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UNNOFITffcpg code

1 Abstract

Milne-Eddington UNNOFITffcpg inversion code, improved by accounting for a magnetic filling factor as the ninth free parameter of the Levenberg-Marquardt inversion. The vertical velocity gradient is also derived from the Stokes I+V or I-V profile asymmetry, as the tenth inversion free parameter.

2 Principles of the code

The UNNOFIT code was built by Landolfi, Landi Degl'Innocenti & Arena [1]. It applies the Levenberg-Marquardt algorithm to make theoretical and observed Stokes profiles coincide. The theoretical profile is computed from the Unno-Rachkovsky solution of the radiative transfer equation for polarized light in the presence of a magnetic field (magneto-optical effects included). The model atmosphere is plane-parallel and Milne-Eddington. The Unno-Rachkovsky solution applied in the code is written in Eq. (9.112) of the monography *Polarization in Spectral Lines* by Landi Degl'Innocenti & Landolfi [2]. The Levenberg-Marquardt algorithm was applied to the eight free parameters of the Unno-Rachkovsky solution: 1/the line-strength η_0, 2/the Zeeman splitting (which contains the magnetic field strength) $\Delta\lambda_H$, 3/the Doppler width $\Delta\lambda_D$, 4/the magnetic field inclination angle with respect to the line-of-sight ψ, 5/the magnetic field azimuth angle with respect to the line-of-sight and positive Q axis φ (due to the funamental or 180° ambiguity, this azimuth is defined within 180°), 6/the collisional + natural line broadening constant Γ (expressed in mÅ, such that the damping constant a appearing in the Voigt function is $\Gamma/\Delta\lambda_D$), 7/the constant $\beta/(1+\beta)$ that appears in the Unno-Rachkovsky solution, and 8/the wavelength of the line center (in mÅ from profile point n°1).

The UNNOFITff code includes in addition the magnetic filling factor α as the ninth free parameter of the Levenberg-Marquardt algorithm. The atmosphere is assumed to be non-magnetic for the $(1-\alpha)$ part, and magnetic with constant magnetic field B as for its α part. See Bommier [3] for definitions in Eq. (1). However, it is shown by tests in this paper that the field strength B and the magnetic filling factor α are not each sufficiently confidently recovered, but that their product αB is. αB is the average magnetic field. UNNOFITffc is the version of the code adapted to a full map inversion (the primary UNNOFIT code was developed for inversion of a single pixel). UNNOFITffcp is the OpenMP parallelized version of the code, in order to improve the computing time for a whole map. UNNOFITffcpg

determines in addition, as the tenth free parameter of the inversion, the velocity gradient between line center and far wings respective formation depths, as developed by Molodij, Bommier & Rayrole [4].

UNNOFIT is for a Normal Zeeman triplet line. UNNOFIT2 is for a non-normal Zeeman triplet line, whose Zeeman structure has to be provided by a zeeman.dat file placed in the same folder as UNNOFIT. zeeman.dat files of some lines are provided. The file corresponding to the line of interest has to be renamed as zeeman.dat in order to be read by UNNOFIT2. Alternatively, the zeeman.dat file can be computed by running the FORTRAN zeeman.for code also provided. For answering the questions of this code, the *L, S, J* level quantum numbers have to be entered in double value (for instance, enter 2 for $J=1$), firstly for the lower level, secondly for the upper level, which is referred to as "primo".

3 Compilation of the code

The code is FORTRAN-77 written and can be compiled with ifort or gfortran, as usual

```
gfortran -o unnofitffcpg unnofitffcpg.for
```

which provides the executable unnofitffcpgh.

The code is OpenMP parallelized, which can be compiled as

```
ifort -qopenmp -O0 -mcmodel=large -shared-intel -o unnofitffcpgh unnofitffcpgh.for
gfortran -fopenmp -o unnofitffcpgh unnofitffcpgh.for
```

(an example of command file unnofitffcpgh.slurm is provided).

