HAZEL2: "synthesis" mode

Shuo Wang
Dept. of Astronomy, NMSU
DKIST Ambassador

NSO 5th NCSP DKIST Data-Training Workshop: He I Diagnostics in the Solar Atmosphere

What is HAZEL?

- HAnle and ZEeman Light (HAZEL)
- A code tool for the synthesis and inversion of Stokes profiles caused by the joint action of atomic level polarization and the Hanle and Zeeman effects in some spectral lines, such as 10830 $\AA$.
- Written by [Andrés Asensio Ramos]

What can HAZEL do?

- I have an atmospheric model, and I want to see how it influences my observables (spectral lines).
  ➡️ **synthesis**

- I have observations, and I want to know the physical properties such as vector magnetic field and velocities of the atmosphere from where they originate.
  ➡️ **inversion**

What can HAZEL do?

Atmospheric Model 🌞	HAZEL	Observables 🔭
Vector magnetic field LOS velocity Thermal velocity Optical depth Damping	➡️**synthesis**➡️ ⬅️**inversion**⬅️	Line profiles of Stokes I, Q, U, V

Hazel Versions

- HAZEL2
  https://github.com/aasensio/hazel2
  for Python user (recommended)
- HAZEL
  for IDL user

What lines can HAZEL2 handle?

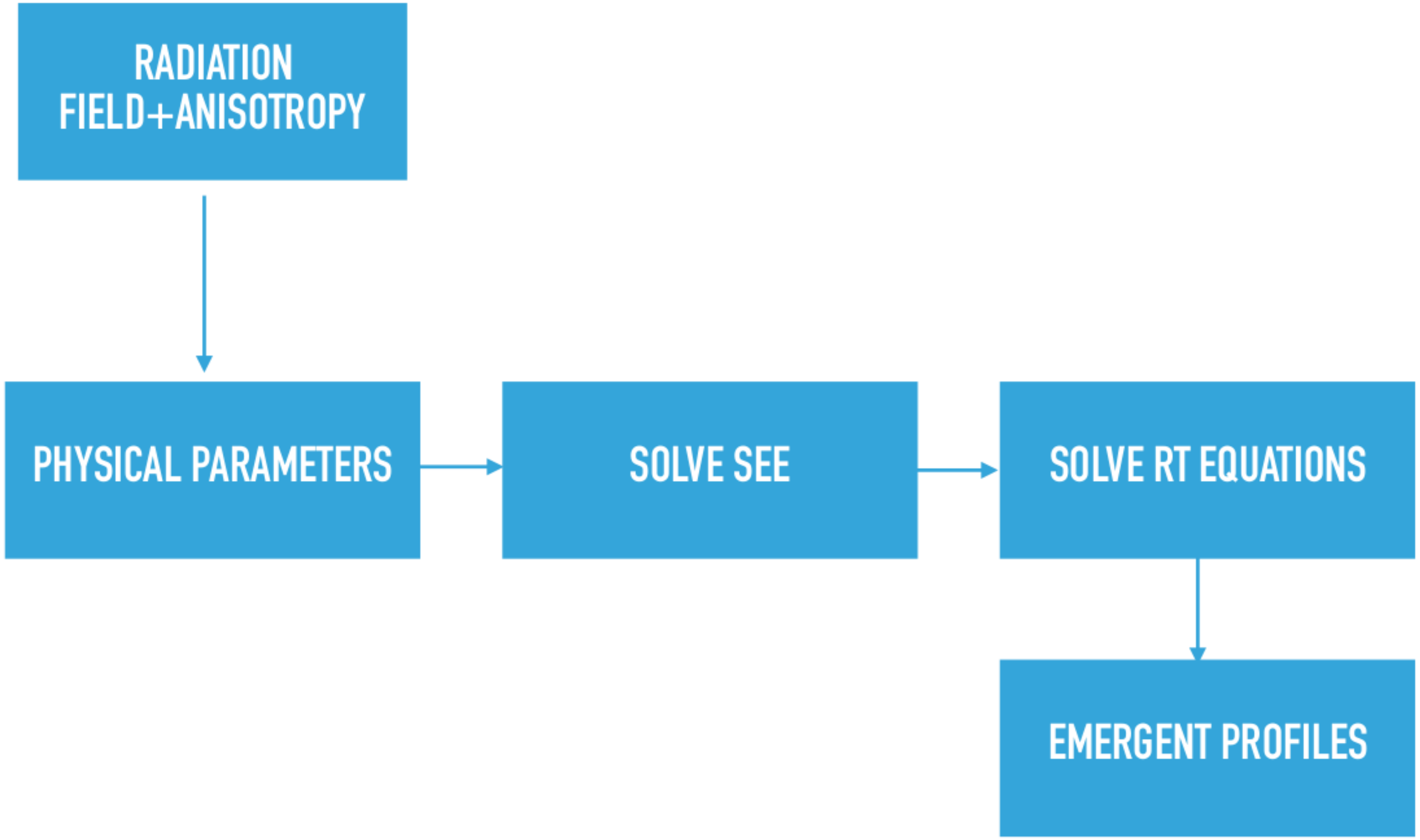
- Chromospheric lines
  - **He I 10830 Å line** (Let's focus on this line.)
  - He I D3 5876 Å line
  - Ca II 8542 Å line
- Photospheric lines📖
- Telluric lines

