

The relation between stars and gas in distant galaxies

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Level 4 Project, MPhys Physics

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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.



Contents

1.	Introduction
1.1.	Classification of galaxies
1.2.	Dynamical studies of galaxies along the Hubble sequence
1.2.1.	Angular momentum and the evolution of galactic dynamics
1.2.2.	Faber–Jackson and Tully–Fisher relations
1.3.	High-redshifts
1.3.1.	Galaxy formation models
1.3.2.	Stellar formation
1.3.3.	Evolution of scaling relations
1.4.	The Hubble Ultra Deep Field
1.4.1.	HST
1.4.2.	MUSE
1.5.	Project study and aims
2.	Observations and data analysis
2.1.	HST HUDF
2.2.	MUSE HUDF
3.	Discussion
3.1.	Galaxy velocity dispersions
3.1.1.	[OII] modelling
3.1.2.	Full spectrum modelling
3.1.3.	σ results
3.2.	Galaxy velocities
3.3.	Voronoi tessellation
3.3.1.	Tully–Fisher
3.3.2.	Faber–Jackson
3.4.	Applicability of locally derived scaling relations
3.5.	Future studies
4.	Conclusions
A.	Remaining galaxies from sample

1. Introduction

1.1. Classification of galaxies

Edwin Hubble in 1926 was the first to classify galaxies into ellipticals, spirals, and irregulars (Hubble 1926). Reducing a sample of 400 extra-galactic objects through studying their morphological features, they were able to produce the *Hubble sequence* or *Hubble Tuning Fork*.

As demonstrated by Figure 1, ellipticals are codified by E_n , where n represents the integer galaxy ellipticity ($([a - b]/a)$). E_0 equates to non-elliptical galaxies and E_7 corresponds to galaxies with the largest ellipticities.

Moving along the fork, lenticulars (S_0) were introduced as these galaxies contain a central bulge and disc but contain no visible spiral features, therefore a fourth grouping was subsequently added (Sandage 1961, 1975, Sandage and Bedke 1994).

Spirals have ellipticities greater than E_7 and are categorised by their structural composition. The first feature to consider is whether they contain a horizontal bar which intersects the central galactic nucleus; if they do then they are barred spirals (SB), otherwise they are normal spirals (S). Both of these groups are split into three additional classes: “early” (Sa, SBa), “intermediate” (Sb, SBb), and “late” (Sc, SBC) types. Early spirals feature nebulosity centred in the nuclear region and closely coiled/unresolved arms, intermediates have large nuclear regions with thin arms, and late types have an inconspicuous nucleus and highly resolved arms.

If the structural features of a galactic object cannot be equated to those found in ellipticals, spirals, or lenticulars (for example, a lack of a dominant nuclei and rotational symmetry), then they are sorted as irregular galaxies.

Subsequent identification schemes would refine and build on the Hubble sequence as larger datasets became more readily available. These would contain a greater variety of extra-galactic objects and allow for arguments such as expanding the spiral category due to the importance of rings and lenses

