Analysis of VLT-MUSE observations of NGC 1365

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We study the features of NGC 1365 using data from VLT MUSE. From the data cube, we obtained the spatial image which provides information showing that NGC 1365 is a star-forming galaxy with morphological classification SB(b)s, meaning a barred spiral galaxy. We also visibly see the supermassive black hole in the middle of the galaxy. The optical spectra show the majority of the emission is from the following lines: Hα, Hβ, and [OIII]λ5007. By studying the total emission map of Hα and [OIII], we locate the star-forming region to be in the central region of the galaxy and locate a couple of planetary nebulae near the nucleus.

I. INTRODUCTION

This paper will study a nearby galaxy NGC 1365 using data obtained from VLT MUSE in 2014. NGC 1365 is a spiral galaxy located 56 million light-years away in the constellation Fornax [14]. In the centrum of the galaxy lies a supermassive black hole.

MUSE data is called a data cube and provide information in three dimensions: 2D spatial image and wavelength information. By studying the data cube we aim to learn more about this galaxy. The 2D spatial image provides information on what the source looks like and its morphological features. From the optical spectra, we can study its continuum to learn whether or not this is a star-forming galaxy or not. We can also study the spectral lines in order to locate the brightest and faintest features within the galaxy for different wavelengths. Lastly, we are also able to study the kinematics of the ionized gas from this data.

Figure 1: Image of NGC 1365, the great barred spiral galaxy, taken by 1.5-metre Danish telescope at the ESO La Silla Observatory in Chile [1].

II. THEORY

A. ESO MUSE-VLT

European Southern Observatory (ESO) Very Large Telescope (VLT) is an optical/infrared telescope placed on Cerro Paranal in the Atacama Desert of northern

Figure 2: Laser from UT4 of the ESO VLT [3]

Chile [4]. This telescope consists of 4 units that can be used individually [6]. Mounted on the Nasmyth cabin of the UT4 of the ESO VLT is the Multi Unit Spectroscopic Explorer (MUSE) instrument [2]. MUSE is an integral field spectrograph (IFS, sometimes also referred to as IFU) that allows for imaging and spectroscopy simultaneously.

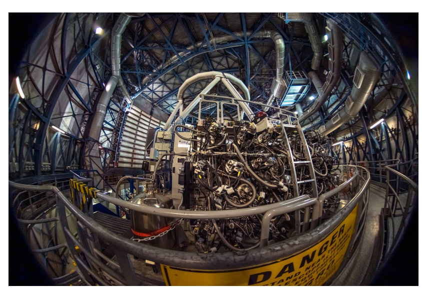

Figure 3: Instrument MUSE which is mounted on UT4 VLT [5]

The pixels of an IFS are called spaxel, and each spaxel has three dimensions [2]. IFS is called 3D spectrographs due to its ability to produce data in 3 dimensions: the 2D of the spatial image and the wavelength information. MUSE operates in two modes: Wide-Field mode and Narrow field mode. Wide-field mode exploits the total field of view of 1 x 1 arcmin^2. Narrow field mode provides a higher spatial resolution, but over an eight-time smaller field [2].

B. Optical galaxy spectra

In the optical/ultraviolet observing bands, we find electronic transitions of atoms and ions, produced in the ionized interstellar medium of galaxies [2]. Some of the most commonly observed and brightest lines in these bands are listed in table I. Forbidden lines are reported in brackets and have a low associated probability to be de-excited spontaneously [2].

Table I: Some commonly (and usually the brightest) observed lines in the UV and optical bands and their rest frame wavelength (air) [2].

Emission line	**λ rest frame** [Å]
Hα	6562.8
[NII]	6583.4
[NII]	6548.1
[SII]	6717.0
[SII]	6731.3
Hβ	4861.3
[OIII]	4958.9
[OIII]	5006.8

The expected observed wavelengths from a galaxy can be calculated with the equation below, granted that we know its redshift z.

$$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}} \rightarrow (1+z) = \frac{\lambda_{obs}}{\lambda_{em}} \qquad (1)$$

C. Right ascension and declination

Right ascension (RA) and declination (Dec) may be appropriate coordinates to use when producing a map of MUSE data. RA and Dec are sky coordinates that correspond to latitude and longitude on Earth. RA measures east and west on the celestial sphere, in hours, minutes, and seconds of time. Dec measures north and south in degrees [7]. The benefit of using RA and Dec is the fact that they provide a more intuitive understanding of data presented in a map, rather than indices or arcsec.

