Computation for astronomers

Graded practical I

Rules: The product of this exam will be a laboratory report — written in English — that you must send to mederic.boquien@uantof.cl by the 23rd of March 2020 at 08:30 at the latest. The mark will be based not only on the ***correctness of your results*** but also on the ***clarity of your answers***, on the ***justification of the choices*** you have made, on providing ***adequate illustrations*** (e.g., if your code produces images, it is expected that you show a representative sample), and on the ***quality of the code*** (proper use of classes, functions, etc.) you have written (it must run without errors, be well-structured, adequately commented, etc.). ***Answers provided without justification will be considered incorrect***. You have the right to access documentation and resources over the Internet but this remains an individual work. You must ***not*** work together in any substantial manner among yourselves. If a snippet of code is reused from a website it must be clearly indicated.

Recommendations: Make good use of the 2 hour in-class session at the beginning of this practical exam. Clarify and doubts you may have on the topic. Then do not wait the last minute to produce a report, it will be too late. Start early and work regularly to avoid any last-minute panic.

From 3D cubes to 2D images

As you enthusiastically head back to class for a new semester to learn about the marvelous wonders of our universe, you cross path with Dulcinea with whom you enjoyed working so much last semester. After enquiring about the latest progress of her research, you ask her if you could be of service to her in any way. After thinking for a second Dulcinea tells you that, indeed, there is something very useful that you could do for her. For her latest project, she is currently working with spectra. More precisely, with spectral cubes. She tells you that these are FITS files with three dimensions: two spatial dimensions (let's call them x and y) and one spectral dimension (let's call it λ). In other words, each pixel is a spectrum. "Ooooooh! Aaaaaaah!", you say with amazement. While there are various softwares doing a great job to explore this sort of data, they are not always very convenient when it comes to creating beautiful 2D images of what the observed object would have looked like in a series of filters similar to those used at telescopes. Essentially, she says that what she would like to do is to compute 2D photometric data from 3D spectroscopic data.

She explains you that if you have the spectrum of an object, you can easily compute the flux in any filter: $f_\lambda(T)= \int_\lambda T(\lambda)\times f_\lambda(\lambda)d\lambda \ / \ \int_\lambda T(\lambda)d\lambda$, with T the filter bandpass defined in units of energy as a function of the wavelength λ, $f_\lambda(\lambda)$ the input spectrum giving the flux per unit of wavelength, and $f_\lambda(T)$ the monochromatic flux in the filter T. Before you embark into this new project with the greatest enthusiasm possible, she presents you with the technical specifications of the script you will need to develop.

1. First, she wants you to explain why you think the filter needs to be defined in terms of energy rather than in terms of photons. She adds that looking at the equation should give you the answer.
2. She indicates that the script will take as an input the filename of the spectral cube as a first argument and the filename of the filter as a second argument. Dulcinea says that the arguments can be obtained with the `sys` module using `sys.argv`. The format of the filter will be the same as the one file provided, with the wavelength in Å. The format of the spectral cube is indicated in the FITS header. It will also be possible not to pass the filter filename but just the wavelength range in the form of the lowest and highest wavelengths `lambda1 lambda2`, that will provide the flux between wavelengths λ_1 and λ_2 defined in nm.
3. Internally all wavelengths will be converted to nm and all fluxes will be converted to W/m²/nm. Beware that by default the filter files are defined in Å.
4. If the filter is defined in terms of photons rather than in energy, it will be converted to energy. Dulcinea says that for that you can multiply the throughput by the wavelength to do so. She also suggests that the integral of the filter be normalised to one. Explain why you think that it is indeed a good idea.
5. You will need to build an array of wavelengths for the cube based on the FITS header keywords `CD3_3`, `CRVAL3`, and `CRPIX3`, such that the wavelength for index `i` is `λ[i]= CRVAL3 + CD3_3 * (i-CRPIX3).`
6. Before computing the flux, both the spectra and the filters will need to be interpolated over the combination of the wavelength. That is, if the spectrum is defined for wavelengths $\lambda_{s1},\ldots,\lambda_{sm}$ and the filter on wavelengths $\lambda_{f1},\ldots,\lambda_{fn}$, both the filters will be interpolated on wavelengths $\lambda_{s1},\ldots,\lambda_{sm} \cup \lambda_{f1},\ldots,\lambda_{fn}$. Dulcinea tells you that to define the set of wavelengths to interpolate onto, you may want to stack the two wavelength arrays, sort them, and eliminate duplicate elements. After that you can interpolate both the filter and the spectra.
7. She wants you to compute the image using the vector capabilities of `np.trap().` That is, there will be no loop of any kind. You explain why you think that this is better than using loops and why in that case it would be very slow.
8. The output image will be stored as a FITS file. Dulcinea says that with astropy you can construct FITS images. Make sure you set the FITS keywords right for an image (`NAXIS, NAXIS1, NAXIS2, BUNIT, CRPIX1, CRPIX2, CD1_1, CD2_2, CUNIT1, CUNIT2, CTYPE1, CTYPE2, CRVAL1, CRVAL2`, at least).
9. You will compute images in the `r_prime.dat` and `i_prime.dat` filters and also in filters defined directly with wavelengths between 674 nm to 681 nm and between 683 nm to 689 nm.
10. Once done, you can compare the fluxes in the images and the fluxes of the spectrum at similar wavelengths. Dulcinea reminds you to be careful about the units! What can you say for at least one of the wavelength-defined filters?