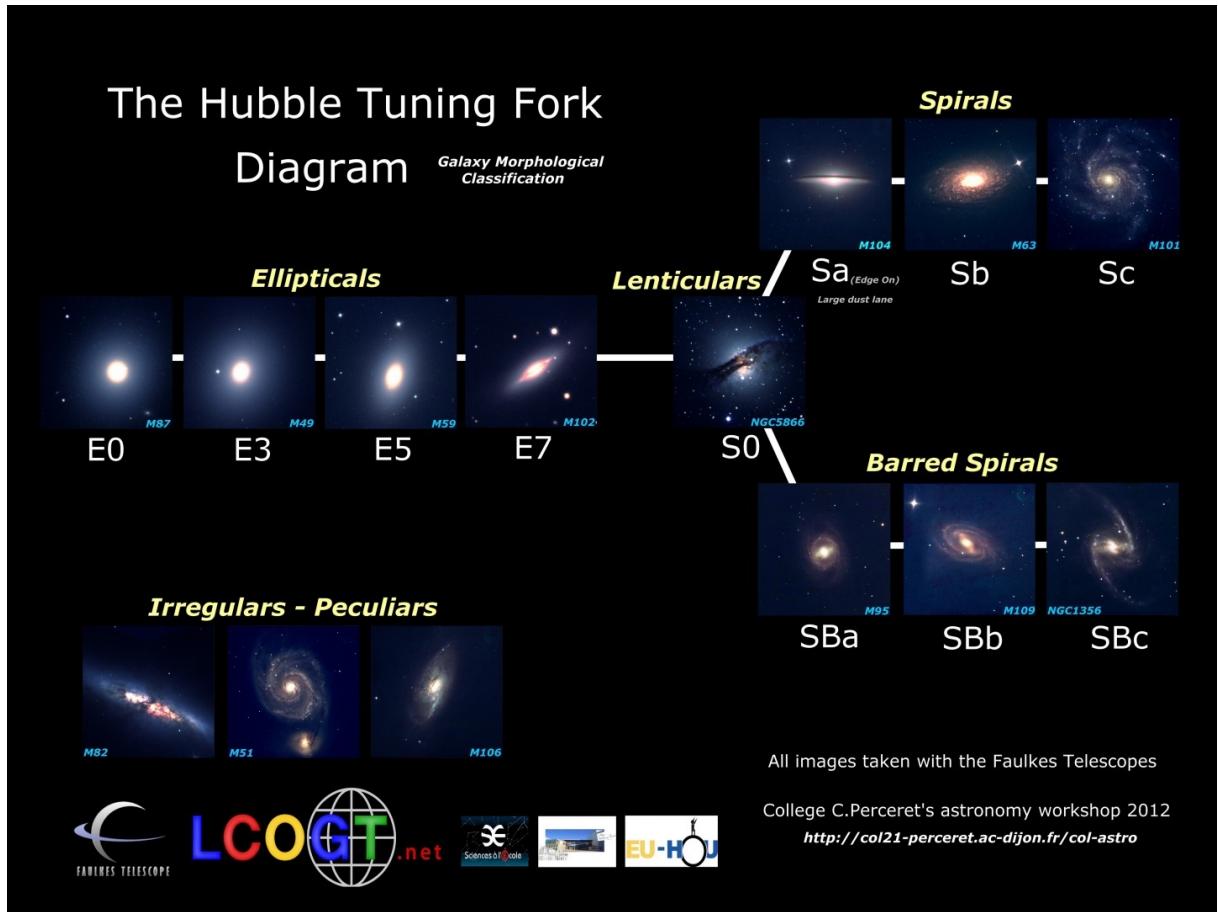


Figure 1. The Hubble sequence demonstrated graphically as the Hubble Tuning Fork (from Astronomie au collège PERCERET 2012). This diagram illustrates Hubble’s classification of galaxies by their morphologies into ellipticals, spirals, lenticulars, and irregulars.

as their defining features (de Vaucouleurs 1959).

Through Hubble’s work, galaxies are comprehensively classified by their morphologies, however these do not fully reflect the internal content of a galaxy. For an indicator of the inner dynamics, fundamental parameters should be employed in tandem with the morphological classification.

1.2. Dynamical studies of galaxies along the Hubble sequence

1.2.1. Angular momentum and the evolution of galactic dynamics

The mass, energy, and angular momentum are three physical values which are used as a quantitative classification of a galaxy.

The angular momentum is of particular interest as the defining morphologies of a galaxy is most likely a result of the

primeval mass–angular momentum distribution (Sandage et al. 1970). The acquisition of this angular momentum in a protogalactic system was proposed by Peebles (1969) to be a result of the tidal interactions with nearby protogalaxies. Within a young spiral system, these tidal torques induce galactic spin and lead to massive extended haloes if spiral discs have radii comparable to present day observations. By extension, the dynamics of these discs and their stellar populations are modelled to demonstrate that their observed sizes and rotation velocities are consistent with the conservation of early angular momentum (Dalcanton et al. 1997, Mo et al. 1998).

