provided a table of 89 magnetic stars with measured field strengths and a table of 66 stars which probably show Zeeman effects. Many of the magnetic stars show periodic variability as a result of their rotation. The technique was advanced further by photoelectric determinations of the circular polarization in the red and blue wings of spectral lines (e. g., see Landstreet, 1980). Linear polarization studies have also been made of the continuum light of Ap stars (e. g., see Leroy, 1995).

## 1.7
## Polarization and Geometry

The key attribute of polarization is the vectorial nature of the electromagnetic disturbances that is carried. The orientational properties that are encrypted in the received flux relate to aspects of the source geometry, whether the light has a direct route, or is redirected towards the observer as a result of scattering. By teasing out the polarizational characteristics of the light from any object, the reduced information may lead to the determinations of astrophysical geometry which could not be ascertained by ordinary photometry. The diagnostics associated with polarimetry provide unique information of source structures.

Perhaps the most readily appreciated aspect of this relates to the possible determination of the orientation of a magnetic field by measurements of the Zeeman effect. According to classical Lorentzian theory (see, for example, Jenkins & White, 1965, and Chapter 9), the light emitted by atoms radiating in a strong magnetic field will be polarized. When the field is longitudinal to the line of sight, the resultant emission line is split into two components, shifted in wavelength either side of the original value. The two generated lines are circularly polarized with opposite handedness. For a transverse field, the original line splits into three components, two found either side in wavelength of the original line value, the third being undisturbed in position. The two wavelength-shifted components are linearly polarized while the central component is also linearly polarized but with an orthogonal azimuth. In principle, by measuring the full polarizational behaviour, with sufficient spectral resolution, through Zeeman broadened lines, the longitudinal and transverse components of the magnetic field may be determined and compounded to provide the orientation of the field in the environment of the radiating atoms.

Reference has also been given to the behaviour of the polarization produced by particles in the interstellar medium (see Figure 1.4), indicating the presence of some alignment mechanism which is locally coherent. Mapping the effects of this polarization gives unique insight into interstellar cloud structures and into the variations of the direction of the alignment mechanism.

Finally, the special property of polarization may be highlighted by exploring a star which has a localized, optically thin, cloud of electrons orbiting about it. Some of the radiated light will be scattered into the line of sight, making the star appear slightly brighter, according to the cloud's distance from the star, the electron density and the phase angle of the scattering. This additional contribution to the apparent brightness will also be polarized according to the phase angle. Overall, the star would appear to exhibit an intrinsic polarization originating in the cloud, but diluted by the unpolarized radiation received directly from the stellar surface. In general, the star might appear to vary in brightness and in polarization, according to the orbital characteristics of the cloud.

Consider a special case for which the electron cloud is in a circular orbit with an inclination of 0°, so that its path is projected as a circle on the sky (see Figure 1.5). As the orbit progresses, the apparent brightness will not vary; the degree of polarization will also remain constant. The azimuth of the polarization will rotate, however, running through the angular positions of 0° through 90° to 180°, twice over the orbital cycle. The presence of the cloud would only be apparent from polarimetric studies monitoring the rotation of direction of vibration, there being neither brightness nor spectral variations. Such a star can be considered uniquely as a *polarimetric variable* with special characteristics. It goes without saying that

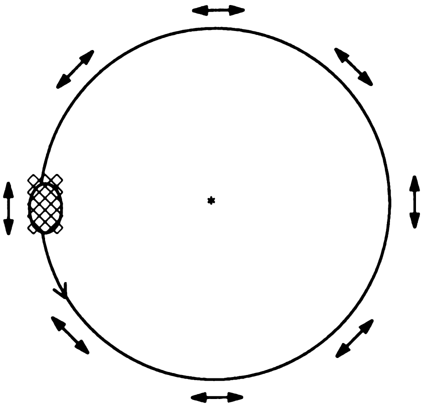

**Fig. 1.5** As a cloud of electrons executes a circular orbit in the plane of the sky about a point source star, the azimuth of polarization vector rotates from 0° through 90° to 180° twice per orbit, but its strength maintains at a constant level with the overall brightness of the system also remaining constant.

any quest to find such a perfectly behaved object is likely to draw a blank. However, from phase-locked polarimetric variability detected in some stars, it has been possible to determine the geometry of orbiting material which could not be ascertained from the brightness variability alone. See Chapter 11 for a more incisive presentation on this point.

## 1.8
## Chirality and the Origin of Life

Some 150 years ago, Louis Pasteur demonstrated that certain molecules with helical structures occur in two forms, or *enantiomers,* referred to as being either left- or right-handed. Such molecules are said to be *chiral.* In the laboratory, chemical reactions producing chiral molecules generally produce equal amounts of the two types. Organic compounds from living matter, however, are almost always of one handedness or the other. Amino acids that form the building blocks of proteins are all left-handed (L(aevo)-configuration), whereas the sugars including ribose and deoxyribose, important components of RNA and DNA, are always right-handed (D(extro)-configuration). A quest followed by Pasteur was the search for the asymmetric physical force that could account for the origin of biological homochirality which, according to him, was the only well-marked demarcation between the chemistry of dead matter and the chemistry of living matter. He considered circularly polarized light as being one such possible triggering source although he did not investigate this proposition by experiment. All explorations of this suggestion produced negative results until the experiments by Kuhn around the 1930s (see, for example, Kuhn & Braun, 1929) successfully demonstrated enantio-differentiating reactions with circularly polarized light in the UV region. Since then, numerous arrangements have been used involving circularly polarized light to selectively produce either left- or right-handed forms of particular molecules. The principle relies on one of the enantiomers preferentially absorbing circular polarized light of a specific handedness and exciting the molecule to a state which allows further constructive chemical reaction to take place more frequently than for the other form. The importance of chirality in respect of possible life beyond the Earth has been discussed by many researchers including Thiemann (1975), for example. The circular polarization present in the scattered light of the daytime sky has been considered by Wolstencroft (1985) as a local source for affecting a bias on the distribution of enantiomers on the Earth's surface.

