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Polarimetric shapes of spectral lines in solar observations

Egidio Landi Degl'Innocenti *

Department of Physics and Astronomy, University of Florence, Largo E. Fermi 2, Firenze, Italy

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Abstract

A century has elapsed since the first observation of the polarimetric profile of a line of the solar spectrum. Since then, dramatic progress has been made in the instrumentation, which is now reaching unprecedented levels of sensitivity in the measurement of polarization signals in solar spectral lines. At the same time, the theoretical framework needed for the interpretation of polarimetric observations has steadily evolved from the pioneering methods, based on simple formulae, to the sophisticated structure that is nowadays used with success in the interpretation of solar observations. The present paper is intended to give a historical perspective of the evolution of this research field and of its major achievements, with particular emphasis on the role played by the magnetic field in determining the polarimetric shapes of spectral lines.

Keywords: Solar physics; Polarization; Line profiles

1. Historical introduction

While there is no doubt of what is the meaning of a "line shape" in the framework of traditional spectroscopic observations, when speaking about "polarimetric line shapes" it is necessary to start by clarifying what we really mean by these words, namely what is indeed a polarimetric line shape. There is here some ambiguity because a real result of a measurement is always a recording, on a series of pixels, of a signal which is proportional to the intensity of radiation. If no polarimetric device is introduced, when observing an astronomical object, like the sun or a star, one generally gets a familiar profile with the intensity forming a kind of dip around line center. When performing polarimetric observations the situation changes. To find the polarization signal the observer is obliged to perform at least two observations and then to compare them in order to extract the polarization signal.

A typical example of this procedure, particularly important from the historical point of view, can be found in Hale (1908). George Ellery Hale was indeed the first to perform spectro-polarimetric observations of a celestial body, in particular of the sun. Thirteen years earlier (1895) Zeeman had discovered in the laboratory the effect carrying his name and Hale had the idea of employing it in solar observations, to see whether sunspots were indeed harboring magnetic fields, as it was suspected from Hα images of the chromosphere, showing what were called, at the time, the observed "vortices" surrounding sunspots. For his research Hale used a Nicol prism (acting as a polarizer) and a Fresnel rhomb (acting as a retarder). By changing the direction of the axis of the rhomb he was basically capable of measuring the circular polarization of radiation, thus discovering the presence of a magnetic field in sunspots.

Obviously, things have enormously evolved since the pioneering work of Hale, but even today, when measuring polarization, we are always obliged to refer to the difference of two separate, spectroscopic images obtained by

* Tel.: +39 0552755223.
E-mail address: landie@arcetri.astro.it.

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changing some polarimetric device in the telescope optical train in such a way to alter the polarization characteristics of the observed radiation in a known way. A spectropolarimetric profile thus remains something that is vaguely defined, unless referring to a set of conventions and definitions. Fortunately, today we can make use of a convention that is almost universally accepted (at least for observations in the visible, UV and IR). This convention is based on the Stokes parameters.

The Stokes parameters where introduced in the scientific literature as early as 1852 (Stokes, 1852). By means of their definition, which implies a statistical average of the electromagnetic signal associated with a radiation beam, it was possible to get a fully satisfactory description of polarization. In particular, through the operational definition given by Stokes, it was possible to correctly describe in mathematical terms even an unpolarized radiation beam (or a beam of "natural radiation"). This was not at all trivial. In prior formulations, like e.g. the one used by Fresnel, which only considered pure monochromatic waves, the radiation always resulted in being 100% polarized. One has to wait, however, for more than a century before the Stokes parameters start being used in a systematic way in theoretical and observational astrophysics.

With no doubt this was due to the work of Chandrasekhar (1947) and Chandrasekhar (1950) and to the seminal paper of Unno (1956) who was the first to establish a radiative transfer equation for the Stokes parameters of a spectral line formed in a stellar atmosphere pervaded by a magnetic field. Since then, Stokes parameters have entered the jargon of solar physics and it is now fairly well acknowledged that, when speaking about a spectropolarimetric profile, we have to speak about the profiles of the four Stokes parameters as a function of wavelength (or as a function of frequency). What is a single plot in traditional spectroscopy, the plot of the function $I(\lambda)$ (with I the specific intensity and λ the wavelength), becomes in spectro-polarimetry a set of four plots: $I(\lambda), Q(\lambda), U(\lambda)$, and $V(\lambda)$, with I, Q, U, and V the four Stokes parameters, in modern notations. However, it has to be well kept in mind that Stokes parameters always rely on specific conventions, since they are defined with respect to a reference direction that has to be selected by the observer. Moreover, there are two further conventions that enter their definition and which specify the sign for the 3rd and the 4th parameter. In a recent paper (Landi Degl'Innocenti et al., 2007) an effort has been made for a possible standardization of the Stokes parameters. This standardization coincides with the one that is adopted in the book *Polarization in Spectral Lines* (Landi Degl'Innocenti and Landolfi, 2004) and seems to be more and more adopted today (with the exception of radioastronomers who prefer to give the opposite definition for circular polarization). From now on, we will refer to the "polarimetric shapes" of spectral lines as the profiles of the Stokes parameters as a function of wavelength (or frequency).

The first instrument capable of producing such profiles was the "legendary" Stokes I scanning polarimeter installed at the prime focus of the 40 cm coronagraph at the Sacramento Peak Observatory (House et al., 1976). Indeed, the instrument was very slow since the polarimetric analysis was done at the focus of the spectrograph pixel by pixel, but... it was the first. The observations produced by this instrument were very interesting but they were restricted to those targets showing a fairly large amount of polarization, in particular sunspots. Only later, with the advent of better polarimetric techniques and better detectors, other solar structures were targeted, like for instance prominences, where the polarization signal is much lower (of the order of 1% instead of 10–20% typical of the umbrae of sunspots).

2. Polarimetric profiles due to the Zeeman effect

Polarization can be introduced in spectral lines by several different mechanisms. Apart from the Zeeman effect, we can mention, as particularly relevant in solar physics, scattering polarization (and its modification through the Hanle effect), and impact polarization. Moreover, once polarization is generated in a particular point or region of the solar atmospheres, it can be modified by transfer effects due to dichroism and anomalous dispersion. Each of these phenomena introduces particular signatures in the polarimetric shapes of spectral lines, and it is out of the aims of the present paper to give a general review on the subject. From now on we will then restrict to considering only the signatures introduced in spectral lines by the Zeeman effect.

Since the first observations performed on sunspots, the Stokes parameters profiles typically showed an anti-symmetric shape in circular polarization (Stokes V) and symmetric shapes in linear polarization (Stokes Q and U). Obviously, it was soon realized that the profiles had a large domain of variability. This is obvious because, whereas a "traditional" line profile (the intensity profile) depends on the usual spectroscopic factors, namely (a) the strength of the line (proportional to the element, or ion abundance and to the oscillator strength); (b) the damping constant (due to natural broadening and to collisional broadening); (c) the run of the physical parameters (like temperature, pressure and r.m.s. velocity) in the line forming region, the polarimetric profiles also depend on the magnetic field vector (intensity and direction), and on other atomic properties, like the Zeeman pattern, of the spectral line.

Given that the shape of polarimetric profiles changes with the magnetic field, this property has been used over the years for the diagnostics of magnetic fields in the sun and stars. Indeed, the intensity of the magnetic field might be simply derived, at least in principle, by measuring the wavelength shifts of the different Zeeman components. Unfortunately, this procedure, widely used in the laboratory, can be applied only in very few special cases of astrophysical interest because the Zeeman splitting is generally of the same order of magnitude, if not smaller, than the typical shifts introduced by the other mechanisms which