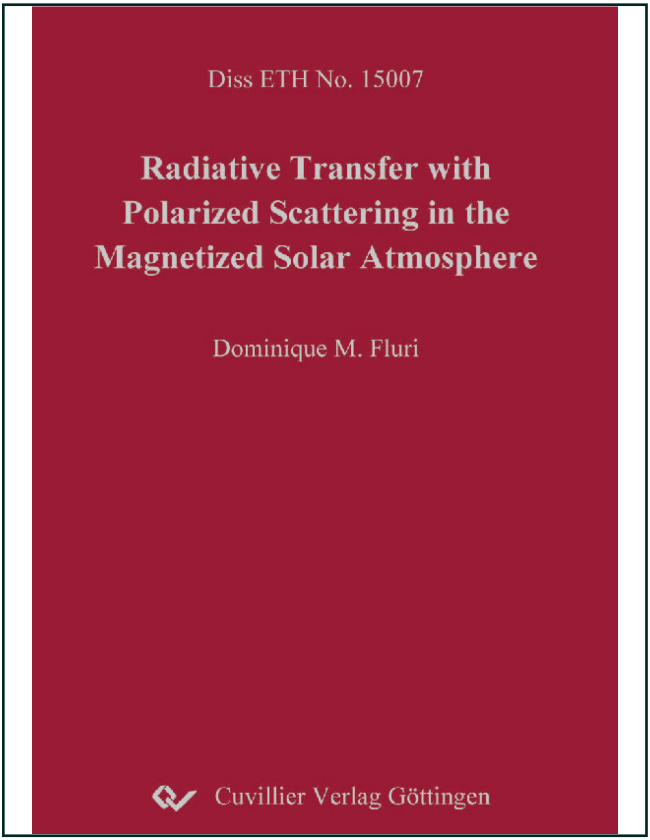
Dominique M. Fluri (Autor)

Radiative Transfer with Polarized Scattering in the Magnetized Solar Atmosphere



Diss ETH No. 15007

Radiative Transfer with
Polarized Scattering in the
Magnetized Solar Atmosphere

Dominique M. Fluri

Cuvillier Verlag Göttingen

https://cuvillier.de/de/shop/publications/3284

Chapter 1

Introduction

1.1 Sources of astrophysical information

Observational astrophysics is based on remote sensing. In that respect, astrophysics is a unique field in physics, because the “experiment” is continuously going on. We just have to look at it. Most information is collected from electromagnetic radiation, while particles reaching us from astrophysical objects play only a minor role as a source of information. Examples of the latter are the solar wind, cosmic rays, and neutrinos produced in supernovae.

In the current thesis we use exclusively electromagnetic radiation as tool to explore the Sun. The light formed on a astrophysical object carries information of that object. The task of the astrophysicist is to observe that light and to decode the imprinted information in order to gain insight into the physical properties of the object. Therefore, it is essential to understand in detail the properties of electromagnetic radiation, its formation processes and its interactions with matter. We will find in this thesis that especially the interaction mechanisms between matter and electromagnetic radiation are not yet well enough known to fully interpret the polarized light spectrum of the Sun. In fact, one of our tasks is exactly to improve our understanding of these interactions.

Spectroscopy is the classic tool to extract information from the observed electromagnetic radiation. It looks at the intensity of light and its frequency dependence. Because we obtain only one observable, spectroscopy only allows to retrieve scalar quantities such as chemical composition and the temperature and density stratification in the observed astrophysical object.

Spectro-polarimetry on the other hand deals with the polarization state of the radiation field, which consists of two linear polarization states as well as circular polarization. These three additional observables make it possible to determine vector quantities, such as velocity fields and magnetic fields. In this thesis we concentrate on the interpretation of the polarized spectrum, in particular on polarization which is formed in scattering processes.

1.2 The role of the Sun in astrophysics

The Sun plays a special role in astrophysics. So far, the topic of scattering polarization was mainly studied on the Sun. Not that it does not occur on other stars or in galaxies. But we are just about starting to explore other objects for scattering polarization. Therefore, it is necessary to see the astrophysical context of the Sun.

The most exclusive property of the Sun is its proximity to Earth, being the closest star. Thus it serves as the one astrophysical laboratory, which can be explored in much more details than any other star. Current telescopes resolve areas on the solar surface with a diameter of the order of 100 kilometers. All other stars, with the exception of very close examples appear only as point sources. Physical properties observed on stars are therefore averaged out. On the Sun, however, we can study physical processes in detail. Once understood, we can then apply the acquired knowledge to other objects.

