

The relation between stars and gas in distant galaxies

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Optical and spectroscopic observations of galaxies provide a way to understand the internal dynamics of the stars and gas within it. Data for the Hubble Ultra Deep Field (HUDF) from the Hubble Space Telescope and the Multi-Unit Spectroscopic Explorer (MUSE) on the VLT provides a potential sample of more than 10,000 galaxies. This data-set was reduced by considering objects with redshifts $z > 0.3$ and with V-band magnitudes brighter than 25.0 mag. The ~ 30 remaining galaxies were extracted and then analysed by fitting for different regions of the galaxy spectra. The [OII] emission feature could be separated and fitted with a Gaussian doublet to represent the gas dynamics. Applying a Penalized Pixel-Fitting method (pPXF) to the entire spectrum could quantify the stellar dynamics, however various issues were encountered in this initial research which prevented the successful operation of the fitting routine. Various tests were performed and a different spectral template library was applied in an attempt to remedy the problems. The next step in future work will be based around isolating the source of the issues and then further extending the routine to consider variations to the spectra.

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1. INTRODUCTION

1. Hubble sequence and the local Universe

The classification of galaxies into the three general groupings of ellipticals, spirals, and irregulars was initially performed by Edwin Hubble in 1926 (Hubble 1926). A sample population of 400 extra-galactic objects were classified and sorted by their morphological features into the groupings which are still used to this day. Ellipticals can be codified by their ellipticity (E_n) starting from non-elliptical E0 and running in integer steps until high ellipticity galaxies E7. Spiral galaxies have values of ellipticity greater than E7 and are subsequently defined by their structures. The first feature considered is whether a spiral galaxy contains a horizontal bar which runs through the central galactic nucleus, if they do then they are barred spirals (SB), but if they do not then they are “normal” spirals (S). Hubble then further sequenced the two categories by looking at: *a*) the relative size of the unresolved nuclear region, *b*) the extent to which the arms are unwound, and *c*) the degree of resolution in the arms. This led to the spiral classification of “early” (Sa, SBa), “intermediate” (Sb, SBB), and “late” types (Sc, SBC). Finally, irregulars contain galaxies which do not fall into ellipticals or spirals as they appear to lack both dominant nuclei and rotational symmetry.

Hubble’s classification provides a comprehensive overview of the morphological natures of various types of galaxies, Figure 1 demonstrates this categorisation in the form of the Hubble Tuning Fork. It must be understood however, that the sample of galaxies used by Hubble was from the local redshift $z = 0$ Universe

2. Dynamical studies of galaxies along the Hubble sequence

1. *Evolution of galactic dynamics*
2. *Tully-Fisher and Faber-Jackson relationships*

3. High-redshifts

1. *Galaxy formation models*
2. *Stellar formation*
3. *Gas collapse in dark matter halos*
4. *Evolution of scaling relations*

4. The Hubble Ultra Deep Field

1. *HST*
2. *MUSE*
3. *Testing the local-Universe scaling relation*

5. Project

2. OBSERVATIONS AND DATA ANALYSIS

1. **HST HUDF**
2. **MUSE HUDF**
3. **DISCUSSION**

1. σ_* vs. σ_{OII} & V_* vs. V_{OII}

2. Voronoi

Amongst the different types of cosmic structure within our universe, galaxies can be described as the most unique and diverse. With each containing countless numbers of stars and vast amounts of gas, dust, and dark matter (Carroll and Ostlie 2007), it would be surprising if these various inner objects were not connected in any way.