III. METHOD

Our observations of a nearby galaxy NGC 1365, are obtained from MUSE in Wide-Field mode. The data is called a data cube due to containing information in 3 dimensions: 2D of the spatial image and the wavelength information.

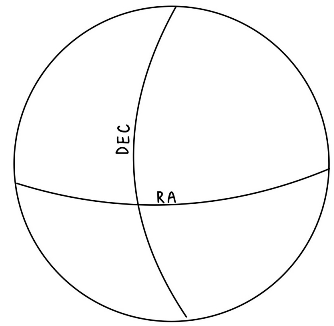

Figure 4: RA and Dec on a celestial sphere, corresponding to latitude and longitude on Earth.

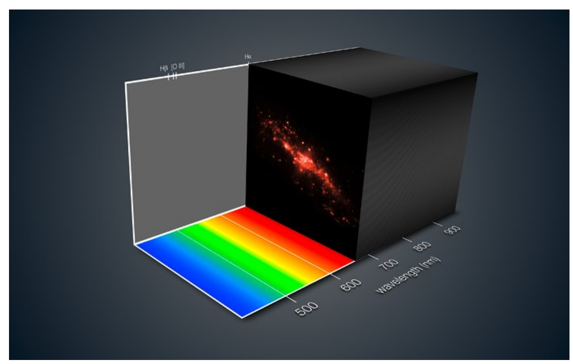

Figure 5: Illustration of a 3D MUSE data cube [8].

To produce a continuum map over the whole wavelength spectrum of the data cube, we need to collapse the spectral dimension of the data cube. This can be done by averaging or summing the flux values within the spectral range, so we are left with a 2D image [9]. The units on the axis will be indices and not actual distances. To convert the indices to RA and Dec coordinates we use `astropy.wcs` in `Python`.

Sometimes we are only interested in studying the continuum map of one emission line in particular (rather than the entire wavelength spectrum). To do so we slice the data cube in its wavelength dimension first, so that we are only left with a small spectral range. Essentially, we are trying to isolate the emission line. This spectral range is then averaged to produce a continuum map of the emission line.

Producing a continuum map can be done in `Python`, but it does not allow for visualization of the 2D spatial image as you are working with the data. The dataset can instead be opened in QFitsView. This is beneficial as we can extract information (i.e. spectra) from regions we find interesting on the 2D image. The information can be exported to `Python` to be analyzed.

IV. RESULTS

The redshift of NGC 1365 is z = 0.005476 [11].

Table II: Rest frame wavelengths (air) of emission lines typically observed in galaxies and expected observed wavelengths for NGC 1365, calculated based on its redshift.

Emission line	**λ rest frame** [Å]	**λ observed** [Å]
Hα	6562.8	6599.2
[NII]	6583.4	6619.9
[NII]	6548.1	6584.4
[SII]	6717.0	6753.2
[SII]	6731.3	6768.6
Hβ	4861.3	4887.9
[OIII]	4958.9	4986.4
[OIII]	5006.8	5034.6

Table II provides information about the expected observed wavelengths of the commonly observed emission lines in UV and optical bands. This was calculated with equation 1 and information from table I.

Figure 6 shows the continuum obtained by collapsing the MUSE data cube in the wavelength range 4750-9351 Å.

Table III: Observational and technical parameters of MUSE data obtained from the header of the data cube. The asterisk indicates information on ESO's website [10].

