Spectropolarimetric Studies of Sunspot and its Fine-structure

A Thesis

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By

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DECLARATION

I, **Mr. Rahul Yadav**, S/o Mr. Ram Gopal Yadav, resident of C-2, USO staff quarters, Badi road, Udaipur-313001, hereby declare that the research work incorporated in the present thesis entitled, **"Spectropolarimetric studies of sunspot and its fine-structure"** is my own work and is original. This work (in part or in full) has not been submitted to any University for the award of a Degree or a Diploma.

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To

My Family

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ABSTRACT

Solar activity is governed by the magnetic fields, which are ubiquitously distributed on small or large spatial scales on the Sun. The interaction of the magnetic fields with vigorous convection on the solar surface manifests itself in the different form of structures. Among these, the sunspots (∼30000 km) and the pores (∼4000 km) are the most prominent manifestations of the magnetic fields which are observed frequently on the photosphere depending on solar activity. Predominantly, the sunspots harbor strong magnetic fields (∼3000 G), which are responsible for solar activities such as flares and coronal mass ejections. These activities cause fluctuations in the solar irradiance which directly influences the solar atmosphere and ultimately the space weather and the Earth. A better understanding of solar activities demands a careful investigation of sunspot's formation and stability, which is yet to be fully understood. The high-resolution observations of sunspots have revealed the presence of fine-structures of sunspots such as umbral dots, penumbral filaments and grains, which can play an important role in understanding the physical nature of sunspots. The study of sunspot fine-structures, using high-resolution imaging and spectro-polarimetric observations, can provide us insights on the evolution and stability of the sunspots, and can give crucial inputs to the realistic sunspot models.

The magnetic and thermodynamical properties of the solar atmosphere are generally inferred from the interpretation of observed Stokes profiles using inversion techniques. The inferred solar atmosphere can be utilized in understanding the physical mechanism of the solar features. This thesis aims at undertaking studies in this direction and comprises of two parts. The first part includes the development of a Milne-Eddington based Stokes profile inversion (SPIN) code for the polarized radiative transfer equation, which will be dedicated to invert the photospheric spectro-polarimetric data obtained from the Multi-Application Solar Telescope (MAST). The SPIN code can be employed to interpret the Stokes profiles in order to infer the magnetic and kinematic properties of the solar photosphere. The second part of the thesis is focused on the understanding of

the physical properties of umbral dots, which are the transient dot-like bright features observed in the dark umbra of a sunspot. The high-resolution observations obtained by *Hinode*, a Japanese space-based observatory, are utilized to investigate the physical properties of umbral dots and their relation with the macroscopic-properties of sunspots such as, size, epoch, decay rate and filling factor.

The thesis is organized in the following way. In Chapters 1 and 2, we present some of the basic concepts and discuss the solar features which are necessary for understanding the contents of the thesis. Chapter 3 presents the details of SPIN code developed specifically to invert the MAST's spectro-polarimetric data. The SPIN code has adopted the Milne-Eddington approximations to solve the polarized radiative transfer equation (*i.e.,* synthesis of Stokes profiles). A modified Levenberg-Marquardt algorithm has been employed to minimize the differences between the observed and the synthetic Stokes profiles. We also present the details of the tests performed to validate the SPIN code by comparing the results from the other widely used inversion codes namely, MERLIN, VFISV and SIR. In this regard, we have used the spectro-polarimetric data obtained from the *Hinode* spacecraft. The retrieved physical parameters obtained after the inversion of an active region using SPIN and other inversion codes exhibit similar results. Physical parameters of an active regions such as magnetic field strength, line-of-sight (LOS) velocity, inclination and azimuthal angle can be readily inferred with SPIN. This code is capable to invert any single photospheric Zeeman triplet spectral line.