HAZEL

- 5-term atom
- Simple slab with constant physical properties
- Line formation is “hidden” on the optical depth
- Atomic level polarization + Zeeman (Paschen-Back) + Hanle effect
- Flat spectrum
- Fixed pumping radiation field
- Very simple formal solution
- Serial/MPI version

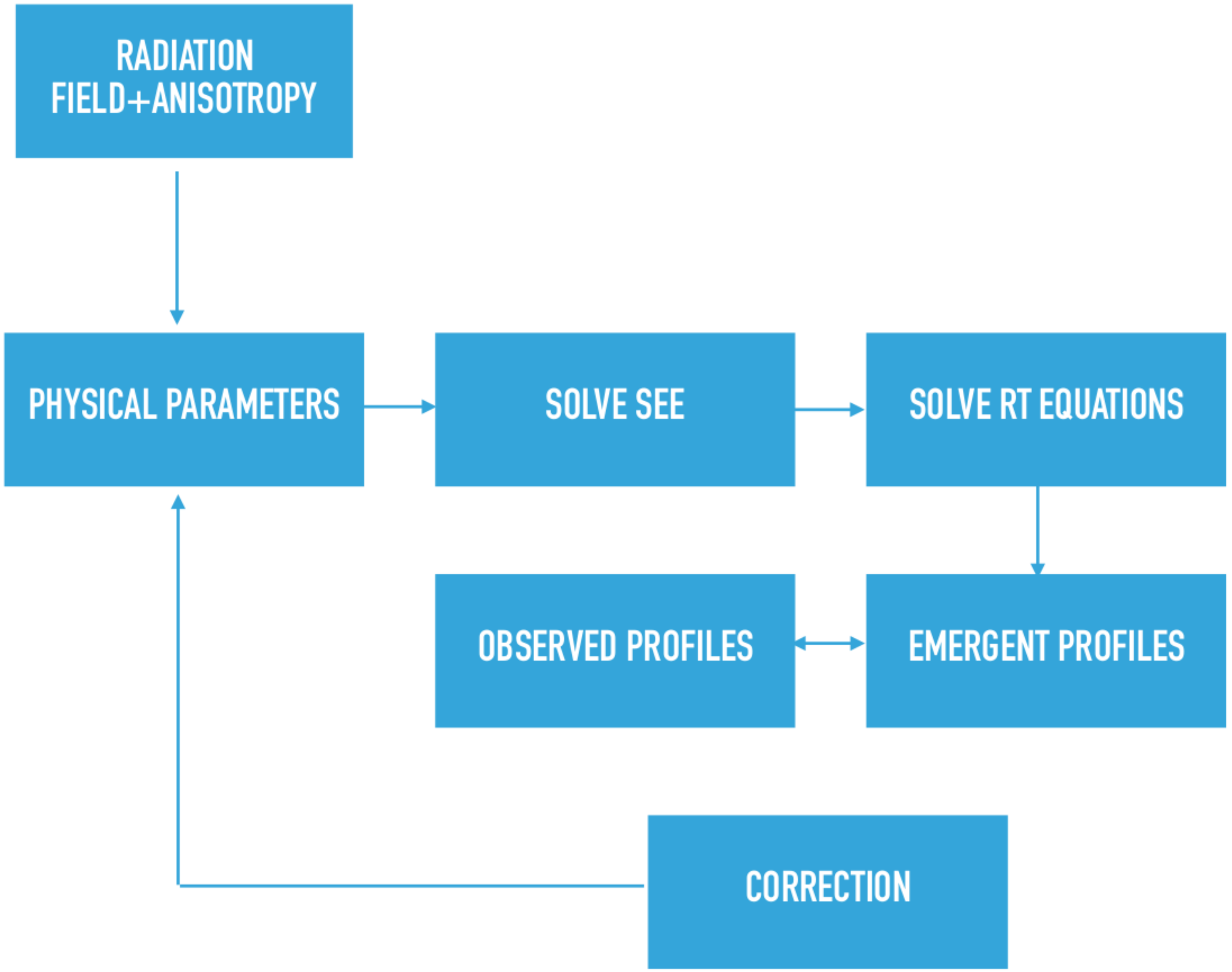
https://github.com/aasensio/estes_park18/blob/master/presentations/he_theory.pdf

