SPECTROPOLARIMETRY AND MAGNETOGRAPHY FROM THE GROUND

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ABSTRACT

Most of what we know today about solar magnetic fields has been learned through the measurement and interpretation of the polarization of spectral lines. In this contribution, I review the different instruments used for solar polarimetry, the techniques we apply to extract information from the measurements, and the advantages and disadvantages of polarization studies from the ground. I will describe some recent results obtained from high precision, full Stokes spectropolarimetry in order to illustrate the potential of ground-based observations. In particular, I will discuss advances in the understanding of the structure of sunspot penumbrae, a topic of active research these days. Finally, expected developments and applications of solar polarimetry from the ground will be briefly mentioned.

Key words: polarimetry, magnetometry, solar photosphere, sunspot penumbrae.

1. INTRODUCTION

Polarization provides us with a unique means to investigate the magnetic structuring of the solar atmosphere, even if we do not resolve the individual constituents. Spectral lines formed in the presence of magnetic fields split in several $\sigma$ and $\pi$ components. This is the well-known Zeeman effect [1] (for a historical review see [2]; a modern physical description can be found in [3]). The wavelength separation of the $\sigma$ components with respect to the central wavelength $\lambda$ is $\Delta \lambda_B = 4.67 \times 10^{-13} g_{\text{eff}} \lambda^2 B$, where $g_{\text{eff}}$ and $B$ represent the effective Landé factor of the atomic transition and the magnitude of the vector magnetic field, respectively (wavelengths are expressed in Å and $B$ in G). In addition, the polarization and relative strength of the various $\sigma$– and $\pi$–components are determined by the orientation of the vector magnetic field with respect to the observer.

Except in sunspots, the wavelength shifts induced by the Zeeman effect are difficult to measure directly in the intensity spectrum because they are smaller than the typical line width. Fortunately, the detection and characterization of magnetic fields is much easier in polarized light. The polarization of a light beam is completely specified by the four Stokes parameters $I$, $Q$, $U$, and $V$. $I$ represents total intensity, $Q$ and $U$ linear polarization, and $V$ circular polarization. For a description of the Stokes parameters, see, e.g., [4] and [5].

Information about solar magnetic fields can be obtained by measuring the Stokes parameters of spectral lines formed in the atmosphere of the sun. This is the goal of solar polarimetry. Over the years, a wealth of instruments have been built and refined for high precision, full Stokes spectropolarimetry of solar magnetic structures. In parallel, sophisticated diagnostic techniques have been developed for the interpretation of the ever-increasing amount of data produced by solar polarimeters. Ground-based observations have been used to study all types of structures and layers of the solar atmosphere. In the following, the emphasis will be on photospheric magnetic fields and results obtained by means of the Zeeman effect. Magnetic fields in the chromosphere and the corona have recently been reviewed in [6] and [7], respectively. The diagnostic capabilities of the Hanle effect are discussed in [8] and [9] and references therein.

2. EXTRACTING INFORMATION

The basic observational material is some or all four Stokes parameters of a spectral line at one or more wavelengths. In Sect. 3.2 a brief description of the instruments used for solar polarimetry will be given. For the moment, let us concentrate on how we extract information from the measurements. This inverse problem is nontrivial because the Stokes vector $I = (I, Q, U, V)^T$ depends not only on the vector magnetic field, but also on the physical conditions of the atmosphere (temperature, velocity, pressure, etc.). Such dependences are described by the radiative transfer equation (RTE) via the absorption matrix $K$ and the source function vector $S$ [10].

In principle, the complete line transfer problem has to be solved if we want to derive information from the observations. That is, the RTE must be integrated

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in a given model atmosphere in order to compute synthetic Stokes profiles at the surface. If they do not coincide with the observed ones, the model atmosphere has to be changed to remove any difference between them. The procedure just mentioned requires radiative transfer calculations. Under certain idealized conditions, however, much simpler solutions of the RTE exist. These solutions lie at the core of several methods that have been used in the past to infer single values of the magnetic field strength from the observations. Although largely superseded by more sophisticated inversion techniques, they have significantly contributed to our understanding of solar magnetism. In what follows, some of them will be discussed because of their historical significance, but also because they illustrate important properties of the Stokes parameters.