Parameter	**Value**
Spatial resolution (FHWM)	0.86”
Spectral resolution	3027.07
Field of View*	59.9”x 60.0”
Pixel size	0.2” /pixel
Wavelength range and units	4750 - 9351 [Å]
Flux density units	10^{-20} erg s^{-1} cm^2 Å^{-1}
Observation date	2014-10-12
Observation time	3682.48 [s]

In figure 7 we have marked the three different regions from which the spectra have been extracted. Their pixel coordinates can be found in the same figure. From now on, the blue mark with coordinates (164, 155) px will be referred to as the nucleus (N), the orange mark with coordinates (82, 239) px as the upper arm (U), and the green mark with coordinates (150, 100) px as the lower arm. Their relative coordinates with respect to the galaxy cen-

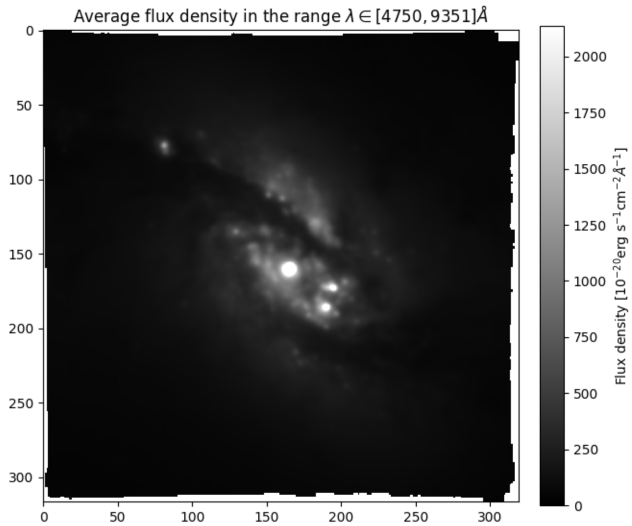

Figure 6: Continuum emission from MUSE collapsed over the full wavelength range of the cube. The averaged flux density is linearly scaled. The numbers on the x and y axes are index numbers, not actual distances. East is to the left

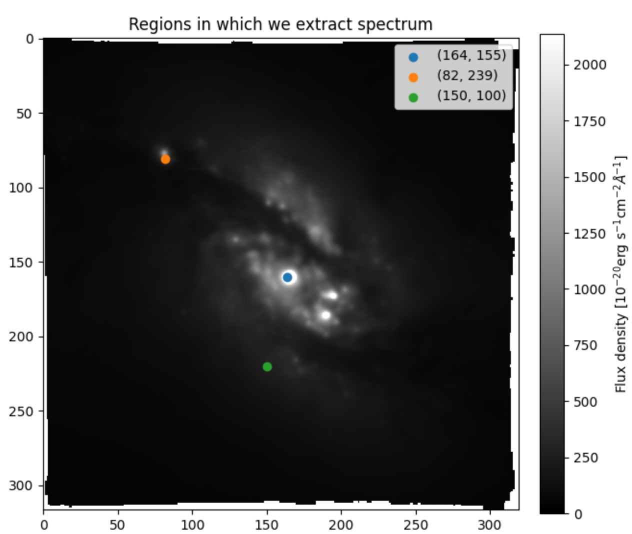

Figure 7: Spectra extraction regions and their pixel coordinates fig. 6

ter can be found in table IV.

Table IV

Region	Coordinates [px]	Relative coordinates [px]
Nucleus	(164, 155)	(0, 0)
Upper arm	(82, 239)	(-82, 84)
Lower arm	(150, 100)	(-14, -139)

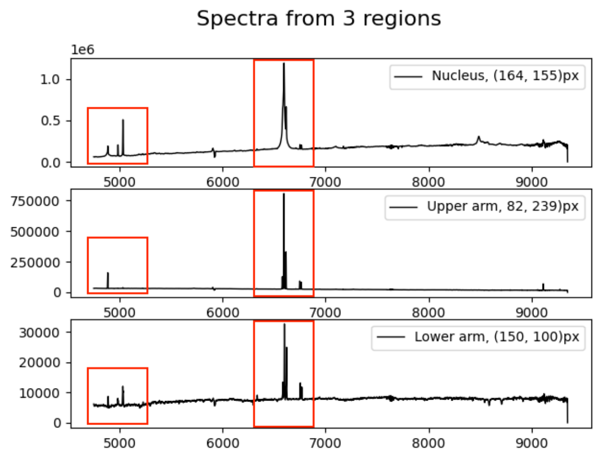

Figure 8: Representative spectra extracted from 3 circular regions with a radius of 3 spaxels, $\lambda \in [4750 - 9351]\mathring{A}$

Three representative spectra (in the wavelength range 4750 - 9351 Å) extracted from circular regions with radius 3 spaxels are shown in figure 8. This corresponds to an aperture of 6 spaxels or 1.2”. The red boxes indicate which sections of the spectrum we chose to study further.

