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ScienceDirect

Advances in Space Research 55 (2015) 891–896

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

On the diagnostics of solar small scale magnetic fields

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Received 26 January 2014; received in revised form 30 July 2014; accepted 4 August 2014
Available online 12 August 2014

Abstract

The model of small scale magnetic fields was proposed. The fields are described by two distribution functions: for unsigned magnetic field and for field vectors directions. The distribution functions were used to derive expressions for elements of the line absorption matrix and to deduce function that characterizes mutual cancellation of magnetic fields. We received the solutions for polarized radiative transfer problem within 3D MHD model of the solar photosphere and determined Stokes profiles parameters for two magnetosensitive lines Fe I $\lambda 525.0$ nm and $\lambda 524.7$ nm. The Stokes profiles parameters of the lines were used for further test diagnostics of small scale magnetic fields. A regression approach to diagnostics of the magnetic fields was proposed. The correlation between theoretical and reproduced parameters of small scale magnetic fields is greater than 0.95.

Keywords: Sun; Photosphere; Small scale magnetic fields; Stokes diagnostics

1. Introduction

As solar surface small scale magnetic fields possess enough magnetic energy to play a dominant role for the energy balance of the Sun's atmosphere and cover all spatial and temporal scales that observations can currently resolve, the quiet Sun magnetism is now a hot topic of researches.

Studying of small scale magnetic fields with different approaches are still far from consensus. However, it is commonly recognized that these small scale mixed polarity magnetic fields occupy the entire surface of the quiet Sun and contribute significantly to the total magnetic energy and unsigned flux in the solar photosphere outside the active regions (Trujillo Bueno et al., 2004). These fields are still uncertain in origin but, possibly, may incorporate contributions from different sources: turbulent dynamo, fragmentation of magnetic fields of active regions remnants, and emergence of small scale fields from deep layers (Vogler and Schussler, 2007).

The quiet Sun magnetism studies discovered both the intermittent magnetic fields of kG strengths with small filling factors, and the tangled turbulent fields with strengths of about 10–100 G, that cover most of the photospheric surface (Stenflo, 1982, 2012; Trujillo Bueno et al., 2004).

According to small scale solar magnetic field observations (network and internetwork in the quiet Sun) the main results are the following: strong fields tend to be vertical and weaker fields – horizontal. Vertical kilogauss fields are found in the magnetic network and are concentrated in intergranular lanes. Horizontal magnetic fields are ubiquitous on the Sun (Trujillo Bueno et al., 2004; Harvey et al., 2007; Stein, 2012). Weak horizontal fields have no preferred orientation. According to Stenflo (2013), the weak intranetwork fields are more peaked around the vertical direction in the low to middle photosphere, while they are more horizontal in the upper photosphere.

In accordance with Milne–Eddington inversion results of the observed (Hinode/SP) linear polarization data (Orozco Suarez and Bellot Rubio, 2012; Bellot Rubio and Orozco Suarez, 2012) the internetwork fields have strength in the range of 100–200 G, the maximum for the

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http://dx.doi.org/10.1016/j.asr.2014.08.004
0273-1177/

field inclination distribution function is near 90 degrees, whereas the azimuth of the fields has no preferable orientation and filling factors are in the range of 0.2–0.4. Furthermore, from the results, obtained in Orozco Suarez and Bellot Rubio (2012) and Bellot Rubio and Orozco Suarez (2012) it follows that quiet sun internetwork and hidden fields share the same field strengths, inclinations and azimuths. So the two types of fields (the internetwork and the hidden Hanle fields) overlap over a much larger fraction than was thought so far. Therefore internetwork fields discovered by Hinode/SP and the fields, that generate the Hanle depolarization of some atomic lines, may have a lot more in common. As pointed in Marti'nez Pillet (2013), the internetwork fields may include a fraction of vertical kG fields that do not contribute to the Hanle effect and weak granular fields that depolarize the light in spectral lines with no any imprint in the Fe I Zeeman lines observed by Hinode/SP. And because of continuous distribution of fields, the range of hG strengths (with transverse orientations) contributes simultaneously to Zeeman and Hanle observations.