Strong field regime. If the magnetic splitting is much larger than the line width (i.e., if \( \Delta \lambda_B >> \Delta \lambda_D \)), where \( \Delta \lambda_D \) is the Doppler width of the line), then the wavelength separation of the \( \sigma \) components is directly measurable in the intensity or polarization profiles, and it can be used to determine the field strength \( B \) (assumed to be constant along the atmosphere). This approximation is very useful in the near infrared, where many spectral lines are almost completely split with relatively modest field strengths (in the case of the Fe I line at 1.56 \( \mu \)m, with \( g_{\text{Ze}} = 3 \), the strong field regime can be considered to be a good approximation for Stokes \( V \) if the field strength is larger than about 500 G).

Weak field regime. When the magnetic field (or the effective Landé factor) is sufficiently small so that the Zeeman splitting is negligible in comparison with the line width, a series expansion of the absorption and dispersion profiles appearing in \( K \) leads to the following expressions for \( V \) (see, e.g., [11] and [12])

\[
V(\lambda) = -\Delta \lambda_B \cos \gamma \frac{dI_0}{d\lambda},
\]

where \( \gamma \) is the inclination of the vector magnetic field with respect to the line of sight. To first order in \( \Delta \lambda_B \), \( I_0 \) is the intensity that would emerge from exactly the same atmosphere with zero magnetic fields. Stokes \( V \) is therefore proportional to the longitudinal magnetic field \( (B_\parallel = B \cos \gamma) \) and to the effective Landé factor of the transition. In this regime, the separation between the peaks of the Stokes \( V \) profile does not change when the magnetic field strength is increased, only the amplitude of the circular polarization signal does. Eq. (1) is usually referred to as the magnetograph equation. It has been widely used to convert magnetograph measurements into magnetic field strengths. Despite its popularity, one must be careful with its range of applicability, as it is valid only when the field is weak and constant with height. In sunspot umbrae where magnetic fields of up to 3000 G prevail, for example, its application would be very questionable. Even if the magnetic field is weak, we still have a calibration problem because \( I_0 \) cannot be observed directly and must be estimated. Normally, one uses the quiet sun intensity profile (to varying degrees of sophistication) in the hope that it will give a good approximation to \( I_0 \), but this does not need to be the case. Reference [10] describes in detail the standard calibration of magnetograph measurements, and [13] points out some of its limitations.

In the weak field approximation, Stokes \( Q \) and \( U \) are zero to first order in \( \Delta \lambda_B \). To second order, \( Q \) and \( U \) are given by

\[
Q(\lambda) = -\frac{1}{4} (\Delta \lambda_B)^2 \sin^2 \gamma \cos 2\chi \frac{H''(a,v)}{H'(a,v)} \frac{dI_0}{d\lambda},
\]

\[
U(\lambda) = -\frac{1}{4} (\Delta \lambda_B)^2 \sin^2 \gamma \sin 2\chi \frac{H''(a,v)}{H'(a,v)} \frac{dI_0}{d\lambda},
\]

where \( H(a,v) \) is the Voigt function, \( a \) the damping parameter, \( v = \Delta \lambda/\Delta \lambda_D \) the specific wavelength, and primes represent derivatives with respect to \( v \) (see [12] for details). In the limit of weak lines, the intensity profile has the same form as the line absorption coefficient, \( (H''/H')(dI_0/d\lambda) \approx d^2I_0/d\lambda^2 \) and Eqs. (2) and (3) can be rewritten in terms of the second derivative of the intensity profile. From these expressions we see that \( Q \) and \( U \) depend quadratically on the transverse magnetic field \( (B_\perp = B \sin \gamma) \) and that, contrary to \( V \), they also depend on the azimuth \( \chi \) of the vector magnetic field as seen by the observer. Hence, simultaneous measurements of \( Q \), \( U \) and \( V \) allow us to determine the strength and orientation of the vector magnetic field uniquely except for a 180° ambiguity in the azimuth. This important result is valid for any arbitrary magnetic field.