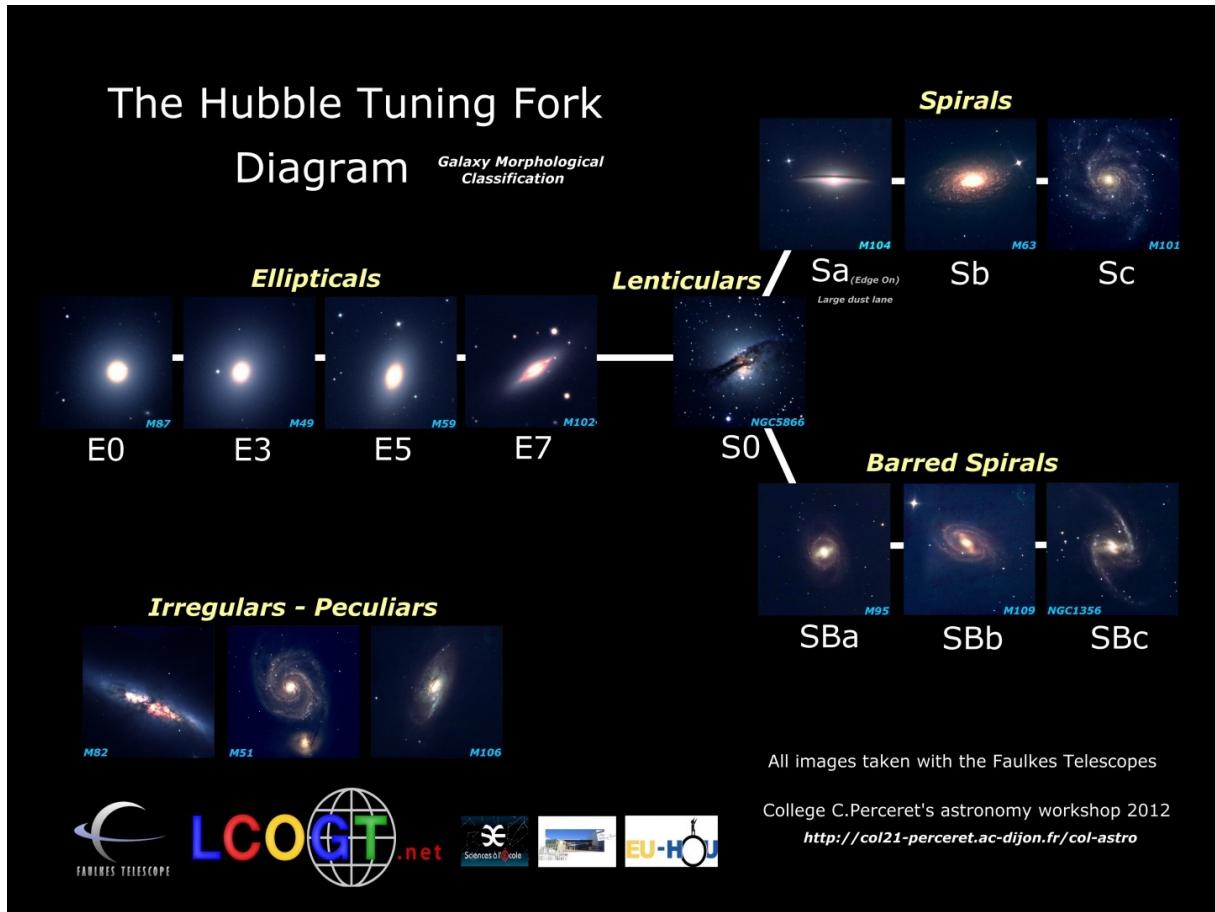


Figure 1: The Hubble Sequence can be demonstrated graphically with the Hubble Tuning Fork. This diagram (Astronomie au collège PERCERET 2012) illustrates the different morphologies of galaxies and their classification into three the groups: ellipticals, spirals, and irregulars.

Through observational astronomy the internal structure of galaxies and the motions of the internal objects can be studied and understood. With approximately $(2.0^{+0.7}_{-0.6}) \times 10^{12}$ galaxies in the universe up to redshift $z = 8$ which in principle could be observed (Conselice et al. 2016), there is definitely not a lack of choice. What is important is how these objects are observed and how the collected data is later analysed.

The initial step one must take though is to understand the basics, therefore developing a comprehension of what a galaxy generally is and how they can be defined and placed into different categories. Once an appreciation is built for galactic classification, the intricacies of the inter-relationships can be explored further.

3. Galactic classification

As stated previously, a galaxy can be quite broadly defined as a collection of gas, dust, stars and dark matter. But if a large enough sample was observed then one would begin to see that galaxies can be grouped and classified together.

The most general categorisation is called the *Hubble Sequence* or the *Hubble Tuning Fork* (Carroll and Ostlie 2007). Developed by Edwin Hubble in 1926, galaxies can be roughly divided into ellipticals, spirals and irregulars (Fig. 1). With early Hubble type ellipticals along the horizontal handle, then the two prongs contain normal and barred spirals (later Hubble types), and irregulars form the third category. What can be seen from the Tuning Fork is a summarised view

of the main galaxy types. However, in reality, there are more than the 11 groupings named.

The sequence itself does not show the evolution of the galaxies, rather it provides a way to view the different potential morphologies. So then, what does each grouping from the sequence actually represent?

