Differentiable stellar disk integration

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Introduction

Inversion of stellar abundance maps based on time series of spectra is a demanding task. The Doppler Imaging (DI) method is successful, but since it is traditionally based on regularized chi-square minimization, it is computationally expensive [3]. The first step to making the progress is to improve the method of generating spectrum for a stellar surface abundances and rotational velocities map. We present a python package that uses Jax [1] (Autograd and XLA package) and is therefore state-of-the-art in terms of computational efficiency.

1 Methods: spectrum generation

To simulate a spectra time-series obtained by repeated observations of the object in several of its rotation phases we are sampling the stellar disk using a predefined number of points. For each point:

1. An array of fluxes for a range of wavelengths assuming an element's abundance at this point is generated.
2. Each point has a different radial velocity towards the observer due to the star's rotation - the fluxes are correspondingly redshifted/blueshifted using the rotation map.
3. Since it's the 2D projection of the stellar disk that's sampled, the surface area of the sample needs to be taken into account as well. This is represented as the integration weights, since the individual flux arrays are going to contribute to the actual spectrum with different weights.
4. The result spectrum is a weighted sum of flux arrays generated for individual points.

We are planning to simulate stellar pulsations as well, since the only required change to do so would be not to generate the rotation map from the rotational velocity and coordinates of the sampling points but use a pulsation velocity field.

Our integrator function is fully differentiable as it is implemented in JAX library. Our code is open-source and available on github as SPICE [2].

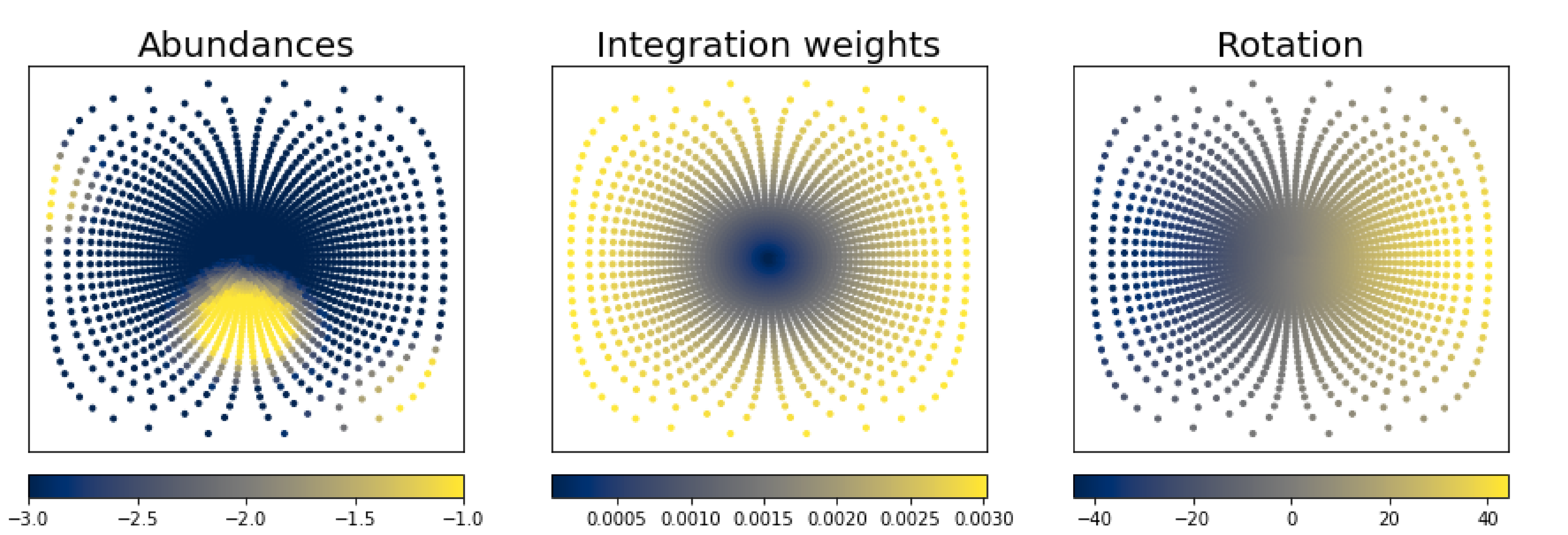

Figure 1: Mapped values.

2 Future work

Computation of the gradients of the operations paves the way for machine learning models which would be able to solve the inverse problem – reconstruct stellar surface maps from the spectral time series.