Unresolved fields. Now consider the case in which unresolved magnetic structures occupy a fractional area \( \alpha \) of the resolution element. In this situation, the observed intensity is the sum of the intensity emerging from the field-free atmosphere and the intensity coming from the magnetic elements. In contrast, Stokes \( Q \), \( U \) and \( V \) are produced only in the magnetic atmosphere. This property allows us to go beyond the resolution limit of the telescope. We cannot see the unresolved structures, but they leave their imprints in the polarized line profiles. For weak fields, the Stokes \( V \) signal is still proportional to the longitudinal magnetic field as in Eq. 1, but now it is also proportional to the magnetic filling factor \( \alpha \). This means that only the apparent magnetic flux \( \alpha B_\text{polar} \) can be determined from measurements of circular polarization. This is one of the major limitations of magnetograph observations.

Several methods have been proposed to separate \( \alpha \) from the longitudinal magnetic field. Among them is the magnetic line-ratio technique [14] (see also [3]), which requires two identical lines except for their different magnetic sensitivities (i.e., different effective Landé factors \( g_1 \) and \( g_2 \)). If the field is weak, the ratio of the Stokes \( V \) amplitudes of the two lines \( V_1/V_2 \) is equal to \( g_1/g_2 \), independently of the magnetic filling factor (cf. Eq. 1). With larger field strengths, the weak-field approximation breaks down earlier for the
line having the largest Landé factor. Due to saturation, the \( V \) signal of that line is no longer proportional to \( B \) and \( V_1/V_2 \not= g_1/g_2 \). This behavior can be used to distinguish between intrinsically weak and strong fields, regardless of the magnetic filling factor. Indeed, the line-ratio technique was employed to demonstrate that flux tubes in plage and network regions have kila gauss field strengths [3].

Unno-Rachkovsky solution. A less restrictive (but still simple) solution of the RTE is obtained under the assumptions that the absorption matrix is constant along the atmosphere and that the source function varies linearly with optical depth. The explicit expressions of the Stokes parameters emerging from such a Milne-Eddington atmosphere are derived in detail, e.g., in [10]. A wealth of outstanding scientific results have been obtained with the help of the Unno-Rachkovsky solution, and indeed it is still used on a regular basis by many solar physicists.

Inversion methods. So far simple techniques and approximations have been discussed. As pointed out before, the Stokes profiles contain much more information about the whole atmosphere than just a single value of the magnetic field strength. If we want to extract all this information, we have to use more complex inversion techniques. Recent reviews on inversion techniques can be found in [15], [16] and [17]. The basic idea behind inversions is to adopt a guess model atmosphere to compute synthetic Stokes profiles which are subsequently fitted to the observations by means of a nonlinear, least-squares algorithm. In this process, the model atmosphere is modified iteratively until the best fit is reached. The main advantages of inversion techniques are: (a) they solve the complete transfer problem, so there is no need for uncertain calibrations; (b) they can handle the four Stokes parameters, which is very important for better constraining the model atmospheres; and (c) they allow us to consider relatively complex scenarios, such as magnetic flux tubes or two-component model atmospheres, in order to interpret the observations more realistically. Well tested inversion techniques include the Milne-Eddington code of the HAO [18], the SIR code of the IAC [19], and the SPINOR package of the ETH Zürich [20].

A few words concerning the performance of inversion methods seem necessary at this point. Sometimes we hear that the inversion problem is ill-posed or that inversions are nonunique (and hence unreliable). There might be some truth in these statements, but for the most part they lack a solid foundation. It has been shown several times that inversion techniques are robust: they find the same solution independently of the initial guess atmosphere and other inversion conditions provided that the physical assumptions are not modified. What is important to realize is that the outcome of inversion techniques is entirely model dependent. If different scenarios (all too simplistic to a larger or smaller extent) are adopted to interpret a given set of observations, there is no doubt that the results will differ. Of course, this behavior does not reflect a uniqueness problem, but rather that some of the models are unable to describe the real solar atmosphere. An example will clarify this point: if we invert Stokes profiles emerging from facular regions with one-component models having no discontinuities along the line of sight, the inferred stratifications will look strange because no allowance is made for the jump of a atmosphere parameters that occurs at the flux tube canopy. This example emphasizes the importance of realistic models, and indeed much effort is being made to implement more complex models in current inversion codes.