Starting with the most broad, irregulars are objects which do not fall into the two main galaxy types (ellipticals and spirals). Nevertheless, irregulars can in fact be split into two sub-categories depending on if a particular galaxy appears to have structure, such as spiral arms (Carroll and Ostlie 2007). If there is structure then they would be Irr I galaxies, and if they appeared to be extremely disorganised then Irr II. Generally, irregulars are not particularly large, their diameters typically range from 1 to 10 kpc, and they have an absolute B-band magnitude of -13 to -20 mag.

This classification by appearance can easily be extended to ellipticals and spirals, and their individual component composition can additionally be studied and explored.

With ellipticals, they span from being virtually spherical (E0) to highly flattened (E7) collections of objects and material (Moore and Rees 2011). Through observations of their stars, it can be seen that the majority of them are old, red types. This may be attributed to the amount of gas used in the initial stages of galactic stellar formation. If a larger proportion was used up initially then current observations would show the stellar-birthrate in ellipticals to be low (Carroll and Ostlie 2007). This could additionally explain the lack of disks which can otherwise be seen in spiral galaxies, if there is not enough surrounding material then the disk and arms features would not be able to form.

Exploring spirals, they can be described as being composed of a central nucleus with a surrounding disk of material. This disk contains denser regions which forces matter to collapse and coalesce to form additional features. One particular spiral char-

acteristic leads to a supplemental classification group, and that is whether the nucleus has a “bar” running through it. Observing and comparing the two different types, one finds that barred spirals appear to be more elongated along the bar axis than their non-barred counterparts.

The other main attribute for spiral galaxies are the protruding arms surrounding the main bulge (Carroll and Ostlie 2007). In the later type spirals (Sc and SBc) they have arms which are more loosely wound than the earlier types (Sa and SBa) (Moore and Rees 2011).

It can be seen then that with more available “raw” gas and dust (Carroll and Ostlie 2007), spirals in their various forms could be assumed to have an overall younger stellar population. It is within the arms of spiral galaxies that new stars are found to be created, however stellar birth is definitely not limited to just these regions. Inside the spiral structure the gravitational field allows for angular momentum to be transported outwards. Older and less massive stars in the galaxy produce a gravitational field which eventually leads to the shocking of interstellar gas (Binney 2016). As a result the density of the gas in the arms increase and certain regions then collapse to form new, young, blue, and massive stars.

There is therefore a range in the age of the stellar population in spiral galaxies. The spiral arms contain young stars whilst the central nucleus is akin to that of elliptical galaxies where they have an older population of stars and fewer new stars are born (Binney 2016, Carroll and Ostlie 2007).

These then are the general characteristics of galaxies, and whilst they can be classified based on their appearance, it is through studying their stellar populations that our understanding of them improves.

4. Galactic stellar formation

One could argue that the main backbone in any galaxy lies with the gas and dust as without them there would be no stars

and galaxies would simply not exist. There are many models which aim to provide an explanation for galactic evolution, from an initial proto-nebulae to structure. It would be difficult to detail them all, but beneficial to at least address some issues which would have to be answered by a comprehensive galactic evolution theory.

One problem is deciding if an initial nebula collapses in free-fall or whether it goes through a slow and dissipative collapse (Carroll and Ostlie 2007). If the time taken to cool the nebula significantly (cooling timescale) is much less than the time taken for free-fall, then the cloud would not be pressure supported and the collapse would be a rapid free-fall. On the other hand, if the cooling time exceeds the free-fall time then a rapid collapse cannot occur as the gas cannot radiate its energy away fast enough, therefore the gravitational potential energy released from a collapse will heat the nebula adiabatically.

This is important to understand as from the heated and collapsed gas, the first stars can then be produced. It is not surprising then that a theory for galactic evolution should also be able to explain the rate of star formation. This rate can be described as a stellar birthrate function, $B(M, t)$, and be expressed as,

$$B(M, t)dMdt = \psi(t)\xi(M)dMdt, \quad (1)$$

where $\psi(t)$ is the star formation rate (SFR), $\xi(M)$ is the initial mass function (IMF), M is the stellar mass, and t is time (Carroll and Ostlie 2007).

Describing the physical meanings of the key terms: $B(M, t)$ is the number of stars per unit volume with masses between M and $M + dM$ which are formed out of the interstellar medium (ISM) between time t and $t + dt$, $\psi(t)$ is the rate per unit volume at which mass in the ISM is converted into stars, and $\xi(M)$ is the relative number of stars which form in each mass interval (Carroll and Ostlie 2007).