EMISSION/ABSORPTION



https://github.com/aasensio/estes_park18/blob/master/presentations/he_theory.pdf

INVERSION PROCESS IN HAZEL



https://github.com/aasensio/estes_park18/blob/master/presentations/he_theory.pdf

Basic Functions of HAZEL2

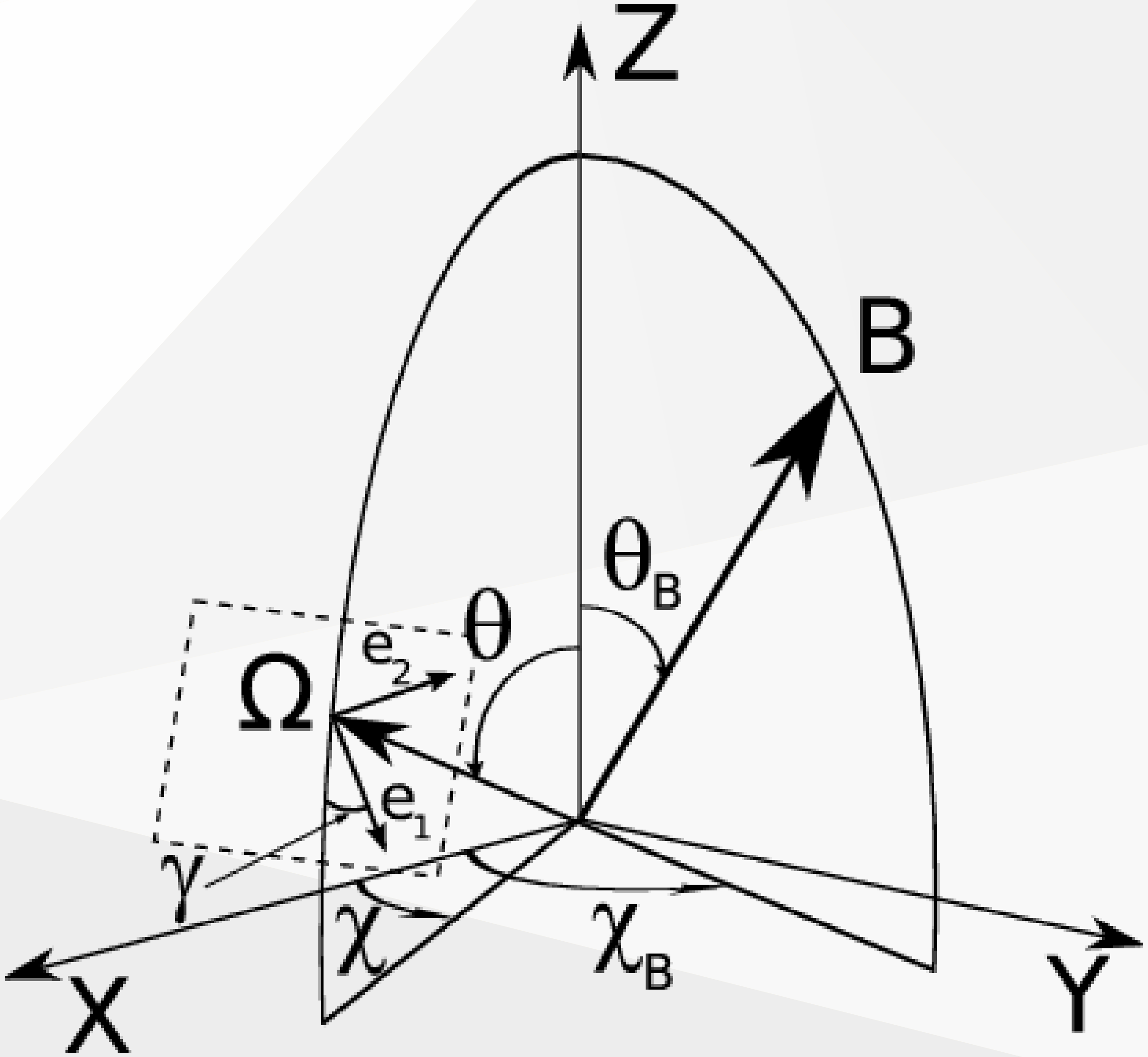
- **Synthesis** (Core function)
- **Inversion** (Call synthesis repeatedly, and return the values with best match.)