3. POLARIMETRY FROM THE GROUND

3.1. Advantages and disadvantages

The goal of solar polarimetry is to measure the polarization state of the light emerging from solar magnetic structures. Ideally, one would like to have the four Stokes parameters of as many lines as possible, with extremely high spectral, spatial and temporal resolution, high polarimetric sensitivity, and 2D coverage. Most of these requirements are met by ground-based observations. Two advantages of solar polarimetry from the ground, as opposed to space, deserve special consideration: flexibility, on the one hand, and multi-line capabilities, on the other. Flexibility means that we can select any line and/or instrument we wish, and that last-minute changes are possible on the spot. Perhaps more important is the multi-line capabilities of some ground-based solar telescopes. Simultaneous observations in several spectral ranges (even combining different spectral ranges, such as the UV, the visible and the near IR) are definitely needed for better constraining the model atmospheres, especially if discontinuities along the line of sight are present.

The major limitation of solar polarimetry from the ground is the distorting effect of turbulence in the Earth's atmosphere. Seeing fluctuations induce false polarization signals if the various intensity measurements used to determine the Stokes parameters are affected by different seeing conditions. A very didactical example of this seeing-induced crosstalk can be found in [21]. One possibility to avoid such false signals is to modulate the incoming light faster than the typical time scale of seeing variations (about 100 Hz). Another possibility is to record two orthogonal polarization states simultaneously by means of a polarizing beam splitter (spatial modulation). Most solar spectropolarimeters adopt a combined strategy involving simultaneous temporal and spatial modulation [22]. In addition, seeing fluctuations degrade the angular resolution and image stability. Over the years, several techniques have been developed to overcome these problems. Modern solar telescopes benefit from real time tip-tilt correction (e.g. [23]), with which resolutions of about 1 arcsec or better can be maintained for hours. The image stabilization provided by correlation trackers is especially important for spectrograph observations in order to keep
the slit at the same position during the measurements. Speckle [24] and phase diversity [25] reconstruction are post-facto techniques capable of delivering near diffraction-limited images. These methods have been applied mostly to narrow-band filter observations, although speckle techniques have also been developed for spectrograph observations [26]. Finally, active wavefront compensation (adaptive optics and multi-conjugate adaptive optics [27]) will soon become available for polarimetric measurements. The combination of existing adaptive optics (AO) systems and spectropolarimeters is underway in NSO/Sacramento Peak Observatory and Teide Observatory, and we may expect diffraction-limited observations of unprecedented quality in a few months time. In addition to compensating the seeing fluctuations, AO systems correct the fixed aberrations of the telescope. They are considered essential components of future solar telescopes, because large aperture diameters increase the likelihood that rays coming from the same spatial point on the sun traverse different turbulent eddies in the atmosphere, leading to enhanced image blurring. Without robust AO systems, ground-based telescopes will hardly be able to resolve the intrinsic spatial scale of magnetic fields in the solar atmosphere, i.e., the photon mean free path (about 100 km in the lower photosphere). It is believed that processes occurring at these scales are crucial for understanding the structure, dynamics and energetics of the whole atmosphere.

3.2. Instruments

Instruments used for solar polarimetry can be classified into two groups: narrow-band tunable filters, and spectropolarimeters.

Narrow-band filters. These instruments are based on Lyot-type filters or Fabry-Perot interferometers (FPs). They provide 2D coverage with large fields of view (typical image size of \( \sim 1 \times 1 \) arcmin). Narrow-band filters have been mostly used to measure circularly polarized light at a single wavelength. However, line profiles can be constructed by scanning the spectrum in wavelength. Multi-line observations are possible, but different lines have to be observed sequentially. A good description of the advantages of FPs for solar observations has been given in [28]. One of the most successful instruments is the Göttingen FPI spectrometer [29]; in combination with a Stokes V polarimeter, it is routinely used at the German VTT of Teide Observatory for speckle spectropolarimetry (e.g., [30]).

Spectropolarimeters. These devices measure the four Stokes parameters along the spectrograph slit. Therefore they can be considered 1D instruments. The principles of operation of Stokes vector spectropolarimeters are described, e.g., in [31]. Spatial maps can be constructed by scanning the slit across the region of interest. A number of spectropolarimeters are currently operational, including the Advanced Stokes Polarimeter [32], the Zürich Imaging Polarimeter [33], the Tenerife Infrared Polarimeter [34] and the La Palma Stokes Polarimeter [34]. POLIS (Polarimetric Littrow Spectrograph), designed for simultaneous observations in the visible and UV [35], has seen first light very recently.