Additionally, assumptions can be made by researchers which subsequently leads to varying results (Carroll and Ostlie 2007).

Some astronomers say that the SFR is time-independent, whilst others describe it as exponentially decreasing with time, and a few even argue that it is proportional to a power of the surface mass density of the galactic disk. Then take the IMF, there is disagreement on the exact form it takes, some model it to be a power-law as a function of mass, but it is not clear if it also varies with time or location.

Through contentious debate and research, astronomers can continue to build these different models and theories which attempt to explain galactic evolution. Whilst on the other hand, the evolution of the stars themselves are known and better understood.

In a brief overview: stars are born from an interstellar medium where the gas and dust coalesce, collapse and heat-up until a protostar is created. Depending on the initial mass of material used, the star can then take various paths which will affect its subsequent future (McCoy 2012). To view the different stages of stellar evolution, Hayashi tracks and a Hertzsprung-Russell diagram can be paired together (Carroll and Ostlie 2007). In doing so, one would find that the majority of stars lie on the main-sequence, including our own Sun.

Type	Colour and notable lines
O	Hot blue-white (HeII, HeI)
B	Hot blue-white (HeI, HI)
A	White (Balmer, CaII)
F	Yellow-white (CaII, FeI, Cr,I)
G	Yellow (CaII, FeI, neutral metals)
K	Cool orange (CaII H and K, metals)
M	Cool red (TiO, VO, neutral metals)
L	Very cool, dark red, infrared (Molecular absorption, CrH, FeH, H ₂ O, CO, Na, K, Rb, Cs)
T	Coolest, infrared (CH ₄ , CO)

Table I: The Harvard Spectral Classification for stellar objects. Stars are defined by their colour and from the features seen from their spectra. Provided in the table are the spectral type, the associated colour plus the main emission or absorption lines to consider.

(*Table adapted from An Introduction to Modern Astrophysics by Carroll and Ostlie (2007).*)

The classification of stars can be made with the *Harvard Spectral Classification* where stars are classed by their spectral types (Table I). It essentially orders stars by their observed temperature and their internal composition. If a star's spectra was observed, it could be identified by the absorption and emission features found in the sequence.

This therefore is one of ways to study the stellar population of a galaxy as the signatures of different spectral types can be matched up in a particular galaxy spectra.

It is clear then that observational data would be required for own study of galaxies and the internal motions of the objects within them.

5. Galactic data

For an investigation of galaxies, one would have to collect data optically and also spectroscopically. The former would be useful as it would allow for a quick identification of the galaxy based on its appearance, this could then be used to infer whether a galaxy would be worth studying. Spectroscopic data on the other hand would be important as a variety of information could be obtained such as the type of stars within a galaxy, the types of gas in the surrounding clouds, and also numerical values such as the redshift z .

Astronomers on a daily basis employ an assortment of telescopes and spectrographs, but there are a few in particular which are worth discussing as they have produced remarkable datasets.

1. HUDF

The Hubble Space Telescope (HST) has been operating since April 1990 and for the duration of that time it has collected over 50 terabytes of data (McCoy 2012). From observing nebulae to attempts to detect extra-solar planets, HST has been used in a variety of searches. However, one of the most impressive and insightful uses of HST was the collection of the long-exposures taken in 1996 to produce the Hubble Deep Field (HDF).

Through a combination of its visible and infrared cameras, the HDF was produced by piecing together different datasets which were collected over a period of 10 consecutive days (McCoy 2012, Williams et al. 1996). The four-band, 0.5 million s exposure revealed sources with redshifts $z > 1$ which would have been difficult to view from ground-based observations (Beckwith et al. 2006).

It is therefore unsurprising that another attempt was made in 2011 which resulted in the Hubble Ultra Deep Field (HUDF). This survey utilised 1 million s of exposure time on an 11 arcmin² area in the southern sky. Viewed again with four different filters, this survey resulted in at least 10,000 objects being detected in the field (Beckwith et al. 2006). With a large majority being galaxies, the HUDF would be a prime dataset for a galactic study as there is such a large range of candidates which span the universe's history.

2. MUSE

In addition to optical observations, as noted previously, spectroscopic data should also be employed in a study of galaxies. One particular instrument which was used to acquire data on the HUDF region is the Multi-Unit Spectroscopic Explorer (MUSE) mounted to the Nasmyth platform on the Very Large Telescope (VLT) (Henault et al. 2003).