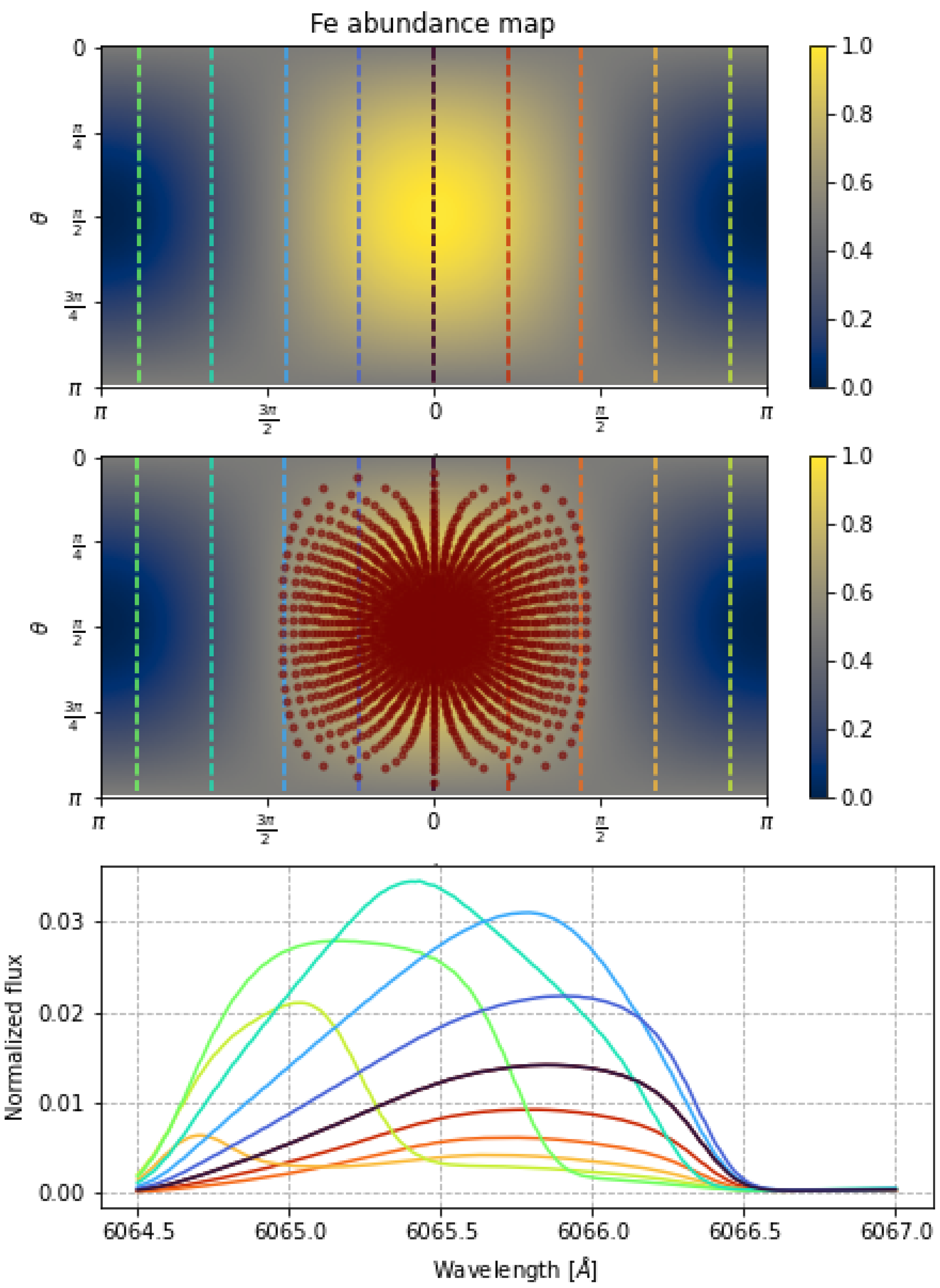

Figure 2: Generated spectral lines.

3 Conclusions

- Our code uses the Jax package which utilizes GPU/TPU and allows us to obtain gradients of the operations.
- The gradients and state-of-the-art efficiency allow for simple gradient optimization methods and pave the way for machine learning methods.
- Our code is versatile and can use many different models of spectra, velocity maps, and representations of chemical overabundances.

References

[1] JAX: composable transformations of Python+NumPy programs, 2018.

[2] http://github.com/maja-jablonska/spice, 2022.

[3] O. Kochukhov. Doppler imaging of chemical spots on magnetic Ap/Bp stars. Numerical tests and assessment of systematic errors. , 597:A58, January 2017.