The two types of instruments are used for different applications. Narrow-band filters provide 2D fields of view, thus allowing for image reconstruction. They are the instruments of choice for very high spatial resolution or investigations of large-scale phenomena. Among their drawbacks we can mention the somewhat poor spectral resolution (compared with typical spectropolarimeters) and the long time (about 30 sec) required to complete the scan of a single spectral line (the temporal resolution is limited by the read-out speed of current detectors). Another disadvantage is that narrow-band filter observations cannot be corrected for instrumental polarization because only Stokes \( I \) and \( V \) profiles are measured.

Spectropolarimeters, on the contrary, record the four Stokes profiles simultaneously. This makes it possible to correct the observations for instrumental polarization. If the slit position is kept fixed, spectropolarimeters permit high cadences which are appropriate for studying very dynamical processes such as the formation of magnetic flux tubes by convective collapse. However, there is no context information in this case, and it sometimes happens that the structures under analysis drift out of the slit due, e.g., to proper motion or image motion. Finally, the time needed to construct spatial maps is in the order of minutes.

4. APPLICATIONS

Since the invention of the photoelectric magnetograph in 1953 by Babcock and Kiepenheuer, polarimetry has been used regularly for the analysis of all kinds of magnetic structures in the solar atmosphere. Reviewing the advances achieved in the different fields is beyond the scope of this paper. The reader is referred to the conference proceedings [36], [37], and [38] for recent results. In what follows, I will concentrate on a particular subject which has received much attention during the last years: the fine structure of the penumbra. The reason for this choice is two-fold. First, this topic nicely illustrates the potential of spectropolarimetric observations. Second, it is my belief that a clarification of the results of recent analyses of the penumbra (especially those based on inversion techniques) is desirable. During the last years we have found evidence of different penumbral components, magnetic field lines coming back to the solar surface already in the middle penumbra, and supersonic flow velocities. One may wonder how inversion techniques manage to obtain this information. The fact is that very often these processes leave clear signatures in the Stokes profiles (especially in the infrared), and this facilitates the interpretation to a large extent. Since polarization line
profiles is the basic material used by inversion codes, I will concentrate on the various spectropolarimetric indicators we have at our disposal.

Reviews of recent observational results in sunspot penumbrae can be found in [39] and [40]. Reference [41] summarizes our current understanding of the penumbra from a more theoretical point of view.

4.1. Structure of the penumbra

High resolution observations reveal that sunspot penumbrae consist of bright and dark elongated filaments which are oriented almost radially. Their intrinsic size is about 250 km as inferred from speckle G-band images [42]. Associated with these fibrils are penumbral grains which move inwards in the inner penumbra and outwards in the outer penumbra. In addition, the penumbra is characterized by a nearly horizontal, outward radial flow – the Evershed flow – which appears to end abruptly at the outer penumbral boundary. Penumbral fibrils, as seen in continuum images, map local temperature variations, but it is generally accepted that such fluctuations are induced by the magnetic field configuration of the penumbra.

Roughly speaking, the inclination of the vector magnetic field increases as one moves from the umbra to the outer penumbral boundary. The polarization signal extends well beyond the visible edge of the penumbra, revealing the so-called penumbral canopy [43]. It is believed that the canopy is formed by field lines spreading out with height. At these large radial distances, such lines overly a non-magnetic atmosphere. Observations indicate that the vector magnetic field is continuous at the outer penumbral edge, giving support to this interpretation. The canopy is not seen in continuum images because they map deep layers already devoid of magnetic fields.

In an axisymmetric sunspot, the line-of-sight component of the vector magnetic field (and therefore the magnetograph signal) changes progressively as one moves around the center of the spot. This was used in [44] to infer the mean inclination of the magnetic field at different radial distances in the penumbra. Deviations of the magnetograph signal with respect to the expected behavior were interpreted as azimuthal fluctuations of the inclination angle. Such fluctuations have been reported by many other authors, often using magnetograph observations or Stokes V profiles only [45], [46], and [47]. Recent measurements of the full Stokes profiles of visible and infrared spectral lines confirm this finding [48], [49], [50], [51]. It is now established that filaments with nearly horizontal fields alternate with fibrils in which the field is more vertical. More inclined fields are weaker, carry the largest fraction of the Evershed flow, and appear dark in visible continuum images. In the infrared, however, they seem to be associated with bright structures [51], although this point need further confirmation.