Chapter 4 gives a brief overview of the spectro-polarimeter (SP) integrated with the MAST. The data acquisition and reduction of the spectro-polarimetric data recorded by the MAST/SP is discussed in detail. We also present the line-of-sight (LOS) magnetic field (B_{los}) retrieved after the inversions of MAST/SP data using SPIN code and its comparison with the B_{los} obtained from the space-based telescope (HMI/SDO). The comparison reveals that both the instruments (MAST/SP and HMI/SDO) exhibit similar B_{los} values across an active regions, considering the fact that MAST observations, unlike HMI/SDO, are limited by

seeing. In addition to this, we carried out the inversions of an active region, recorded with MAST/SP, using 6, 8, 11 and 20 wavelength samples across Fe I 6173 Å spectral line to see the effects of number of wavelength samples on inverted parameters. We found that for MAST/SP, the inversion with different wavelength samples can exhibit similar results. We also noticed that increase in the wavelength samples above 8 does not produces significant improvements, whereas a decrease produces worse results. The mean standard deviation of B_{los} maps (relative to 20 wavelength samples) obtained in umbral regions with 11, 8 and 6 spectral positions are 53 G, 241 G, and 363 G, respectively.

In Chapter 5, we present the details of the analysis carried out using high-resolution *Hinode*/SOT G-band time-series of seven active regions observed close to disk center. In these studies, the umbral dots (UDs) are identified and tracked using an automated identification and tracking algorithm in all seven sunspots. We have also discussed the use of MDI continuum images to estimate the decay rate of selected sunspots. The statistical analysis of UDs exhibit the averaged maximum intensity and effective diameter of 0.26 I_{QS} and 270 km, respectively. Further, we found that the lifetime, horizontal speed, trajectory length, and displacement length (birth-death distance) of UDs are 9.85 minutes, 0.5 km s^{-1}, 284 km, and 155 km, respectively. We also find a positive correlation between intensity – diameter, intensity – lifetime, and diameter – lifetime of UDs. The results from our studies exhibit that the properties of UDs do not show any significant relation with the decay rate and filling factor of sunspots.

In Chapter 6, we present the investigation of the relation between the physical properties of UDs and the macro-properties of a sunspot. For this purpose, we analyzed high-resolution G-band images of 42 sunspots observed by *Hinode*/SOT, located close to disk center. All the images are corrected for instrumental stray-light and restored with the modeled PSF. An automated Multi-Level Tracking algorithm employed to identify the UDs located in selected G-band images is discussed. Furthermore, a method to estimate the sunspot evolving phase and epoch for the selected sunspots using HMI/SDO, limb-darkening corrected, full disk continuum images is also presented. The number of UDs identified in dif-

ferent umbrae exhibit a linear relation with the umbral size. However, we do not find any significant relationship between the mean intensity and effective diameter of umbral dots with the sunspot area, epoch, and decay rate. The observed filling factor ranges from 3% to 7% and increases with the mean umbral intensity. Moreover, the filling factor shows a decreasing trend with the umbral size. We also found that the observed intensities of UDs is correlated with the mean umbral intensity.

Chapter 7 provides the summary and conclusions of the thesis work. In this chapter, we also present a brief description of the future work.

Keywords : Photosphere, Sunspot, Magnetic fields, Umbral dots

LIST OF PUBLICATIONS

1. "*Imaging Spectropolarimeter for Multi-Application Solar Telescope at Udaipur Solar Observatory: Characterization of Polarimeter and Preliminary Observations*".
   Alok Ranjan Tiwary, Shibu K. Mathew, A. Raja Bayanna, P. Venkatakrishnan and **Rahul Yadav**, *Solar Phys.* (2017) 292(4), 49.
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4. "*Physical Properties of Umbral Dots observed in Sunspots: A Hinode observation*"
   Rahul Yadav and Shibu K. Mathew, *Solar Phys.* (2017), *under review*

Contents

List of Figures

List of Tables

Appendices

Appendix A

A.1 Derivatives of χ^2 and response functions

In Chapter 3 (Equation 3.4.3), we have defined the merit function (χ^2). The derivative of χ^2 with respect to a parameter (say, x_p) is used to evaluate the Hessian matrix which determines the changes in the parameters for the next iteration. More details about the derivatives can be found in (del Toro Iniesta 2003; Borrero et al. 2011) and (Orozco Suárez and Del Toro Iniesta 2007).