In figures 9 and 10 we have identified emission lines in the two wavelength intervals indicated by red boxes in figure 8. The dashed lines mark where we expect to observe an emission line, calculated in table II.

In figure 11 and 12 we see the map of total emission for Hα and O[III].

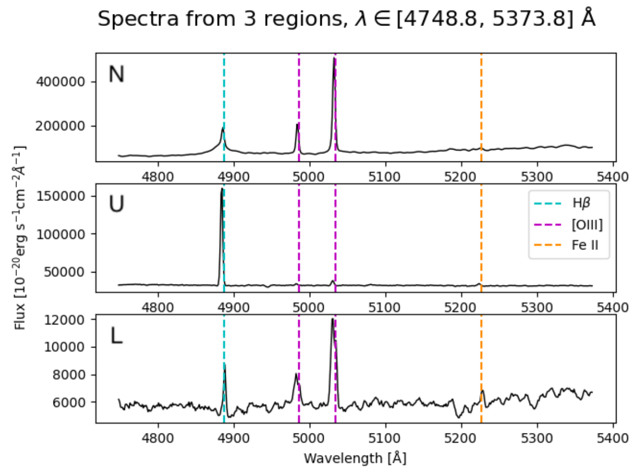

Figure 9: Identified emission lines in wavelength range [4748.8, 5373.8] Å: Hβ, [OIII], Fe II. N indicates the nucleus, U indicates the upper arm and L indicates the lower arm.

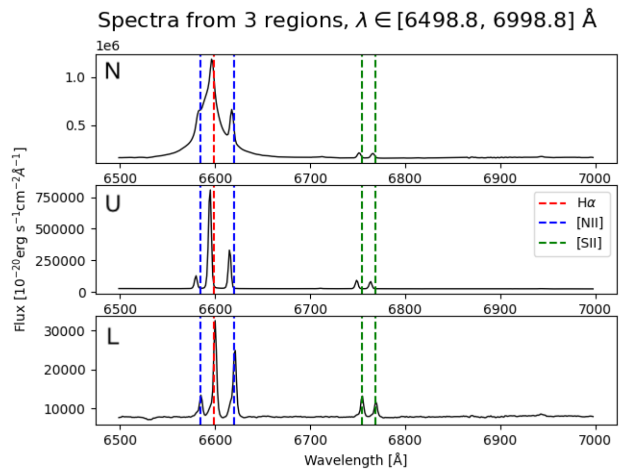

Figure 10: Identified emission lines in wavelength range [6498.8, 6998.8] Å: Hα, [NII], [SII]. N indicates the nucleus, U indicates the upper arm and L indicates the lower arm.

V. DISCUSSION

A. NGC 1365

Due to atmospheric turbulence, ground-based telescopes like VLT do usually not achieve diffraction-limited resolution. The consequence is a degradation of the quality of astronomical images and in particular of their angular resolution, commonly referred to as astronomical seeing

NGC 1365 is classified as a spiral galaxy (SB(s)b) according to the Hubble and de Vaucouleurs galaxy morphological classification [11]. It has two large, prominent arms in the shape of the letter ”Z”. The shape is not as visible in our continuum map in figure 6, but can easier be seen from a picture of NGC 1365 taken by 1.5-meter Danish telescope at the ESO La Silla Observatory in Chile on ESO’s website. ”SB” in its morphological classification means barred spirals and NGC 1365 is in fact also known as Great Barred Spiral Galaxy. Barred spiral galaxies have a central bar-shaped structure composed of stars, along with arms extending from the bar-shape [13]. Its physical extent is 22.70 ± 1.59 Mpc [11].

