Problem Set

Rebecca Centeno

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1 Introduction

The spectro-polarimeter (SP) on board the Hinode satellite (Japan/US/UK) carries out precise high resolution spectropolarimetric observations of the Sun's Photosphere from space. SP is a slit-spectrograph instrument that measures the four Stokes parameters of the Fe I 6301.5 Å and 6302.5 Å line pair, as a function of wavelength. In this problem set you will get to play with some intensity and polarization spectra from this instrument. There is a lot of information encoded into these spectral profiles that you'll get to extract in qualitative and quantitative manners.

Figure 1 shows a reconstructed continuum image of the dataset you will be working with. SP is a slit instrument, so it measures the intensity and polarization spectra in a one-dimensional slice of the Sun at a time. In order to get two-dimensional spatial information, the measurement is repeated as the spectrograph slit scans across the surface of the Sun. Figure 1 only shows a continuum image, but for each pixel in this image we have a full set of Stokes spectra (containing the two neighboring Fe I spectral lines).

2 Analyzing Stokes profiles in different areas of the Sun

On the website you will find 8 sets of full Stokes spectra, each set in a file labeled with the name "stokes_profiles_n.txt" (n = 0, 1, ... 7). Each file contains the intensity and polarization spectra for one of the spatial positions marked with a cross in Figure 1. There are two Quiet Sun spectra (n = 0, 1), two spectra corresponding to a facular region (n = 2, 3), two from the sunspot penumbra (n = 4, 5) and two from the umbra of the sunspot (n = 6, 7). The files contain numbers in plain text format. They are arranged in 5 columns, corresponding to : wavelength array, Stokes I (intensity), Stokes

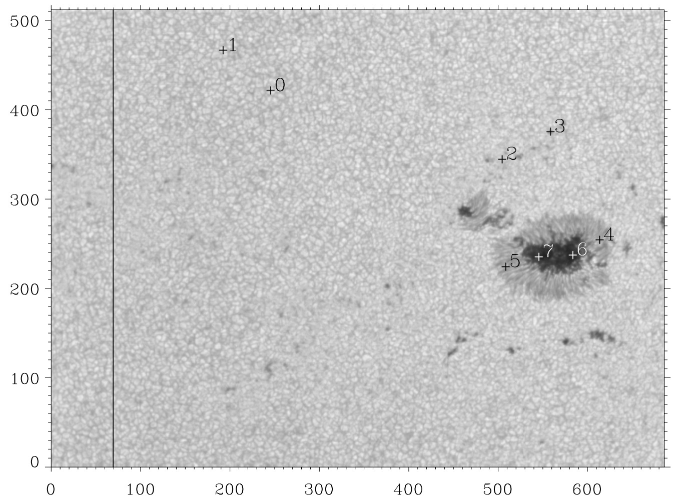

Figure 1: Hinode/SP map

Q, Stokes U (linear polarization) and Stokes V (circular polarization). There are 112 rows (i.e. number of wavelength points). This particular portion of the spectrum contains two Fe I lines, at 6301.5 and 6302.5 Å (see an example of a set of Stokes profiles in Figure 2). The "effective" Landé factor of these lines is $g_1 = 1.67$ and $g_2 = 2.5$, respectively, and they both form in the solar Photosphere.

1. Which one of the lines do you expect to be the more magnetically sensitive?

2. Read all the files and plot the intensity and polarization spectra for each spatial position as a function of wavelength, following the example of Figure 2.

3. Just from looking at the spectra from the different files, order them roughly by magnetic field strength and justify your order.

4. Again, by looking at the spectra, can you say something about the direction of the magnetic field at each of the locations?

5. Compute the net circular polarization (NCP) for all pixels in both spectral lines. What do you think these results indicate? (you can

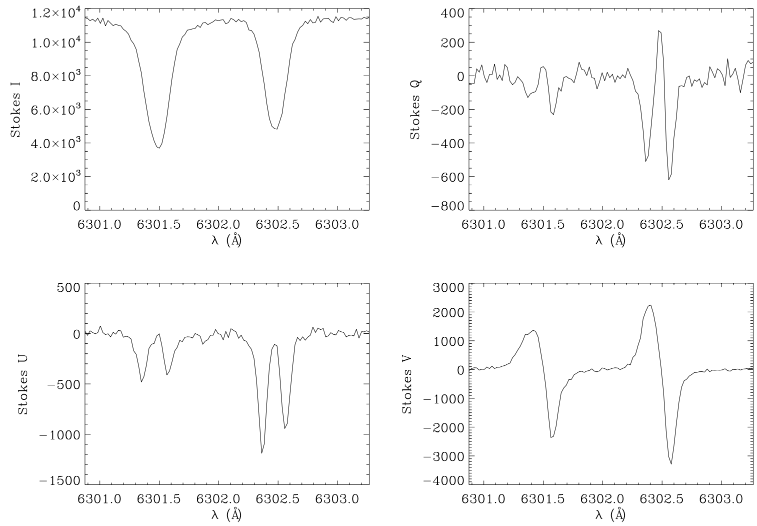

Figure 2: Stokes profiles for a point in the penumbra of the sunspot

estimate the noise level for the NCP measurement using profiles n = 0 and n = 1).