🚧 Inversion will be discussed the next day (Wed) in more detail.

Geometry

- Observer angles (θ, χ, γ)

Symbol	Definition
Z axis	$\perp$ solar atmosphere
Ω	LOS
X axis	in Z-Ω plane,$\chi = 0$
e1	Stokes Q+ direction



📖Hazel2 documents > 5.3.1.

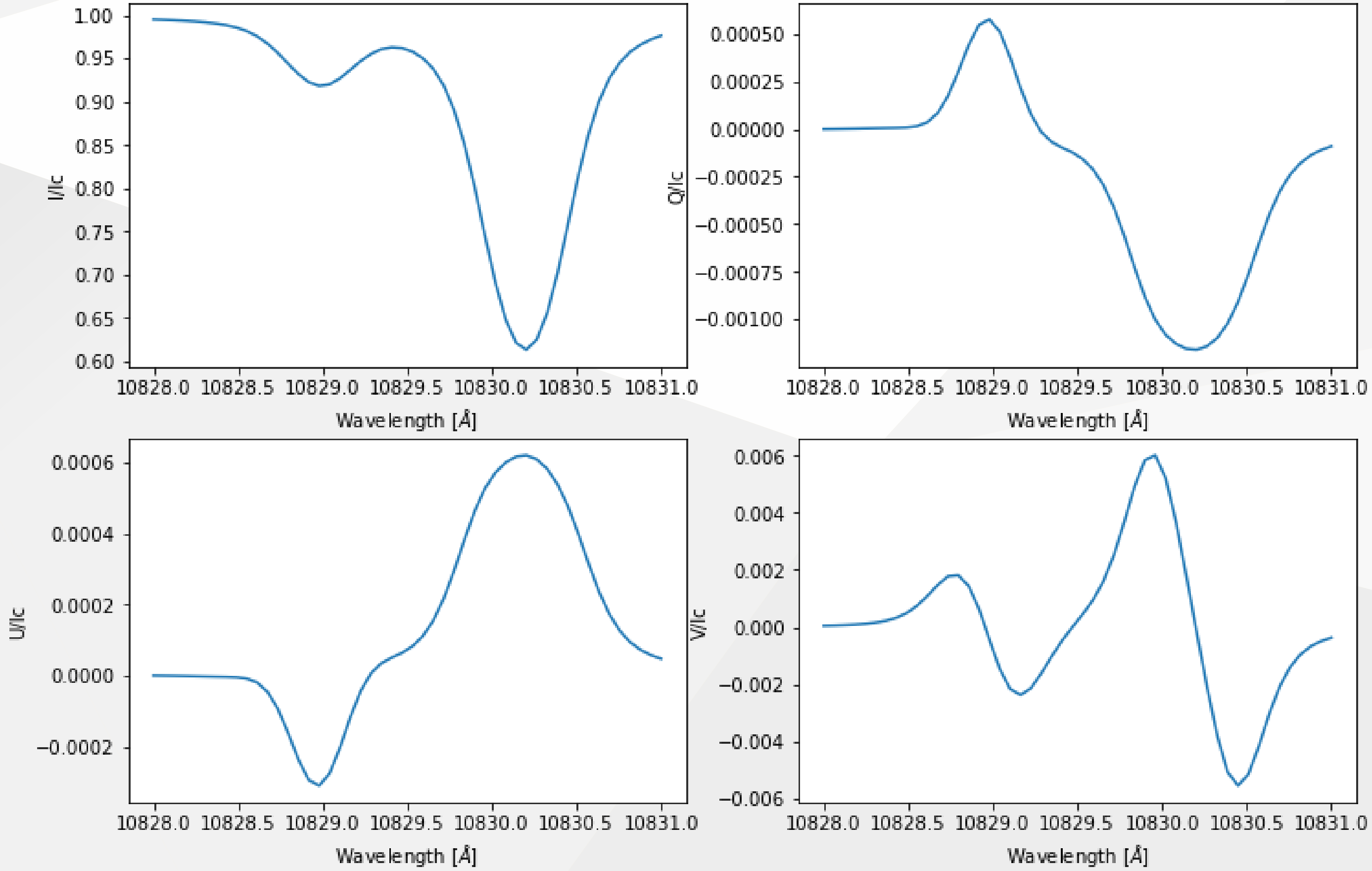
Input ➡️ Synthesis

- Magnetic field vector (B_x, B_y, B_z)
- Thermal velocity affecting the width of the line
- Bulk velocity of the plasma leading to a redshift / blueshift
- Optical depth of the line
- Line damping parameter
- **Observer angles**

❗ The **Observer angles** depend on choice of coordinate system. They are defined in HAZEL as shown in the previous slide.

Synthesis ➡ Output

- Stokes I, Q, U, V profiles



How to install HAZEL2?

Follow instuctions in the following links:

- Hazel2 documents > 1. Installation
- NSO hazel 2 tutorial

How to use HAZEL2?

- GUI (Synthesis only)
- Python code (Both synthesis and inversion)

Synthesis code (Python 3)

0️⃣ Import packages

```
import hazel
import matplotlib.pyplot as plt
```

1️⃣ Construct model.

```
mod = hazel.Model(working_mode='synthesis')
```

- Working_mode: 'synthesis' or 'inversion'

💻 We will do this exercise just after this Intro. So that there will be ample time to test all these commands.

2️⃣ Add spectral region 🔭.