On the Sun we can explore a parameter space of plasma physics, which is not accessible in our laboratories on Earth. By scaling the parameters of the solar plasma down to the size of our terrestrial laboratories the strength of magnetic fields and electrical currents would exceed our technical capabilities by many orders of magnitudes (cf. Stenflo 2002).

Magnetic fields are of special importance for the Sun and in astrophysics. They are ubiquitous in the universe and are closely related to the activity and development of many astrophysical objects. Therefore, it is important to understand the structure and evolution of the magnetic field on stars and in galaxies. Zeeman effect observations on the Sun have led to the concept that strong kG magnetic fields are confined in flux tubes (Stenflo 1971; 1973) that fill about 1% of the volume in the photosphere. The remaining 99% of the photospheric volume is filled by weak magnetic fields with random vector orientations and a typical field strength of 10–30 G, as supported by Hanle effect observations (Faurobert-Scholl 1993; Bianda et al. 1999). Recent studies have however indicated that this model is too simple, though it can serve as good approximation. Rather, there exists a highly intermittent, continuous distribution of magnetic field strengths (Stenflo & Holzreuter 2003).

Magnetic fields are amplified in planets, stars, and galaxies by dynamo processes, which can operate in electrically conducting media with turbulent motions and differential rotation. On the Sun the dynamo produces an oscillatory state between a poloidal and a toroidal magnetic field configuration with a period of 22 years. Correspondingly, the total solar irradiance follows an 11 year cycle with changes of the total irradiance of about 0.1%. There are strong arguments indicating that the variations in the total solar irradiance are caused by magnetic field elements. It is generally accepted that the solar cycle influences the terrestrial climate because the total incoming energy into Earth's atmosphere is modulated. But further analysis is necessary to separate clearly the solar influence from the "man-made" effects on climatic changes. For a detailed treatment of the topic of the Sun-Earth connection we refer to the work by Fligge (1999), Solanki et al. (2000), and Wenzler et al. (2002).

1.3 Description of polarized radiation

It is necessary to introduce the formalism and the notation employed to describe polarized radiation before we proceed. There exist several different frameworks to treat electromagnetic waves (cf. Stenflo 1994). The Jones formalism, based on classical physics, is well suited to describe monochromatic waves. However, in nature we always have to deal with a whole ensemble of photons with different wavelengths, polarizations, and relative phase. Therefore, the natural choice for the interpretation of observations is the Stokes formalism, which can be derived from the Jones formalism. It is able to deal with a mixture of photons which is in general partially polarized. The same information is also contained in the coherency matrix, which is the best representation of radiation in quantum field theory. In this thesis we depend on the Stokes formalism, which is briefly introduced in the following sections.

1.3.1 Stokes formalism

In the Stokes formalism light is represented by a four component vector

$$\boldsymbol{I} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} , \tag{1.1}$$

where I represents the intensity of the light beam, Q and U linear polarization, and V circular polarization. The meaning of the Stokes parameters can be visualized when considering how they are measured with idealized filters. Stokes Q denotes the difference in intensity measured with an idealized linear polarizer under 0° and 90°, while Stokes U represents the difference in intensity obtained from measurements with an ideal linear polarizer under 45° and 135°. The Stokes V parameter results from the difference in the intensity measurements with ideal circular polarizers for right-handed and left-handed circularly polarized light. We follow the convention that an electromagnetic wave is called right-handed circularly polarized if the electric vector rotates clockwise in a fixed plane, perpendicular to the direction of the wave propagation as seen from the observer. Further, since we deal with solar applications, we will always choose the coordinate system in such a way that Q represents linearly polarized light parallel to the nearest solar limb.

The full power of the Stokes formalism becomes apparent when it comes to partially polarized light, describing a whole ensemble of uncorrelated photons. While for a completely polarized beam of light the relation $I^2 = Q^2 + U^2 + V^2$ holds, partially polarized light obeys the inequality $I^2 \geq Q^2 + U^2 + V^2$. In the special case of unpolarized light the Stokes parameters Q, U, and V are identically zero.

1.3.2 Mueller calculus

Mueller calculus is the formalism that allows to calculate the effect of a medium such as a stellar atmosphere or of an optical train on the Stokes vector. Any optical component modifies an incoming Stokes vector $\boldsymbol{I}'$

into the outgoing Stokes vector $\boldsymbol{I}$. Mathematically this process can be described in terms of a 4×4 matrix, the so called Mueller matrix.