Measurements of galactic specific angular momentum allows for the derivation of empirical relations between the stellar component of the angular momentum j_* and

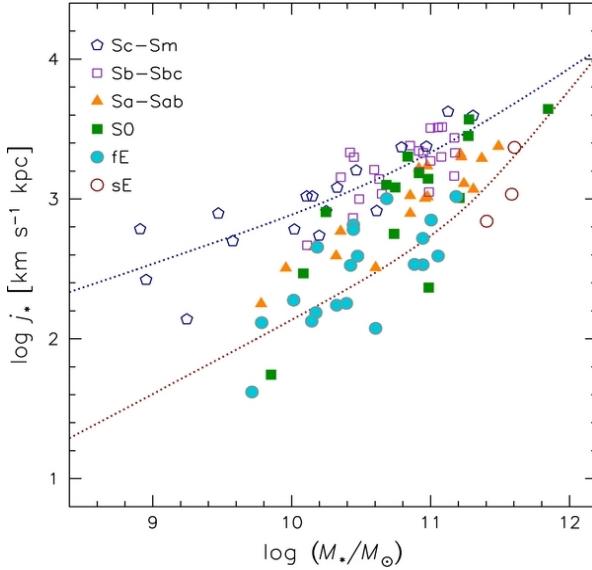


Figure 2. The total intrinsic specific angular momentum j_* against total stellar mass m_* for different galaxies (from Romanowsky and Fall 2012). Legend in upper left shows the galaxy types used. Ellipticals follow a similar relationship to spirals but with an offset of ~ 6 to lower j_* . This diagram represents one of the scaling relations for galaxies which reflect their internal dynamics.

mass M_* . These relationships can then be applied to describe the collective dynamics of galaxies (Fall 1983). If kinematic tracers are employed to measure j_* and M_* for large numbers of early-types (ellipticals and lenticulars) and late-types (spirals), then a plot such as Figure 2 reflects their dynamics by utilising independent variables and conservable physical quantities. The figure shows that both early and late types follow similar parallel trends which indicates an underlying connection between the physical parameters for galaxies.

This coupling between $j_* - m_*$ represents one of the *scaling relations* for galaxies. The importance of this particular relationship arises as it provides a fundamental scaling relation diagnostic for all galaxy types (Romanowsky and Fall 2012). With no full explanation available yet for the galaxy morphologies found in Hubble's sequence, scaling relations provide an opportunity to understand the fundamental dy-

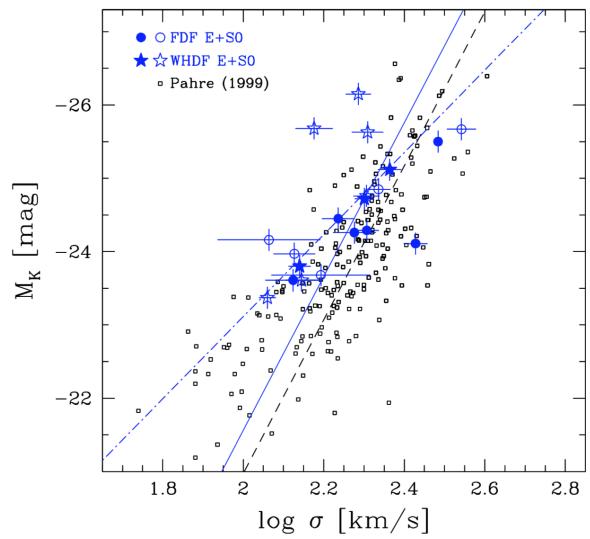


Figure 3. Faber–Jackson relation for early-type galaxies (from Fritz et al. 2009). Data contains elliptical galaxies from FORS Deep Field and the William Herschel Deep Field samples. The FJR relates the luminosity (M_K) with the velocity dispersion σ .

namics which may lead to a comprehensive model of galactic formation and evolution.