```
mod.add_spectral({'Name': 'spec1', 'Wavelength': [10828, 10831, 50],
    'topology': 'ch1', 'LOS': [0,0,90], 'Boundary condition': [1,0,0,0]})
```

- Name: Define the name of the spectral region. Used in 3️⃣ .
- Wavelength: For sampling of line profiles [lower (Å), upper (Å), number of points]
- Topology: Combination of atmospheric layers. Use the value(s) of 'Name' in 3️⃣.
- LOS: Observer angle in degrees $[\theta, \phi, \gamma]$. θ ranges from 0 (disk centrer) to 90 (limb). ϕ is χ in the figure of geometry.

2️⃣ Add spectral region 🔭.

```
mod.add_spectral({'Name': 'spec1', 'Wavelength': [10828, 10831, 50],
    'topology': 'ch1', 'LOS': [0,0,90], 'Boundary condition': [1,0,0,0]})
```

- Boundary condition: The Stokes profiles that are entering the slab from below.
  Defines the boundary condition normalized to the continuum intensity on the quiet Sun at disk center.
  [Stokes I/Ic(mu=1), Q/Ic(mu=1), U/Ic(mu=1), V/Ic(mu=1)]

📖 [Hazel2 Documents > 5.2. How to deal with boundary conditions]

Topology Example

```
'topology': 'ph1 + ph2 -> ch1 -> te1 -> st1'
```

Light Direction	Layers
⬆️st1	st: straylight contamination
⬆️te1	te: telluric contamination
⬆️ch1	ch: chromosphere
⬆️ph1+ph2	ph: photosphere

->: Right arrow shows light path direction.