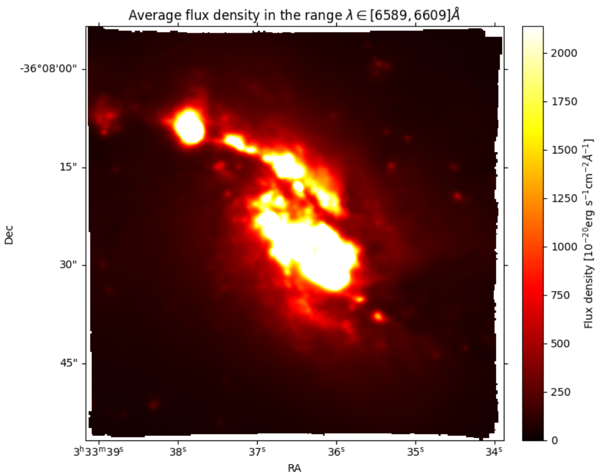

Figure 11: Map of total Hα emission.

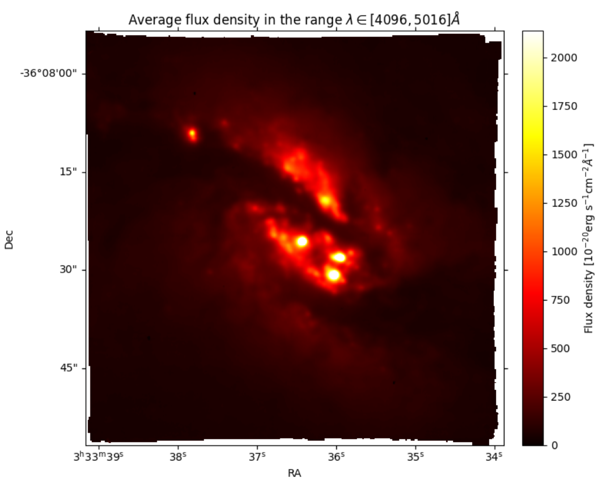

Figure 12: Map of total [OIII] emission.

B. Spectra of 3 regions in the MUSE field of view

The three chosen regions to extract spectra from are shown in figure 7. We decided on the nucleus of the galaxy, the middle part of the lower arm, and the outer part of the upper arm. NGC 1365 has a supermassive black hole in the active nucleus [14], thus making it interesting to study the central region of the galaxy. The position on the upper arm was chosen due to having a very bright region at the outer part. Lastly, I decided to study a part of the lower arm with lower flux density compared to the previous positions.

We can not get information on regions that are smaller than our angular resolution. When studying the spectrum we set an aperture as big as our angular resolution, to exploit all our pixels in our resolution element. Our angular resolution retrieved from the header of the data is 0.86". The three spectra were therefore extracted from circular regions with a radius of 3 spaxels. As mentioned earlier in section IV, corresponds to an aperture of 6 spaxels or 1.2". It is possible to study larger circular regions by increasing our aperture size. However, once more pixels are included we introduce more physical processes into our spectrum.

Representative spectra extracted from three regions can be found in figure 8. We notice the stellar continuum is relatively flat and dominated by emission lines. This is an example of an optical spectrum of a star-forming galaxy with high amounts of gas left for star formation. A galaxy that has not much gas left and little to no star formation left will have few emission lines and a non-flat continuum. The spectra over the entire wavelength range are difficult to study due to the range being large and everything looking compact. We decide to further study the areas indicated by red boxes due to clearly visible and bright emission lines present.

Figure 9 shows representative spectra extracted from the three regions in the wavelength region [4748.8, 5373.8] Å. We were able to identify the following emission lines: Hβ, [OIII] doublet, and Fe II.

Figure 10 shows representative spectra extracted from the three regions in the wavelength region [6498.8, 6998.8] Å. We were able to identify the following emission lines: Hα, [NIII] doublet, and [SII] doublet.

Dashed lines are placed where we expect to observe some of the most common and brightest emission lines, retrieved from table II. As expected these lines are visible and bright, excluding Fe II which was only slightly visible in the lower arm. However, the central wavelength of the different lines does not always correspond to the ones estimated. Especially the spectra extracted from the regions of the galaxy arms, which deviate more than the spectrum from the nucleus.

I suspect it is due to the galaxy's kinematics, NGC 1365 is a rotating galaxy [14]. When calculating the observed wavelengths we only took the cosmological redshift into consideration.

