ASTRONOMY 51 - SPRING 2022
Exercise Sheet 6
DUE by Friday, April 15, 2022
300 points

Constructing the Velocity Map of a Galaxy - Part I

Background: One of the first evidence for the existence of dark matter came from the measurement and modeling of the velocity curve of spiral galaxies. Spiral galaxies can be approximated as rotating disks made of stars and gas. Spiral galaxies are thought to reside in more or less spherical halos of dark matter, which dominates the total mass content of a galaxy at large galacto-centric distances. The rotation curve of a galaxy is the rotation velocity of its content around the center of the galaxy as a function of galacto-centric distance (i.e., distance from the center of the galaxy).

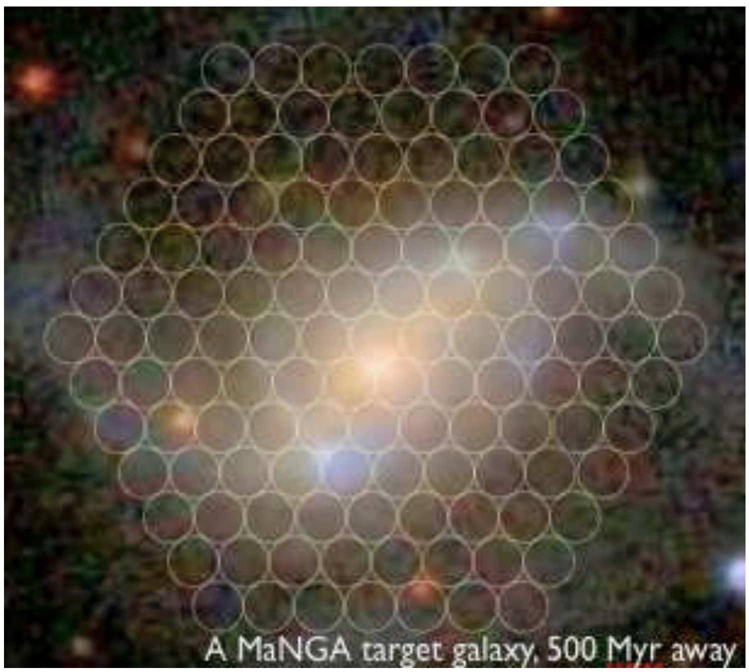

Figure 1: Galaxy observed with the MaNGA fibers. Each fiber produces a spectrum of the light of the galaxy from that position.

There are different techniques to measure the velocity curve of a galaxy, but they all involve spectroscopy and the use of the Doppler shift. The Part I of this project consists of familiarizing with the data which will be use to derive the velocity map of a galaxy. For this project, you will be using data from MaNGA (Mapping Nearby Galaxies at APO; Bundy et al. 2015). MaNGA is a survey of about 10,000 nearby galaxies observed with 17 simultaneous integral field units to obtain spatially resolved spectra of galaxies. Figure 1 shows how the MaNGA survey works. A galaxy is observed with a bundle of fibers. Each fiber, with a diameter of $\sim 2''$, samples a spatial region 1-2 kpc across, depending on the distance of the observed galaxy. Each fiber brings the light coming from the sampled region to the spectrograph, producing a spectrum. In this way, MaNGA is able to construct a map of spectra, or a data cube: two dimensions correspond to the spatial x and y directions, whereas the third dimension is wavelength. MaNGA allows for the construction of 2D maps stellar velocity and velocity dispersion, mean stellar age and star-formation history, stellar metallicity, element abundance ratio, stellar mass surface density, ionized gas velocity, ionized gas metallicity, star-formation rate, and dust extinction.

To determine the rotation curve of a galaxy, we have to measure the Doppler shift in wavelength of an emission (or absorption) spectral line as a function of the spatial position in the galaxy. The Doppler effect (for line-of-sight velocity $v_{\mathrm{los}} << c$) is given by the following equation:

$$\frac{\lambda_{\mathrm{o}} - \lambda_{\mathrm{r}}}{\lambda_{\mathrm{r}}} = \frac{v_{\mathrm{los}}}{c}, \tag{1}$$

where λ_{o} is the wavelength of the emission line being observed, and λ_{r} is the wavelength at rest of the same line. Needless to say, the velocity being measured with the Doppler shift is only the component parallel to the line of sight. Therefore, measuring λ_{o} and knowing λ_{r}, we can obtain the velocity along the line of sight:

$$v_{\mathrm{los}} = c\frac{\lambda_{\mathrm{o}} - \lambda_{\mathrm{r}}}{\lambda_{\mathrm{r}}}. \tag{2}$$

The first thing you have to keep in mind though is that all galaxies are moving away from us, due to the expansion of the universe. Therefore, when we observe a galaxy, the measured $v_{\mathrm{los}} = v_{\mathrm{sys}} + v_{\mathrm{dyn}}(r)$, where v_{sys} is the component along the line of sight of the velocity of the galaxy as a whole, whereas $v_{\mathrm{dyn}}(r)$ is the component along the line of sight of the velocity of the galactic region being observed at a distance r from the center of the galaxy. For a system in rotational equilibrium, $v_{\mathrm{dyn}}(r)$ is interpreted as the circular velocity of the galaxy. As shown in Figure 2, the measurements will only give us the component along the line of sight of the rotation velocity of the galaxy. We will learn in Part II how to obtain the actual rotation curve of the galaxy, i.e., the circular velocity $v_{\mathrm{c}}(r)$ as a function of the radius r.

To measure the Doppler shift, the most commonly adopted spectral line is the Hα in emission produced by excited neutral Hydrogen (HI). The Hα is the most used because it is typically the brightest emission line in a star-forming spiral galaxy. However, other lines, both in emission and/or in absorptions can by used. Figure 3 shows a list of common spectral lines in astronomy (in red those that you may be using in this project, with the Hα in blue, which is the primary line you will be using in this project).