The MUSE Hubble Ultra Deep Field Sur-

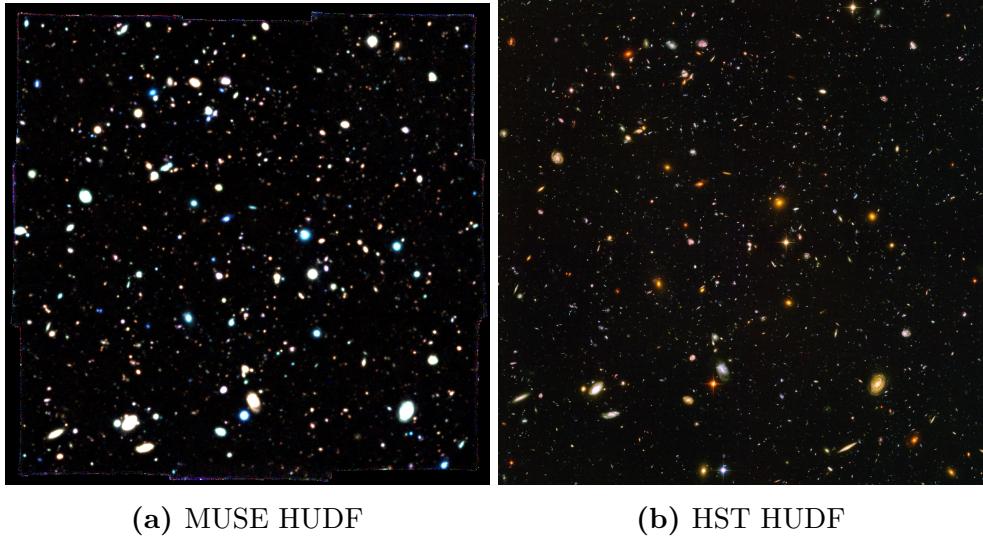


Figure 2: (a) A colour image created from the MUSE spectroscopic data of the HUDF. The spectra wavelength range was split into three equal regions and then collapsed to create three colour bands (R, G, B). A final colour image was produced by combining these separate frames together. (b) The optical HUDF as captured by the Advanced Camera for Surveys instrument on the Hubble Space Telescope (NASA et al. 2018).

vey was performed over a two year time-frame from September 2014 to February 2017 (Bacon et al. 2017). It made use of 137 h of observation time and covers 90% of the HUDF region. The 3D composite data cube mosaic made use of nine fields and represents the deepest spectroscopic survey ever performed. Both HST and MUSE HUDFs can be optically compared together, the latter is achieved by collapsing the cube axis containing the spectroscopic data into three components representing (R,G,B). Looking at both images (Figure 2), the HST data appears to have more resolution whilst the MUSE objects are smeared out. However this is of no particular issue as the main use for MUSE is the manipulation of the spectra data which in turn will inform us on the optical data.

Through a coupling of both, the dynamics of stars and gas in galaxies can therefore be studied. The main analysis arising from the manipulation and comparison of different component areas of the spectra.

6. Project Aims

This paper discusses the study undertaken to understand the dynamics between the gas and stars in galaxies. Data extraction is performed on a MUSE data cube, the sample is reduced, and various fittings are then applied to the dataset.

In Section 4, the methodology of galaxy extraction from the MUSE cube is discussed, as well as the subsequent analysis performed by applying different fitting routines: [OII] Gaussian doublet fittings, and fitting with a penalised pixel-fitting method.

4. ANALYSIS

The initial goal in the analysis was to reduce down the MUSE data cube into smaller cubes which contained individual galaxies. These could then be collapsed to produce a single galaxy integrated spectrum to represent the dynamics of the entire galaxy. Subsequently different fitting routines could be applied which would allow for a comparison of the gas to the stars in a galaxy.

1. Cube extraction

To begin with, galaxies were identified from the 3D MUSE cube using *SExtractor*; an automated routine which detects, de-blends, measures and classifies sources (Bertin and Arnouts 1996). Employed in the astronomical software package *GAIA* (Currie et al. 2013), every potential galactic source was retrieved along with a “segmentation map” which discerns between multiple galaxies if several are close together.

The final object list from SExtractor were compared and merged with a catalogue which contained every object identified in the HST HUDF frame. The latter would contain information such as initial guesses for redshifts, the magnitudes of the objects in the different wavelength filters, and various flux values for different emission and absorption lines.

