SPECTROPOLARIMETRY OF THE SOLAR ATMOSPHERE

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ABSTRACT. A brief historical outline of the major achievements of spectropolarimetry in Solar Physics is presented. Such achievements have been made possible through a succession of technological improvements in the measurement of polarized radiation at higher and higher spatial and spectral resolution. In the meantime, the interpretation of polarimetric observations has required more and more sophisticated theories. The development of such theories is described in some detail, with particular emphasis on the work that has been carried out on this subject by the polarimetry group of Arcetri.

1. Historical outline

The first astronomical application of spectropolarimetry dates back to 1908 when George Ellery Hale discovered the presence of magnetic fields in sunspots. By means of a Fresnel rhomb (used as a quarter-wave plate), and a Nicol prism, (used as a polarizer), Hale observed the sunspot’s spectrum in right and left circular polarization thus finding a definite split in the wavelength of spectral lines. Hale correctly interpreted such a splitting as the manifestation of the Zeeman effect – discovered in the laboratory more than 10 years earlier – and thus obtained the first proof of the existence of magnetic fields in cosmic bodies (Hale, 1908).

The technique used by Hale was indeed very primitive. In modern terms, one may refer to it as a “non-simultaneous, subtractive, photographic spectropolarimetry”, since two different spectra were obtained sequentially on photographic plates. The first technological advance was obtained by introducing beam splitters (such as Wollaston prisms) in the optical path, in order to get simultaneous spectra in opposite directions of polarization. Further advances were obtained by substituting the photographic plates with photomultipliers (and, later, with dyode arrays and CCD cameras) and by improving the schematic polarimeter designed by Hale by means of rotating wave-plates and/or variable retarders (such as the Pockels cells used in the first magnetographs).

All these technological improvements, joined to the improvements in spatial resolution of telescopes, lead, through the years, to the discovery of several important properties of solar magnetism, such as the following:

a) In a given cycle, for a bipolar sunspot’s group, the polarity of the preceding sunspot in the Northern emisphere is opposite to the polarity of the preceding sunspot in the Southern emisphere (first Hale’s law, Hale, 1913).

b) The situation is reversed in the following cycle (second Hale’s law, Hale and Nicholson, 1938).
c) Magnetic fields in sunspots present a characteristic, cylindrically symmetric, “funnel” shape, with quasi-vertical (and more intense) magnetic fields in the umbra, and weaker, quasi-horizontal fields at the boundary between the penumbra and the photosphere. Typical umbral fields are of the order of 3000 G for large sunspots (Hale and Nicholson, 1938; Von Kluber, 1947).

d) Magnetic fields are not present only in sunspots, but they involve in practice all the solar atmosphere, with bipolar and/or unipolar magnetic regions at low latitudes (with apparent, i.e. spatially averaged, fields of the order of 10-100 G) and a weak, bipolar field (∼ 1 G) at high latitudes (Babcock and Babcock, 1955).

e) There are close correlations between solar magnetograms and spectro-heliograms obtained in the K line of CaII (Babcock and Babcock, 1955).

f) There exist magnetic concentrations with apparent fields larger than 100 G and with linear dimension at the limit of the resolving power of the instruments (of the order or smaller than 0.5 arcsec). Such concentrations spatially coincide with the so-called “line gap regions” i.e. regions where spectral lines are highly weakened due, most probably, to local temperature enhancements (Sheeley, 1967; Beckers and Schröter, 1968).

g) The magnetic field outside sunspots is “universally strong”, in the sense that it is concentrated in tiny structures having linear dimension of the order of 100-200 Km (flux tubes), where its intensity is of the order of 1 KG (Stenflo, 1973). According to this hypothesis—still controversial under many aspects—the apparent magnetic field measured with an instrument of moderate spectral resolution (of the order or larger than 0.5 arcsec) will be stronger or weaker according to the number of flux tubes contained within the resolution element.

Though the main applications of spectropolarimetry have concerned the study of solar magnetism, there are many other aspects of the physics of the solar atmosphere that can be investigated by means of this technique. It is indeed known since a long time (Lyot, 1948a,b) that the radiation observed at the solar limb is linearly polarized, the electric vector being parallel to the limb itself. The polarization depends both on wavelength and on the distance of the observed point from the solar limb and can be strongly modified by the presence of a weak magnetic field through a physical mechanism known as the Hanle effect. When observing at a heliocentric angle θ ∼ 84° (cos θ = 0.1), the fractional linear polarization is typically of the order of 10^{-4} in the continuum, and increases to values of the order of 10^{-2} in the core of several spectral lines (typically resonance lines).