The effect of several optical components acting on a beam of light one after the other is thus expressed by a product of (non-commuting) Mueller matrixes $\hat{\boldsymbol{M}}_i$, resulting in the outgoing Stokes vector $\boldsymbol{I}$

$$\boldsymbol{I} = \hat{\boldsymbol{M}}_{\mathrm{tot}}\, \boldsymbol{I}' = \hat{\boldsymbol{M}}_i \hat{\boldsymbol{M}}_{i-1} \ldots \hat{\boldsymbol{M}}_2 \hat{\boldsymbol{M}}_1\, \boldsymbol{I}' \,. \tag{1.2}$$

Mueller calculus is an important tool in spectro-polarimetry, because it can be used to describe the effect of the various optical components in a telescope. This allows to infer the polarization state of the light entering the telescope. As we will see in Sect. 1.5 we employ the formalism also in radiative transfer calculations, e.g. to show the influence of scattering on the Stokes vector.

1.4 Origin of polarized radiation

To interpret an observed polarized spectrum it is essential to understand the processes that lead to polarization on the astrophysical object. While a single photon is always 100% polarized, an ensemble of photons created in uncorrelated processes is not necessarily polarized due to cancelation effects. A necessary prerequisite for creating a polarized radiation field is the breaking of the spatial symmetry. The symmetry breaking can be achieved by several different means. Here, we emphasize in the following the situations most relevant in the solar atmosphere. There, it is mainly the magnetic field and the anisotropy of the radiation field that act as symmetry breaking agents. The magnetic field polarizes the radiation field through the Zeeman effect and the Hanle effect, while the anisotropy of the radiation field is relevant for polarization produced by coherent scattering.

1.4.1 Zeeman effect

The Zeeman effect was discovered by Zeeman (1897) in the laboratory in the year 1896. A magnetic field removes the degeneracy of the magnetic sublevels in an atom. Therefore, if a magnetic field is present in the atmospheric layers where a spectral line is formed, the line splits up into separate components as compared to the non-magnetic case. The wavelength shift $\Delta\lambda$ of the different components relative to the undisturbed case is given by

$$\Delta\lambda = \frac{e}{4\pi m_{\mathrm{e}} c}\, g\lambda^2 B \ , \tag{1.3}$$

where e is the electron charge, m_{e} the electron mass, c the speed of light, g the Landé factor of the transition, λ the wavelength of the transition, and B the magnetic field strength. In a so-called normal Zeeman triplet, i.e. in a $J = 0 \rightarrow 1 \rightarrow 0$ transition, we get one unshifted π component and two σ components shifted by the same amount to either side of the π component. However, in general an "anomalous" splitting pattern arises with several π and σ components.

Due to the line splitting it is in principle possible to proof the existence of a magnetic field and to determine its strength just from the intensity spectrum. Since the splitting scales with the square of the wavelength it would be natural to observe the Zeeman effect in the infrared. In fact, in recent years enormous progress has been made both in infrared polarimetry (Collados 2001) as well as in the interpretation of observations (cf. Rüedi et al. 1998).

In the optical part of the spectrum the Zeeman effect is only directly visible in the strong magnetic fields of sunspots of the order of 1 kG where the splitting can be larger than the line width. In weaker magnetic fields the Zeeman effect can only be observed through the polarization of the different components.

In the "longitudinal" Zeeman effect, with the magnetic field in the direction of the line of sight, the π component of the normal Zeeman triplet remains invisible while the two σ components are circularly polarized with opposite signs. Therefore, even if the intensity profile is not split up, the Zeeman effect is visible in Stokes V with the typical antisymmetric profile shape (see Fig. 1.1). It was Hale (1908) who first observed the Zeeman effect in umbral regions of the Sun making use of the opposite circular polarization of the Zeeman components.