As defined in Chapter 3, response functions (R_p) are the partial derivative of the Stokes vector, $\mathbf{I} = [I,\ Q,\ U,\ V]$, with respect to the model parameters (x_p),

$$R_p(\lambda_i) = \frac{\partial \mathbf{I}^{syn}(\lambda_i, \mathbf{M})}{\partial x_p} \tag{A.1.1}$$

The first and second order of χ^2 in the form of response functions can be expressed as,

$$\frac{\partial \chi^2}{\partial x_p} = \frac{-2}{4N-F} \sum_{i=1}^{N} \sum_{j=1}^{4} [\mathbf{I}_j^{obs}(\lambda_i) - \mathbf{I}_j^{syn}(\lambda_i, \mathbf{M})] \frac{\omega_j^2}{\sigma_j^2} \times R_p(\lambda_i), \tag{A.1.2}$$

$$\frac{\partial \chi^2}{\partial x_p \partial x_k} = \frac{-2}{4N-F} \sum_{i=1}^{N} \sum_{j=1}^{4} \frac{\omega_j^2}{\sigma_j^2} \left\{ R_p(\lambda_i) R_k(\lambda_i) + [\mathbf{I}_j^{obs}(\lambda_i) - \mathbf{I}_j^{syn}(\lambda_i, \mathbf{M})] \frac{R_p(\lambda_i)}{\partial x_k} \right\}, \tag{A.1.3}$$

Neglecting the derivative of the response function in Equation (A.1.3), the equation can be expressed as,

$$\frac{\partial \chi^2}{\partial x_p \partial x_k} \simeq \frac{-2}{4N-F} \sum_{i=1}^{N} \sum_{j=1}^{4} \frac{\omega_j^2}{\sigma_j^2} [R_p(\lambda_i) R_k(\lambda_i)]. \tag{A.1.4}$$

Thus, form above Equation (A.1.4) it can be seen that the Hessian matrix elements can be written in terms of the response functions. In M–E atmosphere, they can be calculated analytically which significantly enhance the computing speed. It can be seen that the derivative of Stokes parameters with respect to the S_0 and S_1 is straightforward to evaluate. The Stokes parameters shown in Equation (2.5.14) are functions of elements of propagation matrix. Thus, the derivative of the propagation matrix elements with respect to the model parameters ($[\eta_0, \Delta\lambda_D, a, S_0, S_1, B, \theta, \phi, V_{los}]$) are required. The derivative of the elements with respect to η_0 can be expressed as,

$$\begin{aligned}
\frac{\partial \eta_I}{\partial \eta_0} &= (1-\eta_I)/\eta_0, \\
\frac{\partial \eta_Q}{\partial \eta_0} &= \eta_Q/\eta_0, \\
\frac{\partial \eta_U}{\partial \eta_0} &= \eta_U/\eta_0, \\
\frac{\partial \eta_V}{\partial \eta_0} &= \eta_V/\eta_0.
\end{aligned} \tag{A.1.5}$$

The derivatives with respect to θ and φ,

$$\begin{aligned}
\frac{\partial \eta_I}{\partial \theta} &= \frac{\eta_0}{2}\left\{\phi_p - \frac{(\phi_b+\phi_r)}{2}\right\} \sin 2\theta, \\
\frac{\partial \eta_Q}{\partial \theta} &= \frac{\eta_0}{2}\left\{\phi_p - \frac{(\phi_b+\phi_r)}{2}\right\} \sin 2\theta \cos 2\varphi, \\
\frac{\partial \eta_U}{\partial \theta} &= \frac{\eta_0}{2}\left\{\phi_p - \frac{(\phi_b+\phi_r)}{2}\right\} \sin 2\theta \sin 2\varphi, \\
\frac{\partial \eta_V}{\partial \theta} &= -\eta_V \tan\theta, \\
\frac{\partial \eta_Q}{\partial \theta} &= \frac{\eta_0}{2}\left\{\psi_p - \frac{(\psi_b+\psi_r)}{2}\right\} \sin 2\theta \cos 2\varphi, \\
\frac{\partial \eta_U}{\partial \theta} &= \frac{\eta_0}{2}\left\{\psi_p - \frac{(\psi_b+\psi_r)}{2}\right\} \sin 2\theta \sin 2\varphi, \\
\frac{\partial \eta_V}{\partial \theta} &= -\eta_V \tan\theta,
\end{aligned} \tag{A.1.6}$$

$$
\begin{aligned}
\frac{\partial \eta_I}{\partial \varphi} &= \frac{\partial \eta_V}{\partial \varphi} = \frac{\partial \rho_V}{\partial \varphi} = 0, \\
\frac{\partial \eta_Q}{\partial \varphi} &= -2\eta_Q \tan 2\varphi, \\
\frac{\partial \eta_U}{\partial \varphi} &= 2\eta_U \cot 2\varphi, \\
\frac{\partial \rho_Q}{\partial \varphi} &= -2\rho_Q \tan 2\varphi, \\
\frac{\partial \rho_U}{\partial \varphi} &= 2\rho_U \cot 2\varphi.
\end{aligned}
\tag{A.1.7}
$$