+: Atmospheres are added with a filling factor.

📖[Hazel2 Documents > 3.3 Topology]

📝 We will do mostly one chromosphere in this workshop.

3️⃣ Add chromosphere 🌞.

```
mod.add_chromosphere({'Name': 'ch1', 'Spectral region': 'spec1', 'Height': 3, 'Line': '10830'})
```

- Name: Define the name of the chromosphere. Used in 5️⃣.
- Spectral region: Use the value of 'Name' in 2️⃣.
- Height: Try 3 arcsec for AR filament; 10-30 for quiescent filament.
- Line: Use '10830' for He I 10830 Å.

4️⃣ Set up model.

```
mod.setup()
```

5️⃣ Set atmospheric parameters.

```
mod.atmospheres['ch1'].set_parameters([-200, 50, 100, 1, -3, 6, 1, 0.5], 1)
```

[Bx, By, Bz, τ (optical depth) , $\mathrm{v}_{\mathrm{LOS}}$, $\mathrm{v}_{\mathrm{thermal}}$, β, a (damping)], ff

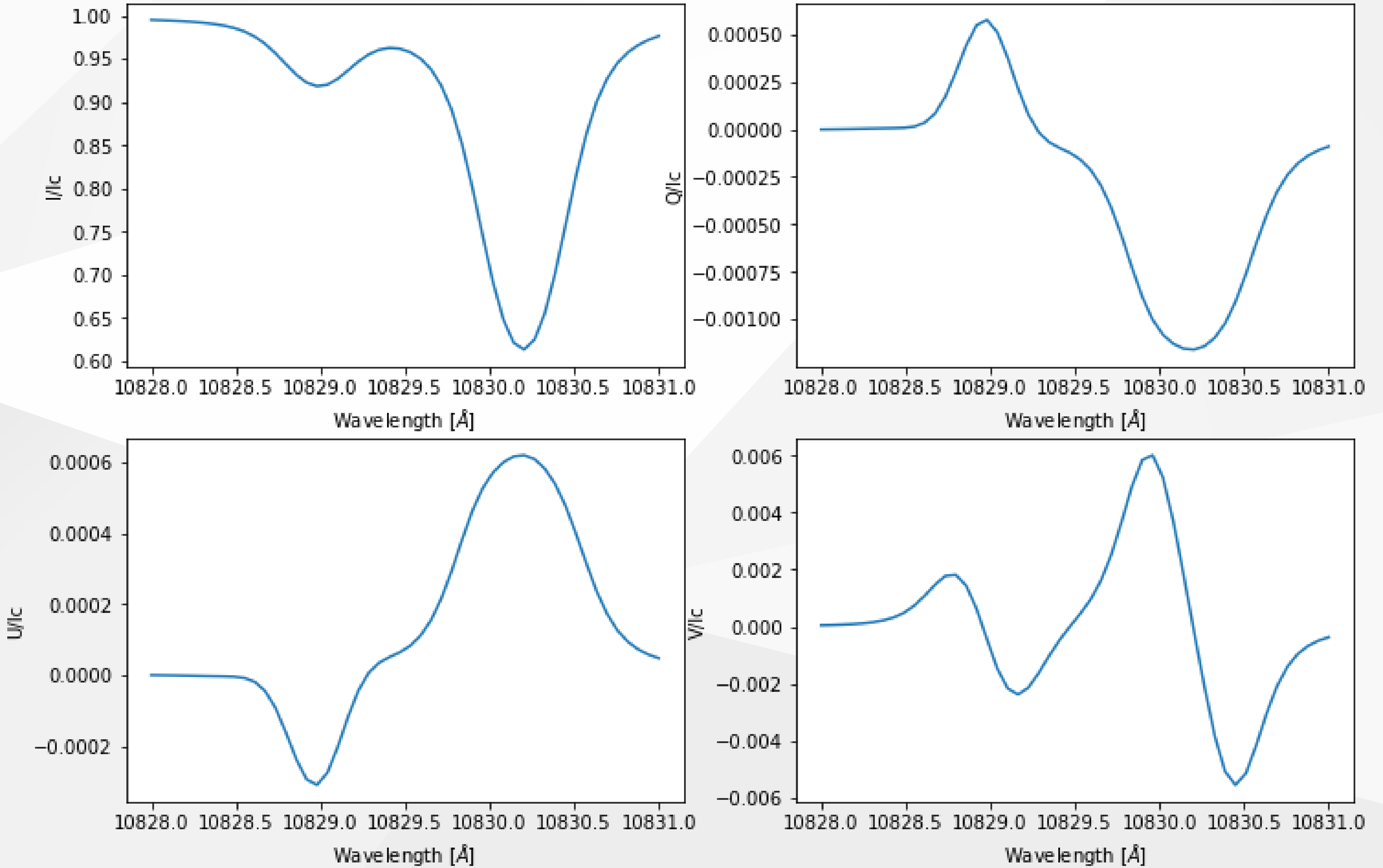
- Components of magnetic field are in Gauss
- Velocities are in km s^{-1}
- β: Enhancement factor for source function in radiative transfer equation. Always use 1, unless in strange situations (i.e., not only in absorption / on disk).
- ff: Filing factor. Ratio of light sensitive area versus total area of a pixel. We will mostly use 1.