4.2. Spectropolarimetric evidence

Azimuthal fluctuations. The observation of dark and bright fibrils strongly suggests that the penumbra is formed by at least two distinct magnetic components. These components would be responsible for the azimuthal fluctuations mentioned in the previous section. Another indication of the existence of different magnetic components is provided by the spatial variation of the Stokes profiles of infrared lines. Fig. 1 shows the intensity, circular polarization, and total linear \( L = (Q^2 + U^2)^{1/2} \) polarization profiles of the Fe I line at 1.56 \( \mu \)m measured along the line connecting the disk center and the center of a spot located at an heliocentric angle of 57°. All profiles have been normalized to its maximum value in order to enhance the weakest signals. The line connecting the disk center and the spot will be referred to as the line of symmetry, and has interesting properties. Along the symmetry line, the vector magnetic field of an axisymmetric spot is contained in the plane formed by it and the observer, which is not true for other positions in the penumbra. In Fig. 1, the limb-side penumbra is on top, and the center-side penumbra at the bottom. The circular polarization map (central panel) clearly shows the neutral line in the middle of the limb-side penumbra. At this location, the Stokes V signal reverses polarity, with an abrupt transition from the negative polarity of the spot to the opposite polarity as one moves toward the outer penumbra. Near the neutral line, the dominant magnetic field is perpendicular to the line of sight and, consequently, it does not contribute much to the observed Stokes V signal. It is because of the fine structure of the penumbra that we detect circular polarization there. Beyond the neutral line, another magnetic component dominates. It is characterized by smaller field strengths (as revealed by the smaller wavelength separation between the peaks of Stokes V) and different inclination angles. In addition, it harbors large flows away from the observer (as revealed by the overall redshift of the profiles with respect to those in the inner limb-side penumbra). We do not see this second component in the center-side penumbra because it has the same polarity as the dominant field, and the separation is difficult because both contribute similarly to the observed Stokes V signal.

The total linear polarization map (right panel) reveals a different, but fully consistent, picture. Using the same geometric arguments as before, there exists a position in the center-side penumbra where the dominant magnetic field is parallel to the line of sight. Consequently, it produces a negligible amount of linear polarization. If we see something there, it is due to the second magnetic component characterized by a different inclination angle. Once again, a sharp discontinuity occurs at this point. The region extending from the middle to the outer center-side penumbra is dominated by the second component, which shows the same properties (lower field strengths, larger inclinations) as in the outer limb-side penumbra. Now, however, the linear polarization profiles are blueshifted with respect to those in
the inner center-side penumbra, indicating motions toward the observer. This is the signature of the Evershed flow. The second component is not clearly seen in the limb-side penumbra because both components contribute similar signals to the total linear polarization (both are almost perpendicular to the line of sight and have more or less the same azimuth angle).

The spatial variation of the $V$ and $L$ profiles directly tells us that there are at least two different magnetic components: a background almost at rest, with strong and more vertical fields, and another component with smaller and more horizontal fields. The Evershed flow is observed predominantly in the second component, producing Doppler shifts toward the red in the limb-side penumbra, and toward the blue in the center-side penumbra.

Different magnetic components in sunspot penumbral fibrils are also inferred from the shapes of the polarization profiles. The angular resolution of current spectropolarimetric measurements is not better than about one arcsec. As a consequence, the Stokes profiles emerging from the resolution element are an average of the signals formed in the various magnetic components. Since they have different properties (inclination angle, material flow), the total Stokes profiles may show abnormal shapes. An extreme case occurs when different polarities coexist within the same resolution element. Especially in the infrared, we often see Stokes $V$ profiles with three or more lobes [51], [52]. They are not only observed near the neutral line, but also all over the penumbra. Figure 2 shows examples of Stokes $V$ profiles of the Fe I line at 1.56 μm having different degrees of anomaly (left panels). Interestingly enough, they belong to a penumbra located close to disk center, where the neutral line should be almost absent. These profiles can be interpreted as the superposition of two different Stokes $V$ signals (Fig. 2, right panels). The dominant signal (thin solid line) is at rest and has a large Zeeman splitting. The second signal (dashed line) has opposite polarity (in fact, it corresponds to inclinations larger than 90°, i.e., field lines coming back to the solar surface), smaller Zeeman splitting, and is affected by a redshift. The sum of these signals (thick solid line) gives rise to profiles which are very similar to those displayed in the left panels of Fig. 2. It is important to emphasize that the amount of Doppler shift (together with the occupation factor) determines the final shape of the profiles, so the visibility of the second component depends mainly on the line-of-sight component of the velocity flow. In particular, such anomalous profiles are more frequent at large heliocentric angle because of the more favorable geometry (the flow channels, being almost horizontal, do not induce significant Doppler shifts near the disk center).