To evaluate the derivatives with respect to other parameters (a, $\Delta\lambda_D$, V_{los} and B), we need to evaluate the derivatives of the Voigt and Faraday functions (Equation 2.4.4 and 2.4.5), which can be expressed by applying chain rule as,

$$
\begin{aligned}
\frac{\partial H(\upsilon, a)}{\partial V_{los}} &= \frac{\partial H(\upsilon, a)}{\partial \upsilon} \frac{\partial \upsilon}{\partial V_{los}}, \\
\frac{\partial H(\upsilon, a)}{\partial \Delta\lambda_D} &= \frac{\partial H(\upsilon, a)}{\partial \upsilon} \frac{\partial \upsilon}{\partial \Delta\lambda_D}, \\
\frac{\partial H(\upsilon, a)}{\partial B} &= \frac{\partial H(\upsilon, a)}{\partial \upsilon} \frac{\partial \upsilon}{\partial B}.
\end{aligned}
\tag{A.1.8}
$$

The expressions for $F(\upsilon, a)$ are same as Equation A.1.8. The derivatives of the Voigt and Faraday-Voigt function can be expressed as,

$$
\begin{aligned}
\frac{\partial H(\upsilon, a)}{\partial \upsilon} &= 2aF(\upsilon, a) - 2\upsilon H(\upsilon, a), \\
\frac{\partial F(\upsilon, a)}{\partial \upsilon} &= \sqrt{4/\pi} - 2aH(\upsilon, a) - 2\upsilon F(\upsilon, a), \\
\frac{\partial H(\upsilon, a)}{\partial a} &= -\frac{\partial F(\upsilon, a)}{\partial \upsilon}, \\
\frac{\partial F(\upsilon, a)}{\partial a} &= \frac{\partial H(\upsilon, a)}{\partial \upsilon}.
\end{aligned}
\tag{A.1.9}
$$

Appendix B

B.1 Start and run SPIN

In this appendix, we provide a brief information about the operation of SPIN. All the subroutines of SPIN have been written in IDL programming language and it also uses some routines available in SSW* packages. The SPIN folder contains the following routines:

1. **spin_input.txt**: This is the spin input file which contain all required initial inputs. More details can be found in Section B.2.

2. **spininv.pro**: This is the main routine which reads *spin_input.txt* file and calls other subroutines.

3. **syn_prof.pro**: This routine solves all four Stokes profiles analytically.

4. **respfun.pro** : The response functions of all Stokes profiles with respect to a particular model parameter are evaluated by this routine.

5. **lminv.pro**: This routine minimizes the difference between the observed and synthetic Stokes profiles.

6. **merit.pro**: The evaluation of Hessian matrix and merit function (χ^2).

7. **svdcal.pro**: To perform the singular value decomposition of Hessian matrix.

8. **fvoigt.pro**: Evaluation of Faraday and Voigt-Faraday function.

*More details can be found at: http://www.lmsal.com/solarsoft/

9. **limits.pro**: This routine impose limits on the model parameters.

10. **macvel.pro**: Evaluates the macro-turbulence velocity.

11. **readinput.pro**: To read the input file.

12. **guess_mod.pro**: It estimates the guess model parameters based on weak field approximation.

13. **calpol.pro**: Evaluates the polarization level of pixels.

14. **plotstk.pro**: Used to plot the fitted and observed Stokes profiles.

15. **combine.pro**: It combines all inverted maps.

16. **view_profiles.pro**: To view interactively the observed and synthetic Stokes profiles for a pixel.

B.2 The SPIN input file

The SPIN is performed and controlled by the *spin_input.txt* file. The input parameters required to run SPIN are given in Table B.1. Presently, there are 24 lines in input files. The first column refers to the input variable name, the colon mark (:) in second column separated the input variable name and their corresponding inputs (column three). We describe briefly the variables used in the input file:

- **cycle-number**: This parameter indicates the number of inversion cycle to be performed for a single pixel.