6. Qualitatively, note whether there is any other asymmetry in the Stokes V profiles that is not reflected in the NCP measurement. What information would this give you?

Remember that the net circular polarization is given by:

$$NCP = \frac{\int_{\lambda_L} V(\lambda) d\lambda}{\int_{\lambda_L} |V(\lambda)| d\lambda} \tag{1}$$

where the integral is calculated over the wavelength span of the spectral line, λ_L. This expression normalizes the NCP to the absolute value of Stokes V integrated over the same range of wavelengths, so that you can more easily compare Stokes V profiles of very different amplitudes.

3 Doppler shifts and continuum intensity

For this problem you will use the spectra of one slit position (black vertical line in figure 1). The data for this measurement are contained in a FITS

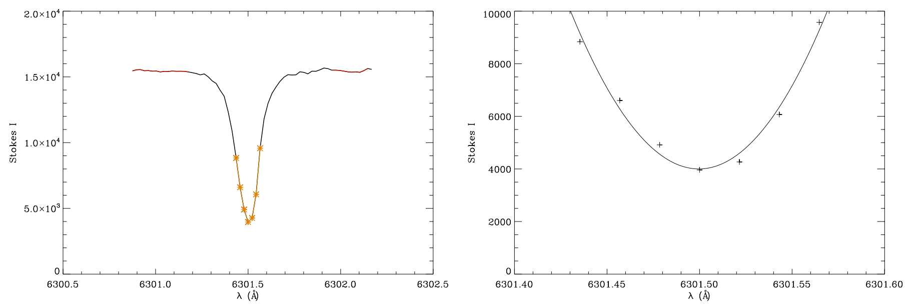

Figure 3: Left: Intensity profile of the Fe I 6301.5 Å spectral line. The red part indicates the continuum of the line, whilst the orange shows the core. Asterisks show the actual sampling of the observations. Right: polynomial fit to the core of the same spectral line. Crosses represent the observed intensity values whilst the solid line shows the best second order polynomial fit.

file (SP3D20151020_020826.1C.fits). Using a standard FITS reader you will extract the data cube from the file. The dimensions of the cube are [112, 512, 4], corresponding to wavelength, pixels along the slit and 4 Stokes parameters (in order: I, Q, U, V). For this problem you will be working only with the Stokes I profile of the 6301.5 Å line. The values for the wavelength vector are contained in a separate file (wavelengths.txt) and are specified in Å.

1. Calculate the continuum intensity for each pixel along the slit, and store it in an array.

2. Calculate the Doppler velocity of the 6301.5 Å spectral line for each position along the slit and store it in another array.

3. Plot the Doppler velocity against the continuum intensity in a scatter plot. Is there a trend? What does it mean?

In order to calculate the continuum of the spectral line you can use an average over the wavelengths that you deem to clearly be continuum (red part of the spectrum in left panel of Fig. 3).
In order to find the wavelength position of the spectral line with enough precision, you will have to fit the core of the line to a parabola; but only the core, because the wings deviate wildly from a parabola shape and using

them will significantly mislead the fitting procedure (see orange part of the spectrum in left panel of Fig. 3). Feel free to use an out-of-the-box polynomial fitting method (poly_fit or svdfit in IDL will work just fine). Then, use the coefficients of the polynomial fit to find the position of the minimum. You can do this analytically or numerically. If you do it numerically, first recalculate the fitted parabola on an interpolated wavelength grid so that you obtain sub-pixel precision when finding the position of the minimum. An example of the polynomial fit to the core of the spectral line can be seen in the right panel of Fig. 3. Here, the crosses represent the observations (Stokes I in the core of the spectral line). The solid line represents the best fit of a parabola to the data. The fit has been recalculated on a wavelength grid with a factor of 50 better sampling.

With this method you will find more accurately the position of the minimum of the spectral line. If you were to extract it directly from the data, your results will be affected by sampling effects (due to the fact that the data don't have infinite spectral resolution!). By comparing your estimate of the wavelength position of the minimum of the spectral line to its laboratory wavelength value, you can calculate the Doppler velocity using:

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c} \tag{2}$$

where c is the speed of light.

Please email your questions and answers to the problem set to me at: rce@ucar.edu.