In the "transversal" Zeeman effect, where the magnetic field is oriented perpendicular to the line of sight, all three components of the normal Zeeman triplet are linearly polarized, the π component parallel to the magnetic field, and the σ component perpendicular to the magnetic

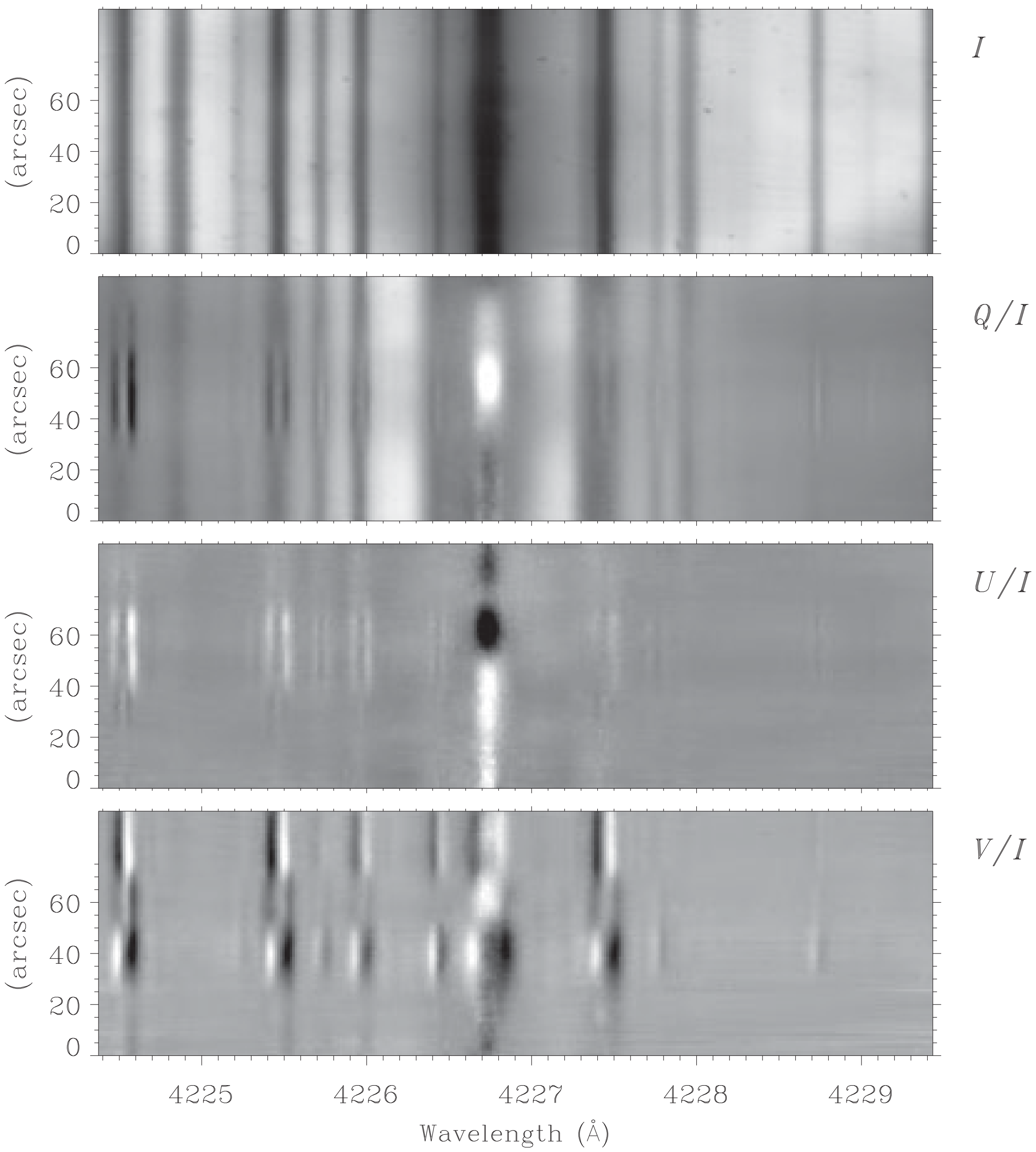


Figure 1.1: Signatures of Hanle and Zeeman effects. This Stokes vector image was recorded with the ZIMPOL polarimeter in March 2002 at the McMath-Pierce facility of the National Solar Observatory (NSO/Kitt Peak). It shows a weak magnetic region with the spectrograph slit placed 20 arcsec inside and parallel to the solar limb. In Stokes Q and U we see the typical Hanle effect signature in the strong spectral line in the middle, which is due to Ca I 4227 Å, and the symmetric line profiles caused by the transversal Zeeman effect in the surrounding lines. Stokes V shows the antisymmetric profiles due to the longitudinal Zeeman effect. Note that the signatures of Zeeman and Hanle effect can be unambiguously distinguished. From Stenflo (2003).