- **obs-profiles (sav-file)**: It refers the name of standard IDL savefile where the observed Stokes profiles are stored in a 3D array. As an example, the format for the Stokes I is [*xpixels, ypixels,* λ].

- **weight-Stokes[I, Q, U, V]**: The weights for Stokes I, Q, U and V used in the χ^2 are given in line 3, 4, 5, 6, respectively.

- **wavelength**: The inversion carried out for this wavelength. For Fe I 6173.334 Å, and Fe I 6302.5 spectral lines set the value as 6173 and 6302, respectively.

Table B.1: Spin input file

cycle-number	:	1
obs-profiles(sav-file)	:	∼/rahul/iquv_AR12353.sav
weight-Stokes I	:	1
weight-Stokes Q	:	2
weight-Stokes U	:	2
weight-Stokes V	:	5
wavelength	:	6173
Landé g-factor	:	2.5
iterations	:	100
invert	:	IQUV
line-centre	:	10
wave-sampling(Å)	:	0.02
heliocentric-angle (μ)	:	1
plot-profiles	:	1
normalized	:	1
instrumental_profile	:	profile.txt
initial-guess	:	1
S/N ratio	:	1000
xaxis	:	0,599
yaxis1	:	0,199
yaxis2	:	200,399
yaxis3	:	400,599
yaxis4	:	400,599
output(idl-sav)	:	∼/rahul/inverted/

- **Landé g-factor**: The effective Landé g-factor of the spectral line used in the inversion.

- **iterations**: The maximum number of iteration performed for each pixels.

- **invert**: Set 'IQUV' and 'IV' to invert all four Stokes profiles, and Stokes I and V profiles, respectively.

- **line-centre**: The pixel value of the line center (rest wavelength position).

- **wave-sampling (Å)**: It refers to the spectral sampling of the observed Stokes profiles.

- **heliocentric angle**: This value refers to the cosine of the heliocentric angle (θ), generally expressed as μ (cos θ). The default value is unity.
- **plot-profiles**: Set 1 to see the fitted and observed Stokes profiles.
- **normalized**: Set 1 if all observed Stokes profiles are normalized to quiet-sun intensity.
- **instrumental profile**: A file containing the instrumental profile data.
- **initial-guess**: Initial guess parameters will be evaluated if set to unity. Otherwise fixed guess model will be utilized.
- **S/N ratio**: The uncertainties in the observed Stokes profiles.
- **xaxis**: The pixels in the horizontal direction to be used in the inversion process.
- **yaxis[1,2,3,4]**: The pixels in the vertical direction to be used in the inversion process.
- **output (idl-sav)**: The inverted output is stored in a standard IDL savefile.

B.3 Output files

SPIN writes the synthetic Stokes profiles and retrieve model parameters (such as magnetic field strength, LOS velocity, inclination and azimuthal angle *etc.*) in a standard IDL savefile. The model parameters and their errors are saved in a structure variable named as 'inv' whereas the synthetic Stokes profiles are saved in 4D float array, i.e. [xpixels, ypixels, λ, [I,Q, U, V]]. The *combine.pro* subroutine combines all the inverted regions. The *view_profiles.pro* can be used to display interactively the observed and best fitted Stokes profiles. The synthetic Stokes profiles can be viewed through a user-friendly IDL widget as shown in Figure B.1 (top panel), where the model parameters can be easily modified using the movable sliders. In addition to this, an IDL widget to carry out the inversion of the Stokes profiles is also developed (see bottom panel of B.1).