This polarized spectrum observed at the limb is often referred to as the “second solar spectrum”. Its quantitative investigation, that started in the late ’70s (Wiehr, 1978; Stenflo et al., 1980) and is still in progress (Stenflo and Keller, 1997), is particularly relevant because of its diagnostic content of the highest layers of the solar atmosphere. The physical quantities that can be investigated through the study of the second solar spectrum span from densities (of electrons and neutral atoms) to weak magnetic fields (of the order of 10 G or smaller, either deterministic or turbulent), to velocity fields. Moreover, to get this research field even more interesting, recent observations have revealed a large number of unexpected phenomena such as, for instance, the ex-
istence of interference patterns between spectral lines belonging to the same multiplet, the polarization observed in molecular lines, the strong signals observed in some resonance lines that, according to the conventional theory of resonance scattering, should be unpolarized, and so on (Stenflo and Keller, 1996).

2. Advances in the theory

The interpretation of the polarization profiles that are nowadays observed with modern spectropolarimeters (APS, ZIMPOL, THEMIS) is, in general, extremely complicated and requires a very sophisticated theory capable of describing all the physical mechanisms which underlie the processes of generation and transfer of polarized radiation in stellar atmospheres. In the scalar case, or, in other words, disregarding polarization phenomena, the basic ingredients needed for the interpretation of spectral line profiles are the transfer equation and, when Non-LTE phenomena are involved, the statistical equilibrium equation which relates the populations of the different atomic levels to the local value of the radiation field. For the polarized case, the situation is in principle similar. The scalar radiative transfer equation generalizes into a vector equation for the 4 Stokes parameters, whereas the statistical equilibrium equation for the level populations generalizes into a similar equation for the density-matrix elements of the atomic system. The diagonal terms of the density-matrix describe the populations of the various magnetic sublevels of any given atomic level, whereas the off-diagonal elements describe the so-called coherences (or quantum inferences) between different magnetic sublevels. The real difficulty here is that the two different sets of equations (radiative transfer for the Stokes parameters and statistical equilibrium for the density-matrix elements) cannot be established—as typical in the scalar case—by intuitive or semi-intuitive arguments based on simple physical concepts such as those, for instance, of the absorption coefficient. In classical text-books (see for instance Mihalas, 1978) such a coefficient is simply defined as the ratio $\frac{dI}{(Ids)}$, where $dI$ is the infinitesimal intensity subtracted from a beam of intensity $I$ when travelling through an infinitesimal element of a stellar atmosphere having thickness $dz$. Given this definition, the absorption coefficient in a spectral line is then related by simple arguments to the population of the lower level involved in the atomic transition and to the appropriate Einstein coefficient.

Passing to the radiative transfer equation for polarized radiation, imagine, for instance, that one wishes to express the elements of the 4x4 absorption matrix for a subordinate spectral line where both the atomic levels involved are excited by collisions and by radiative processes (emission, absorption, and stimulated emission) due to a polarized, anisotropic radiation field. Imagine also that both levels are split by a magnetic field of arbitrary direction and that, moreover, the levels have hyperfine structure. It is obvious that, in this situation, physical intuition can be of little help. On the contrary, an effort has to be made in order to establish a convenient theoretical scheme by which such an equation can be deduced directly from first principles.

My research group has indeed undertaken several years ago the ambitious project of deriving from the principles of Quantum Electrodynamics both the radiative transfer equation for polarized radiation and the statistical equilibrium equation for the atomic density matrix. The original idea of deducing the transfer equation for polarized radia-
tion from Quantum Electrodynamics (Landi Degl'Inocenti and Landi Degl'Inocenti, 1972, 1975), was followed by the derivation –obtained through the same formalism– of the statistical equilibrium equation for the populations of the magnetic sublevels (Landi Degl'Inocenti et al., 1976). In these first works, the off-diagonal elements of the density matrix were neglected, so that the theory could be applied only to a rather limited number of problems. In a subsequent work, this approximation was released (Landi Degl'Inocenti, 1983), and a number of applications of the formalism to specific problems were performed (Landi Degl'Inocenti, 1982, 1984, 1985; Landi Degl'Inocenti et al., 1990). More recently, the theory has been generalized to take into account – though in a rather heuristic way – the phenomena of redistribution in frequency (Landi Degl'Inocenti et al., 1997). This last theory has been used to interpret the peculiar linear polarization profile shown by the NaI D lines in the second solar spectrum (Landi Degl'Inocenti, 1998).

3. Conclusions

Thanks to the work described above, and to similar, independent work due to Bommier (Bommier, 1991, 1997a,b; Bommier and Sahal-Bréchot, 1991), the theoretical aspects of solar spectropolarimetry are nowadays rather firmly established. Though some work has still to be done – especially to deal in a fully coherent way with partial redistribution effects – a theory is now available that can encompasses within a unique, self-consistent formalism, a wide variety of physical processes such as the Zeeman effect (direct and inverse), magneto-optical effects, atomic polarization due to pumping and to depopulation pumping, resonance polarization, impact polarization, the Hanle effect, depolarization due to fine structure, to hyperfine structure, and to elastic and inelastic collisions, etc… The theoretical work that has been briefly described in this communication may be considered as one of the most important results of the Italian research in Solar Physics.

References