The recent discoveries by radio and millimetre astronomy of so many signatures of different kinds of organic molecules demonstrate the abundance in the interstellar medium of the building blocks for life. It could well be that the origins of life on the Earth are from beyond our globe, and have been transported from space by comets, interstellar dust, or were already present in the protoplanetary material. Certainly an important finding is the excess of L-amino acids in the Murchison meteorite (see Cronin & Pizzarello, 1997; Engel & Macko, 1997). The basic path to our homochirality has been summarized by Cronin (1998). The starting point simply requires the setting of an imbalance within some particular astrophysical environment. Bonner (1991a, 1991b) suggested the scenario of electron plasmas in an orbit about a neutron star, with circular polarized light being generated over a wide range of wavelengths as synchrotron radiation. Such light would illuminate the organic matter in nearby molecular clouds. According to the geometry and depending on whether the light originated above or below the plane of the orbiting electrons, one of the enantiomers would preferentially emerge. The imbalance is therefore present in the protostellar systems and their planetesimals and cometary material. Following the discovery of high levels of infrared circular polarization in the Orion OMC-1 region, Bailey, Chrysostomou, Hough, *et al.* (1998) have proposed that enantiometric excesses can be established in organic molecules in protostellar clouds as a result of scattering of the UV radiation from a nearby star.

Although there are alternative mechanisms for the original trigger for our local biological homochirality, effects associated with polarized radiation are strong contenders. It is, of course, of great interest to the astrophysicist to explore the localities in the Universe where the original seeds were set. The diagnostic role of polarimetry may well provide an important contribution to unravelling this enigma.

## 1.9
## Conclusion

The basic history of our understanding of *polarization* as an important attribute of light has been sketched out with particular reference to the discoveries of Malus. The importance of polarimetric measurements for gaining unique knowledge of the geometry of astrophysical systems has been emphasized.

The highlights of the first 50 years of stellar polarimetry have been described briefly in terms of telescopic discoveries and their phenomenology. Admittedly the citations are not complete and may have short-changed some of the important contributors to the field; selection is necessary, however, in striving to keep the introduction to reasonable length. References to many important developments have not been made, but this will be remedied to some degree later in the main body of the text. Little reference has been made to the contemporaneous advances made in understanding the polarigenic mechanisms and the modelling of astrophysical situations. Again coverage of these topics is reserved for fuller discussion in the later chapters. Before this can be done, it is first necessary to describe the concepts associated with polarization more fully, together with the formalism of the mathematical tools required to understand instrumental design, to appreciate the necessary telescope protocol and to decipher its connections with astrophysical phenomena.

In summary, here it might be said that, as well as being a supportive diagnostic to other kinds of observation in astrophysics, polarimetry has sufficient power and independence to be sometimes relied on alone through its own fundamental merits. It is interesting to note that what might be called the first Conference on Stellar Polarimetry was held at the Lowell Observatory, Flagstaff, Arizona, in 1960 (see Lowell Observatory, 1960). In 1972, a conference on *Photopolarimetry* covering *Stars, Planets and Nebulae* (and other topics) was held in Tucson, Arizona. The proceedings were edited by Gehrels (1974); the resulting collection of material is sometimes euphemistically referred to as the *Polarimetric Bible*. More recently a workshop was held at the Vatican Observatory, Castel Gandolfo, in 1987, resulting in the production of a range of papers under the umbrella title ‘Polarized Radiation of Circumstellar Origin’ (see Coyne, Magalhães, Moffat, *et al.*, 1988). Also the Royal Astronomical Society (London) has hosted a one day specialist discussion meeting entitled ‘Astronomical Polarimetry as a Source Diagnostic’ covering its application in various parts of the electromagnetic spectrum (see Clarke, 1992). The essentials of polarimetry which tend to be neglected in undergraduate courses on optics may be set with astrophysical context to provide the bases of postgraduate schools – see, for example, Trujillo-Bueno, Moreno-Insertis & Sánchez (2001). An International Conference on ‘Astronomical Polarimetry – Current Status and Future Directions’ was held in March 2004 in Hawaii (see Adamson, Aspin, Davis, *et al.*, 2005), followed by one in Malbaie, Québec, in 2008 (see Bastien & Manset, 2009).

Key papers on the understanding and mathematics associated with the descriptions of polarization have been collected by Swindell (1975), this work containing some material related to historic papers which are otherwise difficult to obtain for consultation. Descriptive books on the presence of polarization in nature have been produced by Können (1985) and Pye (2001). Other texts also available on Optical Polarimetry describing the physics of polarization phenomena and optical devices used are those of Shurcliff (1962), Clarke & Grainger (1971) and Huard (1997).

On the astronomical scene, polarimetry is the theme of works by Tinbergen (1996), Dolginov, Gnedin & Silant’ev (1995) and Leroy (1998, 2000). The rapidly expanding theme of spectropolarimetry is also supported by a text by del Toro Iniesta

(2003), this providing extensive material on the effects associated with polarization signatures within spectral lines, with particular reference to the Sun.

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