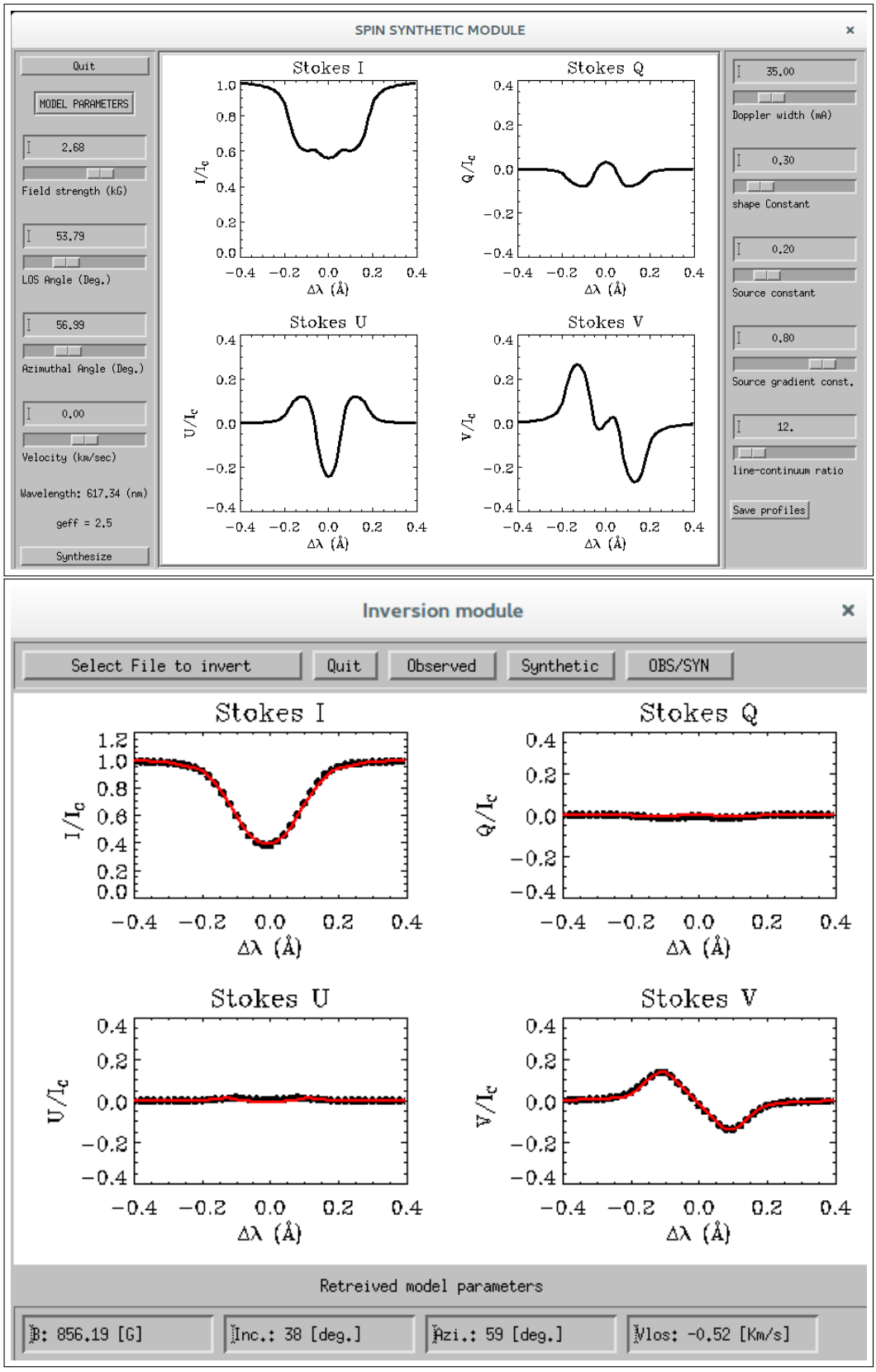

Figure B.1: *Top panel*: a snapshot of IDL widget showing the synthetic module. *Bottom panel*: a snapshot of inversion module. As an example, the filled black circles and solid red line represent the observed and best fitted profile, respectively.

Appendix C

C.1 Inversion of *Hinode*/SP data using SPIN

This appendix shows the inversion results of spectro-polarimetric data observed from *Hinode*/SP using SPIN code. To exhibit the performance of SPIN, the inverted maps of two active regions (NOAA AR 11899 and 11944) are demonstrated. The spectro-polarimetric data of AR 11899, which was located at $\mu = 0.98$, recorded from 0.5:00 to 05:24 UT on 20th November 2013, whereas AR 11944 ($\mu = 0.98$) recorded from 02:50 to 03:45 UT on 7th January 2014. Inversion scheme was same as described in Section 3.8.2, which was carried out across the 6302.5 Å spectral line for 41 wavelength points. The inverted maps of physical parameters such as magnetic field strength, inclination angle, azimuthal angle and LOS velocity obtained after the inversion of NOAA AR 11899 and 11944 are shown in Figure C.1 (AR 11899) and C.2 (AR 11944), respectively.