Vertical fluctuations. The typical horizontal dimension of the penumbral fibrils is of the same order of magnitude as the width of the atmospheric layer where the spectral lines are formed. Thus, it is not unreasonable to expect fluctuations of the vector magnetic field in the vertical direction as well. Detecting these variations is much more difficult, however, because they cannot be imaged directly. Indeed, their only measurable effect is to alter the shape of the polarization line profiles emerging from the penumbra. Let us now concentrate on the various spectropolarimetric indicators of fluctuations along the line of sight.

One of these indicators is the net circular polarization (NCP), defined as the integral of the Stokes $V$ signal over a spectral line. Stokes $V$ profiles emerging from sunspot penumbrae have nonzero NCPs. A necessary condition for nonzero NCP is the existence of gradients or sharp discontinuities of velocity along the line of sight [54]. The NCP is increased by discontinuities of inclination and azimuth of the vector magnetic field. Indeed, the large NCP observed in visible lines suggests that it is produced by the combined action of gradients of velocity and inclination angle along the line of sight [55]. An uncombed model, in which almost horizontal flux tubes carrying most of the Evershed flow are embedded in a more vertical background, was put forward to explain the observations [56]. This model naturally
produces sharp discontinuities of velocity and inclination when the line of sight passes from the background atmosphere to the horizontal flux tube, and then again to the background. It has been demonstrated that such an uncombed model is able to reproduce both the observed amount of NCP and its center-to-limb variation [56], [57].

Another indicator of vertical fluctuations is the spatial variation of the NCP in a sunspot penumbra. The NCP maps of visible lines emerging from round sunspots are more or less symmetrical with respect to the line of symmetry. In contrast, the NCP maps of the infrared Fe I line at 1.56 μm are antisymmetrical [58]. The reason for this difference is that the NCP produced by jumps of the azimuth of the magnetic field is antisymmetric, and depends on the ratio of the Zeeman splitting to the thermal broadening. This is the dominant contribution to the NCP at infrared wavelengths. Jumps of inclination and velocity lead to symmetrical variations of the NCP, and dominate in the visible. The discontinuities of azimuth along the line of sight required to understand the observations are caused by projection effects when an uncombed penumbra is observed off disk center, even if the two interlaced magnetic components have the same azimuth (but different inclinations) in the local reference frame. Indeed, it has been shown [58] that the moving tube model [59]—essentially an uncombed penumbra—is capable of predicting the azimuthal behavior of the NCP of infrared and visible lines, at least qualitatively. The amplitudes of the NCP variations of infrared lines have not been reproduced so far, but fitting them in terms of an uncombed model will certainly provide strong constraints on the magnitude of the vertical fluctuations in sunspot penumbrae.

5. OUTLOOK

A great deal of information about magnetic fields in the solar atmosphere has been obtained by measuring the polarization of the light we receive from the sun together with proper interpretations based on the Zeeman and Hanle effects. However, many important problems remain to be solved, as for example the true nature of sunspot penumbrae. In this endeavor, adaptive optics will be definitely needed to improve the angular resolution and image stability. Adaptive optics, and especially multi-conjugated adaptive optics, will allow us to study many fascinating physical processes occurring at spatial scales of about one hundred km.

In the very near future we can expect significant progress from simultaneous observations of visible and infrared spectral lines, the multi-line capabilities of telescopes like THEMIS and the VTT at Teide Observatory, and the operation of new spectropolarimeters like POLIS, with which we will be able to monitor photospheric and chromospheric layers for a better understanding of the magnetic coupling of the solar atmosphere.

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