ASTRONOMY 51/151 - SPRING 2022
Exercise Sheet 7
DUE by Friday, April 22, 2022
300 points

Constructing the Velocity Map of a Galaxy - Part II

In Part I, you constructed the intensity maps of a few emission lines, namely Hα, [NII], [OIII], [OII], and [SII]. In Part II, the goal is to construct the velocity map of the galaxy using, simultaneously, Hα and the two [NII] lines next to the Hα. The "flux" data cube (extension #1) is a cube of dimensions 74×74×6732, with 74 spatial positions in both the x and y axis, and 6732 wavelength points. Each (i, j, l) point in the "flux" data cube is the flux from the galaxy from the $x = i$ and $y = j$ position and at wavelength λ position l. Similarly, the "ivar" data cube (extension #2) provides the corresponding inverse variance cube, with $ivar = 1/(error_{\rm flux})^2$; therefore, the error of the flux is given by $error_{\rm flux} = \sqrt{1/ivar}$. The data cube "mask" (extension #3) provides a map of the band points; specifically, you should consider only the points for which mask is equal to 0. Finally, you already saw the wavelength vector, which is the extension #4 in the data cube.

In order to construct the velocity map of the galaxy, you need to measure the centroids (i.e., wavelength corresponding to the peaks) of the emission lines at each spatial positions. You will be using Hα and the two [NII] emission lines. At each spatial position, you will have to fit the spectrum (roughly, 200 Å centered on the redshifted Hα) as a superposition of a continuum (i.e., a constant value C) and three Gaussians, one for each of the three emission lines (Hα and the two [NII]). Therefore, you will have to fit the spectrum with the following model:

$$\begin{aligned} flux = C + A_{\rm H\alpha} e^{-[\lambda_{\rm obs} - \lambda_{\rm H\alpha,rest}(1+z)]^2/2\sigma^2} + ... \\ + A_{\rm [NII]a} e^{-[\lambda_{\rm obs} - \lambda_{\rm [NII]a,rest}(1+z)]^2/2\sigma^2} + ... \\ + A_{\rm [NII]b} e^{-[\lambda_{\rm obs} - \lambda_{\rm [NII]b,rest}(1+z)]^2/2\sigma^2}, \end{aligned} \tag{1}$$

where C is the value of the continuum; $A_{\rm H\alpha}$, $A_{\rm [NII]a}$, and $A_{\rm [NII]b}$ are the value at the peaks of the Hα, [NII]a, and [NII]b emission lines, respectively; $\lambda_{\rm H\alpha,rest}$, $\lambda_{\rm [NII]a,rest}$, and $\lambda_{\rm [NII]b,rest}$ are the rest-frame wavelengths of the Hα, [NII]a, and [NII]b emission lines, respectively; z is the redshift at each spatial position; σ is the dispersion of the Gaussian used to model the emission line; and $\lambda_{\rm obs}$ is the observed wavelength (i.e., the independent variable). This equation allows you to fit simultaneously the three lines with 6 free parameters: C, $A_{\rm H\alpha}$, $A_{\rm [NII]a}$, $A_{\rm [NII]b}$, σ, and z. This equation assumes that the three emission lines have the same dispersion σ (a fair assumption).

Therefore, **for each spatial position** $(x_{\rm i}, y_{\rm j})$, with $i = 1, ...74$ and $j = 1, ...74$, you will have to model the spectrum centered on the Hα and with a range of ±100 Å, to derive the 6 best-fit parameters. Let's call λ the wavelength vector centered on the Hα and with width equal 200 Å, and let's call f the corresponding flux vector at the position

$(x_{\mathrm{i}}, y_{\mathrm{j}})$, and e and m the corresponding flux error and mask vectors, respectively. At each position, it is important to consider only the elements in λ, f, and e with $m = 0$ (i.e., "good" points); i.e., you should exclude from the modeling any points in λ, f, and e with m non equal to 0. Note: if there are less than 10 good points at a specific $(x_{\mathrm{i}}, y_{\mathrm{j}})$ location, you should not attempt the fitting of the spectrum at that position.

Depending on the fitting routine you will be using to perform the modeling (I would recommend using *curve_fit*), it is likely that you will have to provide an initial guess for the six free parameters (again, for each spatial position considered). I advice to use the following:

- for C, use the median of f after removing any bad points;
- for z, use the redshift of the galaxy;
- for σ, use 3 Å;
- for $A_{\mathrm{H}\alpha}$, use $[max(f) - median(f)]$;
- for $A_{\mathrm{[NII]a}}$, use $[max(f) - median(f)]/3.5$;
- for $A_{\mathrm{[NII]b}}$, use $[max(f) - median(f)]/2$

If possible, use a fitting routine that allows you to put constraints on the best-fit parameters. Specifically, you should use the following:

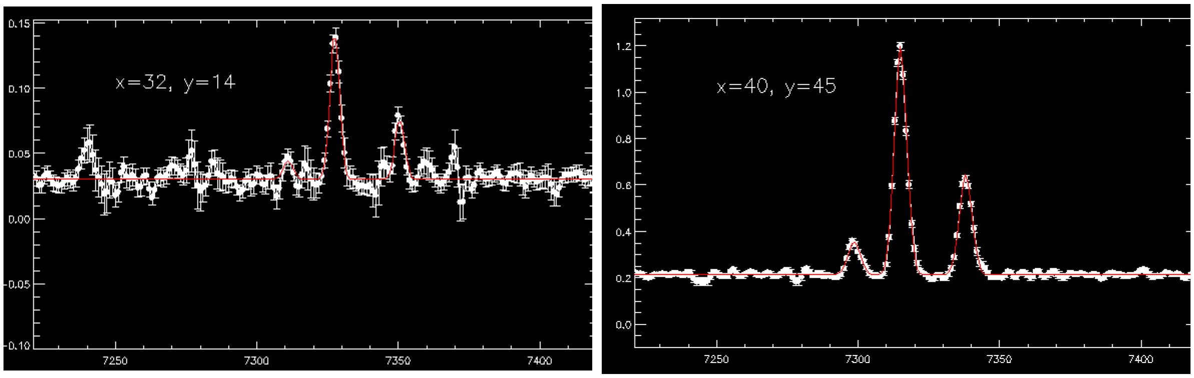
- 1 Å$< \sigma <$5 Å;
- $0 < A_{\mathrm{H}\alpha} < [max(f) - median(f)] * 1.1$
- $0 < A_{\mathrm{[NII]a}} < [max(f) - median(f)] * 0.4$
- $0 < A_{\mathrm{[NII]b}} < [max(f) - median(f)] * 0.7$

Make sure that the fitting routine outputs the errors on the best-fit parameters. I suggest to perform a loop that runs through all the spatial positions $(x_{\mathrm{i}}, y_{\mathrm{j}})$, performing the modeling. Figure 1 shows two examples of the modeling at two different positions, as specified in the left and right panels.

Within the loop, you will populate matrices for the six free parameters and their errors (for a total of 12 matrices). Each element of each matrix correspond to a different spatial positions $(x_{\mathrm{i}}, y_{\mathrm{j}})$. Make sure you save these, so that you will not have to re-run the modeling (which takes quite a bit of time). You can save these matrices in whatever format you want, but one good choice is to use HDF5.

Once the aforementioned modeling is completed, you will need to produce a velocity map of the galaxy (like the one shown in Figure 2). You can obtain this from the z map constructed from the aforementioned modeling. Specifically:

$$v_{\mathrm{map}}[km\ s^{-1}] \equiv v_{\mathrm{dyn}} = (z_{\mathrm{los}} - 0.115137) * c, \tag{2}$$



(a) Figure on left side

(b) Figure on right side

Figure 1: Overall caption

where $c = 2.99792458 \times 10^5$ km s^{-1} and 0.115137 is the systemic redshift of the galaxy. You should apply some additional quality cuts to produce a robust velocity map (like the one shown). Specifically, you may want to limit to $(x_{\rm i}, y_{\rm j})$ positions for which $-500 < v[km\ s^{-1}] < 500$, the fitting routine completed successfully, $A_{\rm H\alpha}/err_{\rm A_{H\alpha}} > 3$, $A_{\rm [NII]b}/err_{\rm A_{[NII]b}} > 3$, and $A_{\rm H\alpha} > 5 \times err_{\rm C}$; you should also disregard the positions at the edge of the MaNGA footprint. Make sure to also include a legend on the velocity map figure, including the range of velocity being plotted.

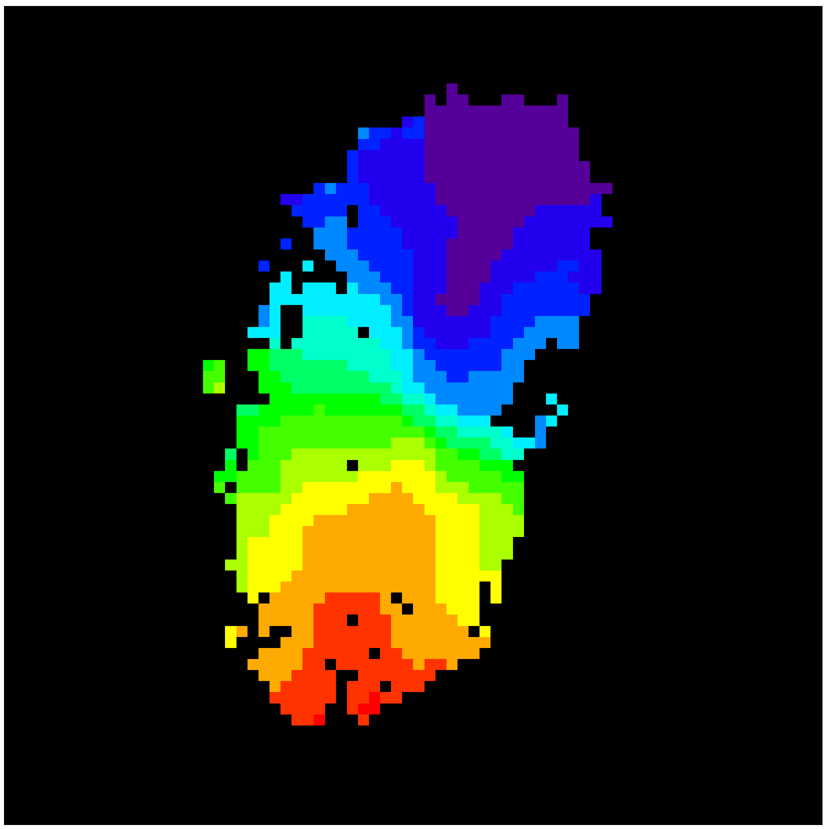


Figure 2: Velocity map.