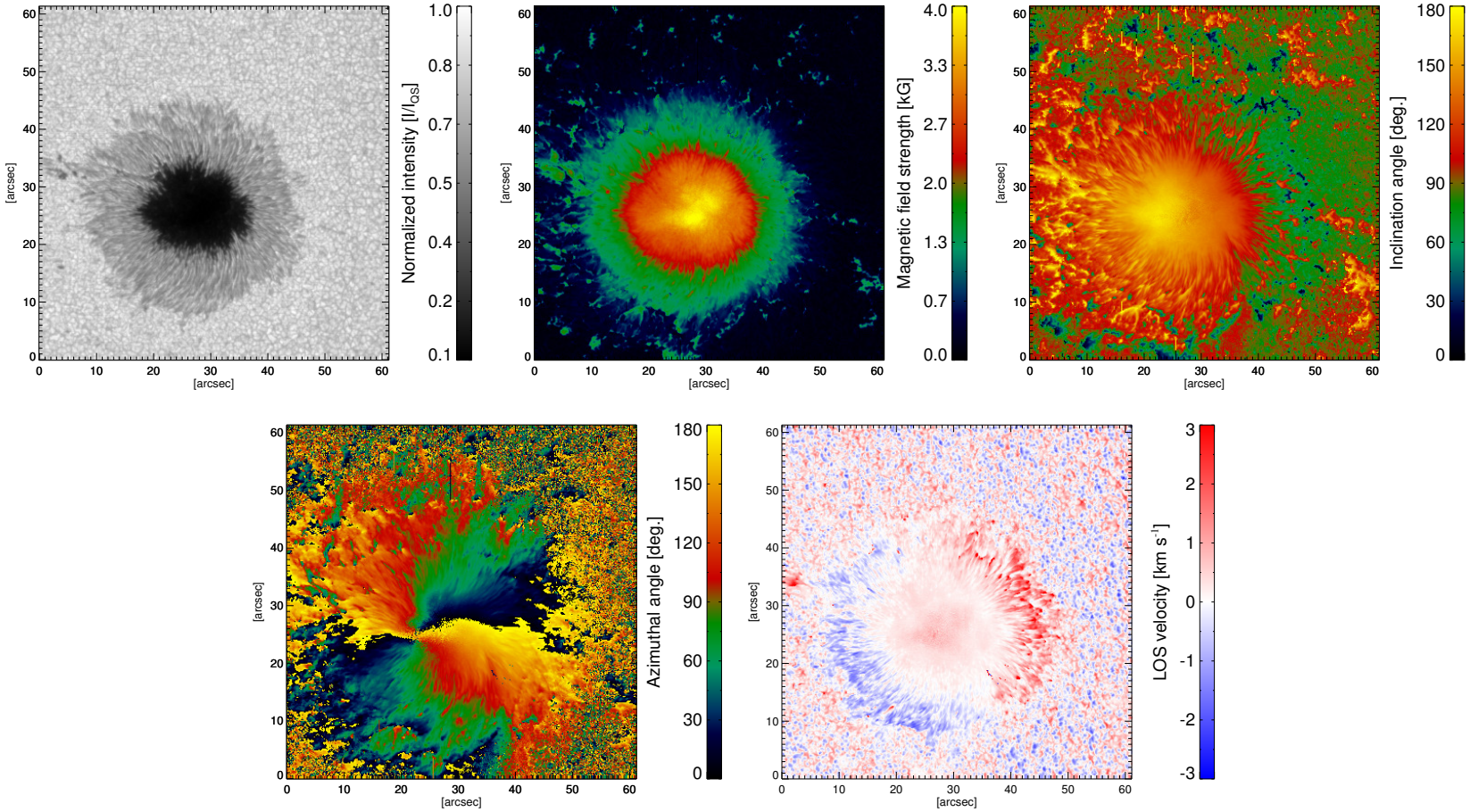

Figure C.1: Inverted parameters retrieved after the inversion of AR 11899 (observed by *Hinode*/SP) using SPIN code. *Top to bottom clockwise*: the normalized intensity map, magnetic field strength map, inclination angle map, azimuth angle map, and LOS velocity map.