6 Run.

```
mod.synthesize()
```

7 Plot results.

```
iq = 'IQUV'
ms = mod.spectrum['spec1']
plt.figure()
for i in range(4):
    plt.subplot(221+i)
    plt.plot(ms.wavelength_axis, ms.stokes[i])
    plt.xlabel('Wavelength [$\AA$]')
    plt.ylabel(iq[i]+'/Ic')
```



I/Ic
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
Q/Ic
0.00050
0.00025
0.00000
−0.00025
−0.00050
−0.00075
−0.00100
U/Ic
0.0006
0.0004
0.0002
0.0000
−0.0002
V/Ic
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
10828.0 10828.5 10829.0 10829.5 10830.0 10830.5 10831.0
Wavelength [Å]

Synthesis GUI

In terminal, type:

```
hazelgui
```

📝 We will not use the GUI in the workshop.

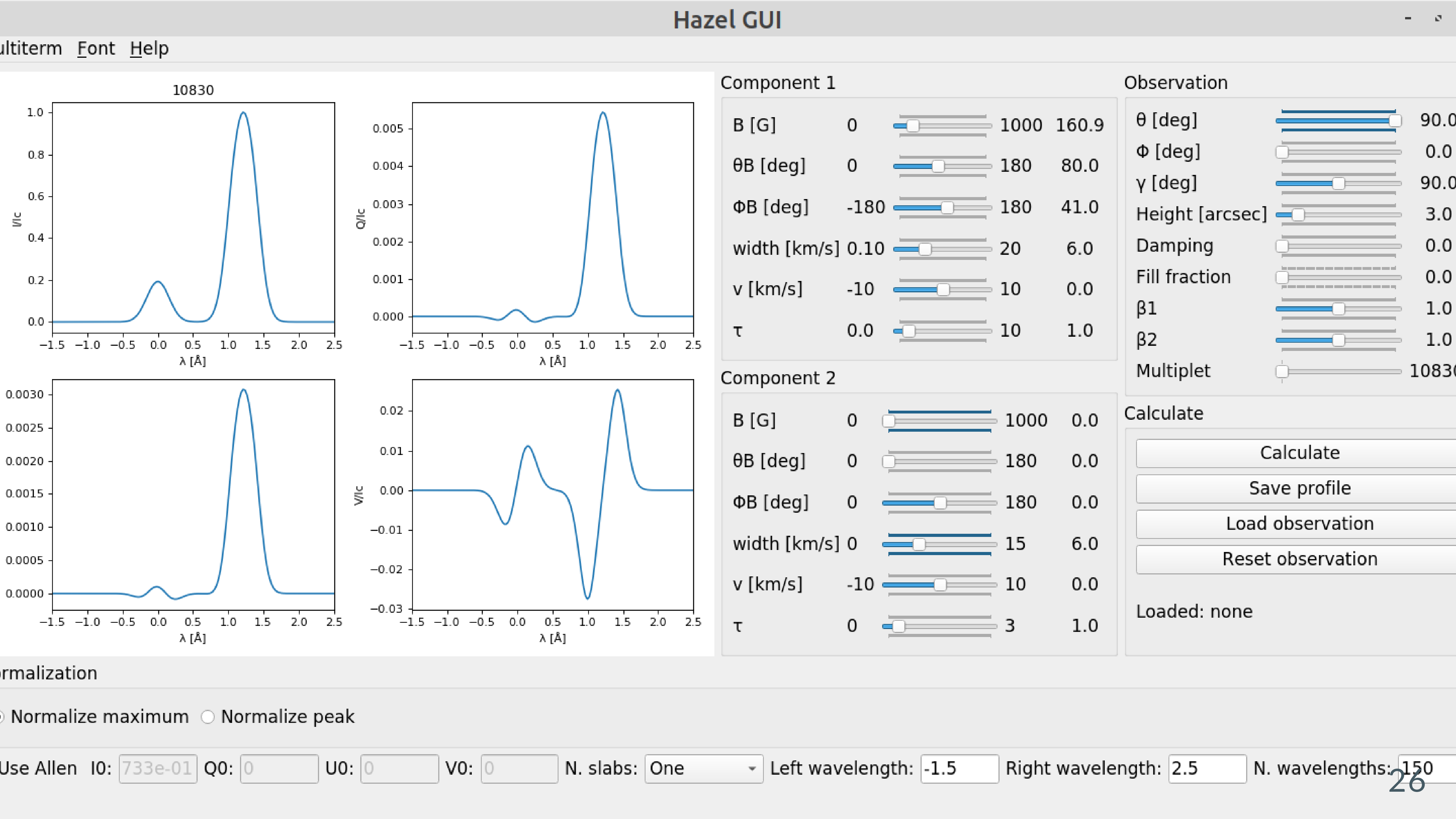
Synthesis GUI

In case you see the following error message:

```
backend =  Qt5Agg
...
File ".../lib/python3.9/site-packages/hazel-2018.9.22-py3.9-linux-x86_64.egg/EGG-INFO/scripts/hazelgui", line 22, in <module>
    from matplotlib.backends.backend_qt4agg import FigureCanvasQTAgg as FigureCanvas