4 Answers to the code questions

In order to initiate the calculation the code asks a series of questions:

input the number of fits

the number of successive trials of the Levenberg-Marquardt algorithm: usually 40

input a random number

in order to initiate the Levenberg-Marquardt algorithm (fist free parameters series)

input weights w1, w2, w3, w4

these weights are applied to respectively each Stokes *I,Q,U,V* contribution to the χ parameter that describes the departure between the theoretical and observed profies in the algorithm. Typically: w1=.1, w2=w3=w4=1. As for myself I applied w1=w2=w3=w4=1.

input line wavelength [Angstrom] and Lande factor

for a Normal Zeeman triplet (UNNOFITffcpg; only the line wavelength for UNNOFIT2ffcpg, which is not for a Normal Zeeman triplet, and reads the line Zeeman structure in the Zeeman.dat file)

input dispersion [mÅ]

distance in mÅ between two spectral pixels

input interval of points for continuum [noff1,noff2]

Enter two spectral pixel reference numbers for defining a reference continuum interval.

input interval [n1,n2] of the fit

Enter two spectral pixel reference numbers that include the whole line profile. Interval for computing the χ^2.

5 Format of the input data file

The stokes.dat input data file must contain:

first line

3 numbers (unformatted):
– the number of scan steps, which is also the number of pixels along the final map *OX* axis.
– the number of spatial pixels along the slit, which is also the number of pixels along the final map *OY* axis.
– the number of spectral pixels along the Stokes profiles.

second line

(unformatted): the pixel size (along the slit) and the step size (perpendicular to the slit), in arcsec.

following lines

for each pixel (loop in scan number, loop in slit pixel, loop in spectral pixels, in this order): the observed Stokes parameters *I*,*Q*,*U*,*V* (unformatted).

6 Output data file

The unnofitffc.dat output data file contains:

first line

2 numbers (unformatted):
– the number of scan steps, which is also the number of pixels along the final map *OX* axis.
– the number of spatial pixels along the slit, which is also the number of pixels along the final map *OY* axis.

second line

(unformatted): the pixel size (along the slit) and the step size (perpendicular to the slit), in arcsec.

third line

titles

following lines

inversion results, for each pixel (loop in scan number, loop in slit pixel, in this order):

1 – the average magnetic field strength αB (in Gauss)
2 – the field inclination angle with respect to the line-of-sight (in degrees)
3 – the field azimuth angle in the plane perpendicular to the line-of-sight, with respect to the positive *Q* axis (in degrees)
4 – the velocity difference continuum-line center (in m/s)
5 – the line strength η_0
6 – the Zeeman splitting $\Delta\lambda_B$ (in mÅ)
7 – the Doppler width $\Delta\lambda_D$ (in mÅ)

8 – the Γ collisional + natural line broadening constant (in mÅ)
9 – the constant $\beta/(1+\beta)$ that appears in the Unno-Rachkovsky solution
10 – the λ_c wavelength of line center (in mÅ, defined as the distance from spectral pixel number 1)
11 – the last χ value of the iteration
12 – a number that describes how the iteration was stopped. This number is:
- 1 if the iteration was stopped by reaching the maximum iteration step number introduced at the beginning of the code
- 2 when the χ^2 gets smaller than a small fraction (1.e-10) of the initial χ^2 (converged iteration)
- 3 when the sum of the absolute values of the increments gets smaller than a fixed number (1.e-2) (converged iteration)

13 – the number of performed iteration steps.

6.1 Case of a single pixel

If there is only one pixel (i.e., one step and one slit pixel), the program provides the final theoretical profile in the output file stokesfit.dat

7 References

1. Landolfi, M., E. Landi Degl'Innocenti, and P. Arena, *On the Diagnostic of Magnetic Fields in Sunspots Through the Interpretation of Stoke's Parameters Profiles*. Solar Physics, 1984. **93**: p. 269-287.
2. Landi Degl'Innocenti, E. and M. Landolfi, *Polarization in Spectral Lines*. Astrophysics and Space Science Library. Vol. 307. 2004: Kluwer Academic Publishers.
3. Bommier, V., et al., *UNNOFIT inversion of spectro-polarimetric maps observed with THEMIS*. Astronomy and Astrophysics, 2007. **464**: p. 323-339.
4. Molodij, G., V. Bommier, and J. Rayrole, *Network velocity gradients in the photosphere. I. Modeling*. Astronomy and Astrophysics, 2011. **531**: p. A139.