With every extracted galaxy, the signal-to-noise (S/N) could be calculated with the flux values from the catalogue. This was then plotted against the V-band magnitude (Figure 3(a)), and one should find that as the S/N increases, the object should become brighter. A similar trend is also found if the S/N was measured using regions of the galaxy-integrated spectrum (Figure 3(b)). The “signal” calculated by taking the median of the region and the “noise” as the standard deviation of a separate sky spectra. Both plots agree which implies that further analysis on the extracted galaxies should in theory produce sensible results.

2. Line fittings and pPXF

After identifying the individual galactic objects from the MUSE cube, the spectroscopic data could then be extracted, manipulated and analysed by using different fitting routines: (i) [OII] doublet fittings, and (ii) *pPXF* absorption and emission line fittings.

It would be quite non-sensical to use the entire catalogue of objects as there are

more than 10,000 plus the majority are not high enough in S/N for spectra evaluation. Therefore several sample reducing methods were applied: (1) galaxies were sorted by redshift and then objects below $z < 0.3$ ignored, (2) sample was then re-sorted by V-band magnitude and just the top 300 brightest objects extracted, and finally (3) the final set was found by considering galaxies with a magnitude brighter than 25.0 mag.

With the reduced sample in hand, the model fitting analysis could then be performed.

1. Gaussian doublet fitting

Through collapsing the entire galaxy into a single spectrum, one should find the [OII] doublet emission line to be the most prominent feature due to its large amplitude when compared to other spectral lines (Figure 5). This therefore allows it to be a useful tool for estimating the SFR, which in turn can be used as an indication of the evolutionary state of the galaxy (Maddox 2018).

For every doublet fitting performed, the region $3600 \times (1+z)$ Å to $3750 \times (1+z)$ Å was extracted to isolate the peaks from other absorption or emission features. The peaks themselves have rest wavelengths 3727.092 Å and 3729.875 Å (Abazajian et al. 2004).

The following was applied as the model,

$$f_{\text{[OII]}}(x) = c + \frac{I_1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x - L_1)^2}{2\sigma^2}\right) + \frac{I_2}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x - L_2)^2}{2\sigma^2}\right), \quad (2)$$

where x are the redshifted wavelengths, c is a constant, I_1 and I_2 are scaling factors, L_1 and L_2 are the [OII] peaks multiplied by $(1+z)$, and σ is the quadrature sum of the fixed instrumental resolution σ_{inst} and the deconvolved width of the doublet σ_{gal} ($\sigma = \sqrt{\sigma_{\text{gal}}^2 + \sigma_{\text{inst}}^2}$).

After a successful fitting, the following variables would be outputted: c , I_1 , I_2 , z , and σ_{gal} . The latter two would become the most useful in later research.

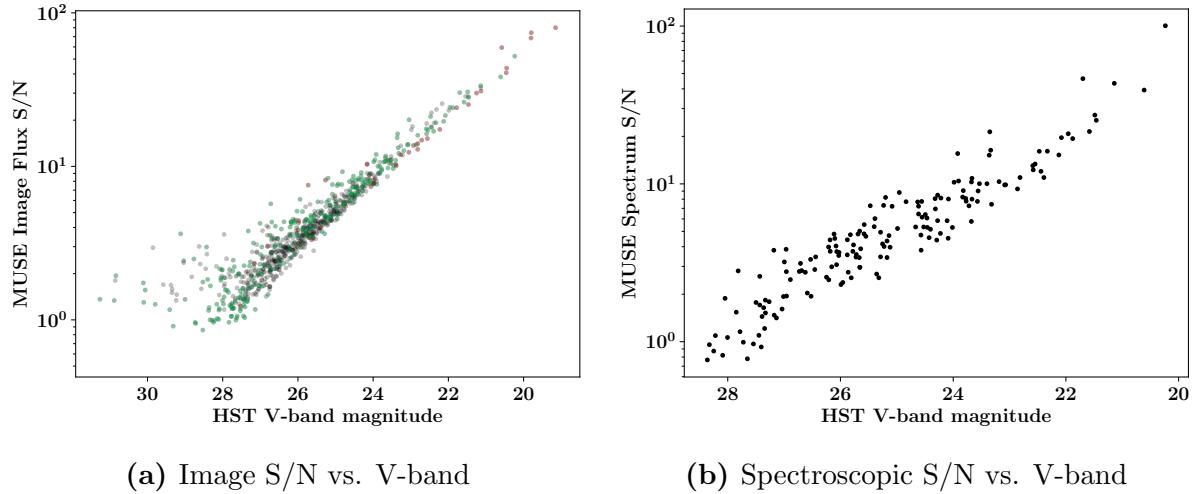


Figure 3: Signal-to-noise (S/N) versus V-band magnitude plots for the MUSE galaxy objects. The V-band magnitudes are from the HST catalogue. (a) S/N is from the collapsed MUSE cube image. The red points represent those with redshifts $z < 0.3$, and the green points are a chosen sample of 300 as defined by the SExtractor probability that they are not stars. (b) S/N used here is from the region $3700 \times (1+z)$ Å to $4500 \times (1+z)$ Å in the galaxy integrated spectra. Objects in this sample are those defined as the “green points” in Figure 3(a).