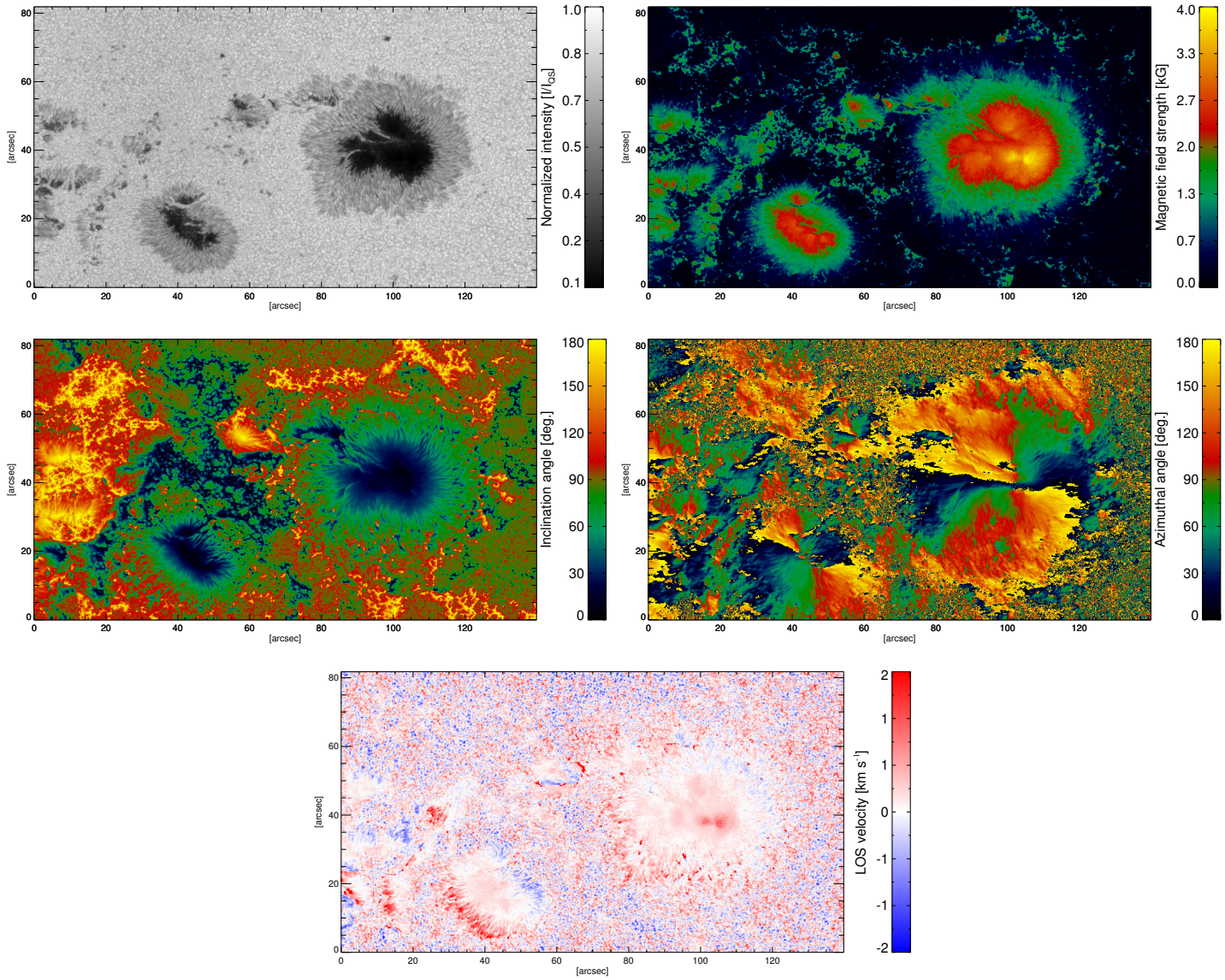

Figure C.2: Same as Figure C.1 but for AR 11944.

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Publications attached with the thesis

1. "*SPIN: An Inversion Code for the Photospheric Spectral Line*"

   Rahul Yadav, Shibu K. Mathew and Alok Ranjan Tiwary, *Solar Phys.* (2017) 292:105.