The small scale magnetic fields in the solar photosphere vary both in space and time. Therefore, given low or insufficient spatial resolution of observations, these fields may be considered as fluctuation fields. As light beam is transmitted through such a quiet inhomogeneous solar photosphere, the fluctuation component of the photospheric magnetic field will drive, in a similar way to microturbulence, the formation of magnetoactive spectral lines. Hereafter, the magnetic field will be assumed to affect the state of the radiation solely through the Zeeman effect.

Mixed polarity fields are "cancelled out" when observed with limited spatial resolution instruments. This leads to decrease in the Zeeman polarization signal; however, this does not apply for the I signal, since the splitting of the levels is determined only by the magnetic field strength.

Simple models of magnetic turbulence and its effect on the Fraunhofer line profiles were considered in paper Unno (1959), as well as in paper Stenflo and Lindegren (1977). Paper Domke and Pavlov (1979) studied the formation of magnetoactive lines in the presence of magnetic microturbulent fields within Milne–Eddington atmospheric models in the LTE approximation; different microturbulence models were considered. Paper Frisch et al. (2007) presented formulas for elements of the line absorption matrix (Zeeman triplet) for different models of turbulent magnetic fields and studied the effect of magnetic turbulence on the profiles of absorption coefficients. Papers Vakarchuk (2002) and Landi Degl'Innocenti and Landolfi (2004) considered the effect of weak turbulent fields on the absorption coefficients for Stokes profiles; this effect reduces to increase of the Doppler halfwidth of the line.

The purpose of our work is to study, within 3D MHD model, the availability of small scale magnetic fields diagnostics based on observations of pair magnetoactive spectral lines. Within proposed model magnetic field is characterized by an average unsigned value of the field at given distributions of its magnitude and direction. In the research the nonequilibrium radiative transfer problem was solved using our formulas obtained for the absorption coefficients; the formulas take into account an integrated contribution of small scale magnetic fields to Zeeman split of the levels of absorption line. The obtained results of the study can be used for diagnostics of solar flares, solar and stellar magnetic fields with low or insufficient spatial resolution, etc.

2. Calculation techniques

There are two basic types of methods to study the properties of the quiet Sun magnetic fields: the Stokes diagnostics, based on Zeeman effect (Stenflo, 1973), and the Hanle depolarization effect (Stenflo, 1982). The main methods of Stokes diagnostics by means of Zeeman effect are the following (Landi Degl'Innocenti and Landolfi, 2004; Khomenko and Collados, 2007; Sheminova, 2009):

1. method of two lines ratio – pairs of lines with different Lande factors are used (Stenflo, 1973; Landi Degl'Innocenti and Landolfi, 2004; Rachkovsky et al., 2005; Sheminova, 2009);
2. method of centers of weight (Landi Degl'Innocenti and Landolfi, 2004);
3. method of distances between V-profiles peaks (Landi Degl'Innocenti and Landolfi, 2004);
4. magnetographic method (weak-field approximation for Zeeman effect (Landi Degl'Innocenti and Landolfi, 2004));
5. Stokes-inversion methods: Milne–Eddington approach (Orozco Suarez et al., 2010), express inversion (Landi Degl'Innocenti and Landolfi, 2004), SIR inversion (Ruiz Cobo, 1992).

In the research we used modified method of two lines ratio. For study we chose a pair of neutral iron lines λ525.0 nm and λ524.7 nm. Both lines have the same excitation potential, have the same gf values and hence the same formation depths. The lines differ in their Lande factors. The line pair is often used for the diagnostics of Zeeman-effect observations (Stenflo, 1987, 2013). Because this approach requires Stokes profiles, we first solved the nonequilibrium radiative transfer problem in the neutral iron lines chosen for study.

2.1. Radiative transfer equation

We considered nonequilibrium formation of neutral iron lines (λ525.0 nm, λ524.7 nm) in the MHD model (Stein et al., 2009) of the solar atmosphere. Polarization free approximation (Socas-Navarro et al., 2000) (PFA – influence of magnetic field on level populations is taken into account by modifying the line absorption coefficients) was used to solve nonequilibrium radiative transfer problem in the case of polarized radiation. And for the formal solution of radiative transfer equations we used the DELO