The redshifts along with the [OII] flux $f_{\text{[OII]}}(x)$ can be used to calculate the luminosity for the doublet, this luminosity can then be plotted against the redshifts (Figure 4). What can be found is a general agreement that the galaxies follow the luminosity-redshift relation, thus the calculated parameters are sensible so they can be applied to other analysis routines.

2. *pPXF fitting*

With the gas dynamics of galaxies represented through the width of the [OII] doublet, a comparison to galactic stars would require the width of the stellar spectra features. To obtain this, a Penalized Pixel-Fitting method (pPXF) can be applied, Cappellari (2017) describes the method and implementation in the form of a Python library *pPXF*.

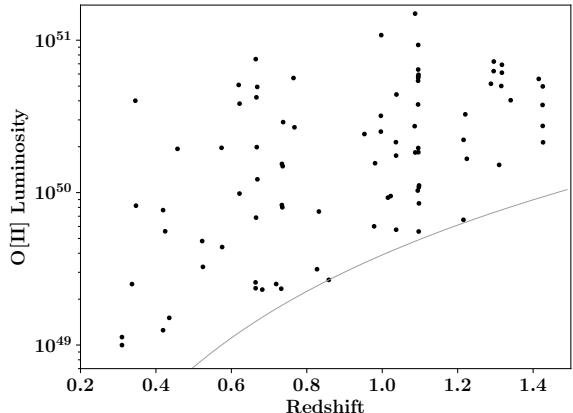


Figure 4: [OII] luminosity plotted against redshift. Variables used for each galaxy were obtained from the fitting of the galaxy-integrated spectra with a model (Equation 2). The line represents the lower-limit of the sample as it was calculated using the galaxy with the smallest flux. All galaxies in the set are above this line and approximately follow the luminosity-redshift trend.

A reasonable initial test would be to pass an entire galaxy spectrum to the kinematics fitter and then examine the output to check if it seems reasonable. As well as a final model spectrum (Figure 5), pPXF also

outputs its optimal variables and amongst them includes a velocity dispersion. However for these values and results to be comprehensible, one must be aware of what initial parameters are being passed to the fitting routine.

An estimate of the redshift can be obtained from the previous [OII] doublet modelling, an instrumental resolution can be found by fitting a single Gaussian profile over the peak at $\sim 6300 \text{ \AA}$ in a spectrum of the sky noise, and different template sets can be passed to the routine.

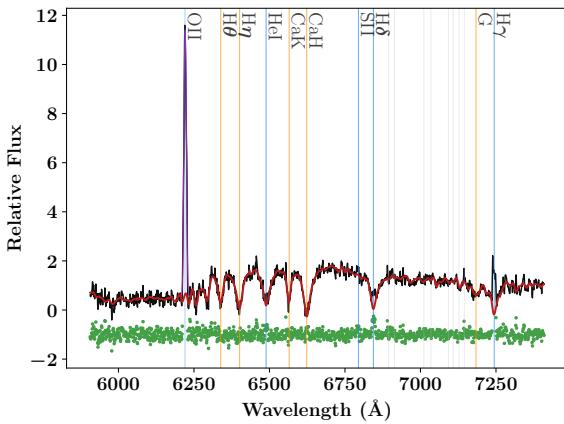


Figure 5: A pPXF fitting for a galaxy spectra. The galaxy data (black) and the best-fitting model (red) were normalised in the flux to avoid numerical errors during the fitting routine. The emission (blue lines), absorption (orange lines), and iron (grey lines) features have been labelled for easier recognition. The residuals between the data and model are provided by the green scatter points below the spectra. pPXF appears to produce good fits from manipulating various stellar templates.

Whilst it may seem trivial to configure these values, the results obtained have not been logical. Using pPXF to estimate the gas population of a galaxy, an additional value can be obtained for the width of the [OII] doublet. This therefore allows us to plot both against each other where one should find a 1-to-1 positive linear trend. What is found instead is that both are not correlated (Figure 6) which is a non-sensical result.