In this case, the wavelengths are elongated ("redder") due to the universe's expansion and not due to the motion of the gas. We could have included the Doppler shift, though I am not sure how much of a different result we would be able to obtain. I would say what we have done now is sufficient. We note a couple of differences between the three spectra. The nucleus and the upper arm of NGC 1365 has more emission of Hα compared to the lower arm. [OIII]λ5007 dominates in the region on the outer upper arm, as well as Hβ. The other emission lines were rather faint.

C. Total emission map of Hα and O[III]

Figure 11 and 12 show the continuum map of Hα and [OIII]. From information obtained from the spectra, we expect the nucleus and upper arm to be some of the brightest features in the Hα map. For the [OIII] map we expect the upper arm to be some of the brightest features. Spectral ranges used to integrate the line emissions to produce the corresponding maps were: $\lambda \in [6589, 6609]\mathring{A}$ for Hα and $\lambda \in [4096, 5016]\mathring{A}$ for [OIII]λ5007 ([OIII] hereafter). I chose a margin of 10Å on both sides of the Hα line, which was enough to isolate the line and exclude the contribution from the [NII] doublets. I did the same for [OII], which looks already well isolated. However, this may not have been the most accurate method to do so. It was done in Python and as mentioned earlier, Python does not allow for visualization as you are working with the data. I should rather have done it in QFitsView as it allows us to see the spectra it would have made the isolation of the line easier. The program also allows us to subtract the continuum to avoid unwanted contributions from the sides.

Hα dominates in an elongated region parallel to the bar, spanning from NE to SW. This was expected. [OIII] dominates in 5 smaller circular regions near the nucleus and at the upper arm.

In the map of total Hα emission, the brightest features lie parallel to the bar, spanning from NE to SW. Hα are indicative of star-forming regions within a galaxy where surrounding gas is begin continually ionized by newly formed stars.

The brightest features in the map of total [OIII] emission are the 5 circular regions near the nucleus. Concentrated levels of OIII are found in planetary nebulae [15]. The term "planetary" refers to their planet-round shape and has no relation to planets whatsoever [16]. The faintest features in this map are on the outer part of the galaxy arms.

What I have not been able to do is estimate the RMS of the data. This is done by choosing a region that is as free as possible from emission lines and using Python's `np.std()` to do so.

VI. CONCLUSION

The purpose was to study NGC 1365 in order to learn about its features.

A continuum emission map was produced by collapsing the MUSE data cube over the full wavelength range. From this, we were able to see the spiral structure of the galaxy. The galaxy has two arms and a "Z" shaped form. We were also able to understand why it is also known as the Great Barred Spiral Galaxy, due to its central bar-shaped structure composed of stars. However, the continuum emission map should have been cropped to exclude the edges.

By studying the optical spectra, we notice a flat continuum with many emission lines. This indicates a star-forming galaxy with a lot of gas. We were able to observe the most common and brightest emission lines as expected, where Hα, Hβ, and [OIII]λ5007 dominated.

We decided to therefore further study the total emission map of Hα and [OIII], by slicing the data cube in spectral ranges $\lambda \in [6589, 6609]\mathring{A}$ for Hα and $\lambda \in [4096, 5016]\mathring{A}$ for [OIII] and collapsing the cube. From this, we saw Hα dominates in the region parallel to the bar, spanning from NE to SW. This is the part of the galaxy with the most star formation. [OIII] dominates in different circular regions near the nucleus, which may indicate locations of planetary nebulae within the galaxy.

Total emission maps could have been improved by isolating the emission lines of interest in QFitsView instead of Python. This would have provided a spectral range as QFitsView allows for visualization of the data as we are working with it. I should also have estimated the average 1σ RMS noise level of each map.

I briefly mentioned the gas kinematics of this galaxy and the fact that NGC 1365 is a rotating galaxy. This is not supported in any of the data I produced. I should have produced a map that visualized the rotation pattern of the galaxy to see it more clearly. This could have been done in the software BBarolo or Python.

ACKNOWLEDGMENTS

I want to thank myself for writing this beautiful document.

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