ModuleNotFoundError: No module named 'matplotlib.backends.backend_qt4agg'
```

Replace line 22 of the file mentioned above with the following:

```
from matplotlib.backends.backend_qt5agg import FigureCanvasQTAgg as FigureCanvas
```


Hazel GUI
ultiterm
Font
Help
10830
I/Ic
Q/Ic
U/Ic
V/Ic
λ [Å]
Component 1
B [G] 0 1000 160.9
θB [deg] 0 180 80.0
ΦB [deg] -180 180 41.0
width [km/s] 0.10 20 6.0
v [km/s] -10 10 0.0
τ 0.0 10 1.0
Component 2
B [G] 0 1000 0.0
θB [deg] 0 180 0.0
ΦB [deg] 0 180 0.0
width [km/s] 0 15 6.0
v [km/s] -10 10 0.0
τ 0 3 1.0
Observation
θ [deg] 90.0
Φ [deg] 0.0
γ [deg] 90.0
Height [arcsec] 3.0
Damping 0.0
Fill fraction 0.0
β1 1.0
β2 1.0
Multiplet 10830
Calculate
Calculate
Save profile
Load observation
Reset observation
Loaded: none
rmalization
Normalize maximum
Normalize peak
Use Allen
I0: 733e-01
Q0: 0
U0: 0
V0: 0
N. slabs: One
Left wavelength: -1.5
Right wavelength: 2.5
N. wavelengths: 150