In an attempt to remedy this issue, several options were explored. The first of which was to artificially create the [OII] feature with a known width and then apply pPXF, the output of this test resulted in yet again a meaningless result. It was then decided that the template spectra being used in the routine were not high enough spectral resolution, ideally one would use a set which has a greater value than the resolution of the MUSE data.

The initial template sets tested were the MILES stellar population models (Vazdekis et al. 2010) and those by Jacoby et al. (1984), but these were found to be too low-resolution. The SYNTHE spectral library (Munari et al. 2005) has an incredibly high resolution of $R = 20,000$, however it was difficult to integrate this into the pPXF routine. What was decided on was the Indo-US Library of Coudé Feed Stellar Spectra (Valdes et al. 2004) library with $R \sim 4200$, this should be high enough to not produce additional problems.

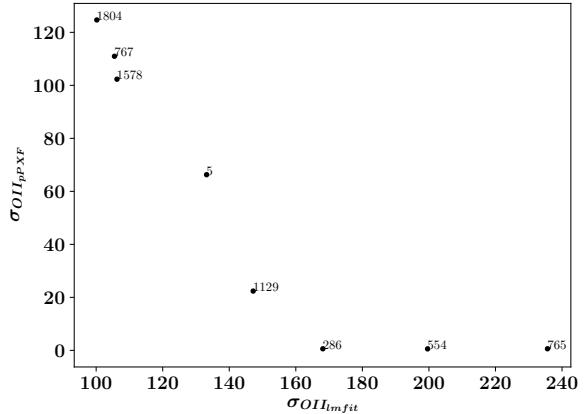


Figure 6: The widths of the [OII] doublets obtained from the Gaussian modelling (labelled *lmfit*) plotted against the widths found from the gas population fitter in pPXF. A linear trend is expected, however a failure in the set-up of pPXF has produced the illogical results as shown in the plot.

The Coudé library has yet to be fully tested as other limitations of pPXF were explored. One question which arose was what are the computational limits of pPXF? Amongst the variables outputted, there are

associated uncertainties on those values. How could they be trusted?

Another synthetic test of pPXF was performed where 10 galaxy spectra were each perturbed 300 times. Random Gaussian noise was added sequentially until the spectra were unrecognisable. During each perturbation the spectra was passed to pPXF and all associated outputs were saved and recorded. This allowed for the S/N to be plotted against the modulus difference between the original optimal line width and the values from the perturbation (Figure 7). One finds that as the S/N decreases, the difference (or fractional error) increases dramatically. This is attributed to the fact that there would not be enough resolution for emission or absorption features to be discerned. It can be seen then that one must use data with a high enough S/N for pPXF to be above this high error zone.

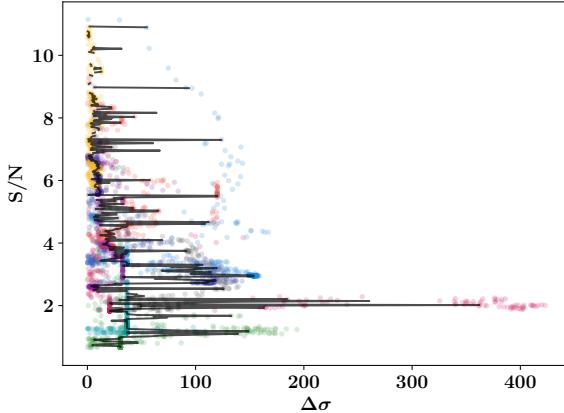


Figure 7: Signal-to-noise versus the modulus difference between the optimal pPXF velocity dispersion and the values from the perturbed models. As the S/N decreases, the difference increases manifold which implies that high S/N galaxies should be used as they would have smaller fractional uncertainty.

Whilst it can be understood what type of data should be passed to the pPXF routine, the routine itself still needs more unravelling if accurate and precise results are wanted in the comparisons of gas and stellar dynamics in galaxies.

5. CONCLUSIONS

In conclusion, the dynamics of gas and stars within galaxies can be explored by analysing their spectra. Through reducing down the MUSE HUDF galaxy sample from $\sim 10,000+$ to a small handful, the individual galaxies can have their [OII] peak fitted for, and then the spectra can be passed onto a stellar-dynamics fitting routine, pPXF. The key issues encountered in this stage of the project were based around the proper-running of pPXF, various tests were performed and a higher resolution template set was chosen, however the problems still remain and more work will be required to solve them.

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