Therefore, in the equation above, $c = 299792.458$ km s^{-1}, while for the Hα with have $\lambda_{\mathrm{r}} = 6564.61$ Å.

Part I of this project consists of becoming familiar with the data cube of a specific galaxy, 2MASX J08520853+5118462. This galaxy is located at RA=08h52m08.5s and DEC=+51d18m46s, and a redshift $z = 0.115137 \pm 0.000019$. It has an estimated stellar

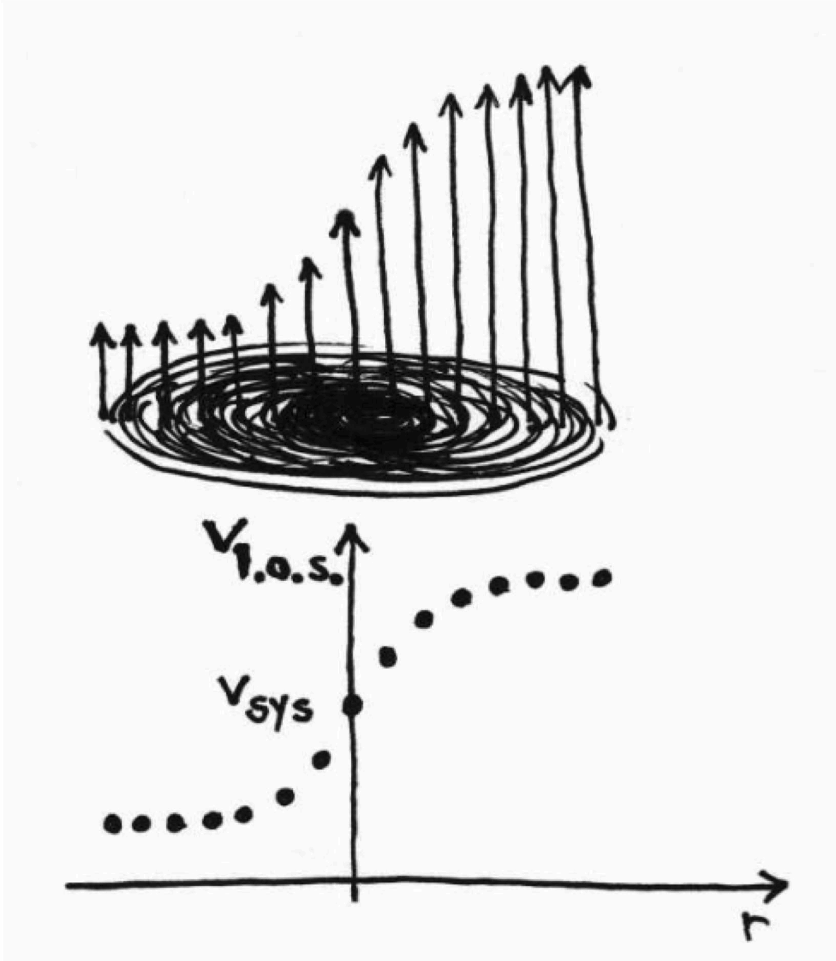

Figure 2:

mass of $M_{\rm star} = 10^{11}$ $\mathrm{M}_{\odot}$, so it is a typical galaxy in the local universe. You can download a zipped directory containing the needed files here or here. To become familiar with the MaNGA data, you will follow the very useful MaNGA tutorial page. In particular, with the data cube that you can download here or here, you will perform the following:

1. After having downloaded the data cube, start becoming familiar with ds9, and start playing with it, following these instructions; ds9 is great for a quick look at the spectra, or images, but it cannot be used to actually perform the analysis.

2. Therefore, follow this Python tutorial to learn how to access the data cube, plotting a spectrum, and constructing emission line (e.g., Hα) maps.

3. At the end, you must construct 2D maps of the following emission lines: Hα, the two [NII], [SII], [OIII]5008, and [OII].

For those of you who prefer to use IDL, there is also an IDL tutorial.

You can find out more about the different extensions in the data cube at this link.

# lambda[A]	Name	# lambda[A]	Name
1033.30	OVI	1215.67	Ly_alpha
1239.42	NV	1305.53	OI
1335.52	CII	1399.8	SiIV+OIV
1545.86	CIV	1640.4	HeII
1665.85	OIII	1857.4	AlIII
1908.27	CIII	2326.0	CII
2439.5	NeIV	2800.32	MgII
3346.79	NeV	3426.85	NeV
3728.30	**OII**	3798.976	H_theta
3836.47	H_eta	3889.0	HeI
3934.777	CaII-K	3969.588	CaII-H
4072.3	SII	**4102.89**	**H_delta**
4305.61	G	**4341.68**	**H_gamma**
4364.436	OIII	**4862.68**	**H_beta**
4960.295	**OIII**	**5008.240**	**OIII**
5176.7	Mg	5895.6	Na
6302.046	OI	6365.536	OI
6549.86	**NII**		
6564.61	**H_alpha**		
6585.27	**NII**		
6707.89	Li		
6718.29	**SII**	**6732.67**	**SII**

Figure 3: List of relevant spectra lines and their wavelengths in vacuum.

You'll want to use the LINCUBE file, i.e., the data cube with linear wavelength sampling from 3,622 Å to 10,353 Å (NWAVE=6732 spectral elements) and 0.5 arcsec spatial pixels (spaxels) for a total size of NX x NX x NWAVE pixels. The fluxes are in units of 10^{-17} erg s^{-1} cm^{-2} Å^{-1} spaxel^{-1}.