1.2.2. Faber–Jackson and Tully–Fisher relations

Despite the pairing between angular momentum and mass for various galaxy types as shown in Romanowsky and Fall (2012), scaling relations can be derived specifically for ellipticals and for spirals which would be better suited to describe their own specific properties within them.

For ellipticals, Faber and Jackson (1976) produced a scaling relation between galaxy luminosity and velocity dispersions. The latter variable was chosen because through the virial theorem, the mass of galaxies can be estimated. With the availability of larger data sets, plots such as Figure 3 illustrates the steady relationship between the luminosity and velocity dispersion. Through a well modelled Faber–Jackson relation, one potential use is to assess and understand galactic stellar populations and their evolutions (Fritz et al. 2009), an important component in galaxy modelling.

On the other hand, Tully and Fisher

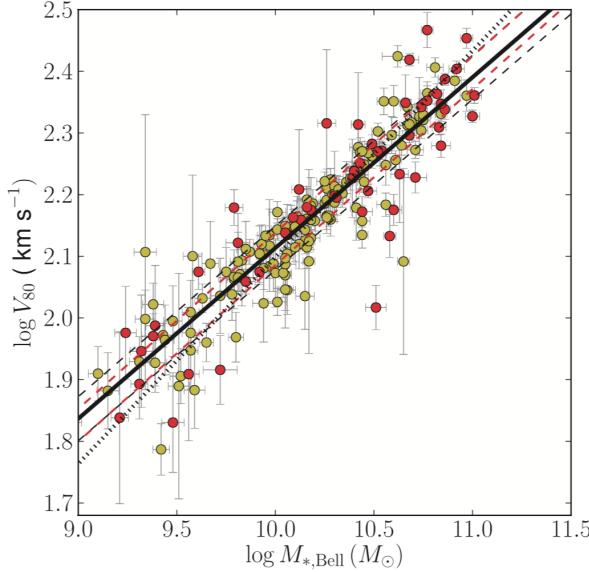


Figure 4. Tully–Fisher relation for spiral galaxies (from Romanowsky and Fall 2012). The TFR relates galaxy stellar mass M_* to the rotational velocity V .

(1977) derived a relation between the absolute magnitudes and H α emission line widths for spiral galaxies. Another form re-expresses this to couple the stellar mass and rotational velocity of a galaxy. Figure 4 demonstrates that there is a consistent relationship between these two parameters. In the production of this plot, Reyes et al. (2011) would calibrate several Tully–Fisher models to consider the contributions from galactic discs, stars, and dark matter. Through these calibrations, the Tully–Fisher relation, like the Faber–Jackson can be applied to the construction of galaxy formation and evolution models.

Both Faber–Jackson and Tully–Fisher relations (FJR and TFR) are important in galactic modelling and it would be particularly useful to verify whether these scaling relations are applicable for galaxies at high redshifts. This is a specific test of these relations as they are generally calibrated with galaxy samples at redshifts $z \sim 0$. These are preferred as the collected spectroscopic data is higher resolution than for distant galaxies. This partial bias can even be seen with the Hubble sequence, where Hubble used local galactic objects as they would provide the

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 (Cannon and Pickering 1916). Stars are defined by their colour (temperature) and features seen from their spectra (Charity 2016, Payne 1925). Provided are spectral types, and their associated colour plus the main emission or absorption lines. Figure 6 provides examples of the possible observed spectra for spectral types *OBAFGKM*.

highest optical resolution to discern the different types of morphological features.

It has been stated and repeated that the derived scaling relations can be used to support galaxy formation models. It would now be key to understand some of these models and how the relationships can be utilised within them.

1.3. High-redshifts

1.3.1. Galaxy formation models

for such as N-body interactions in large-scale galaxy cluster structures or

1.3.2. Stellar formation

1.3.3. Evolution of scaling relations

1.4. The Hubble Ultra Deep Field

1.4.1. HST

1.4.2. MUSE

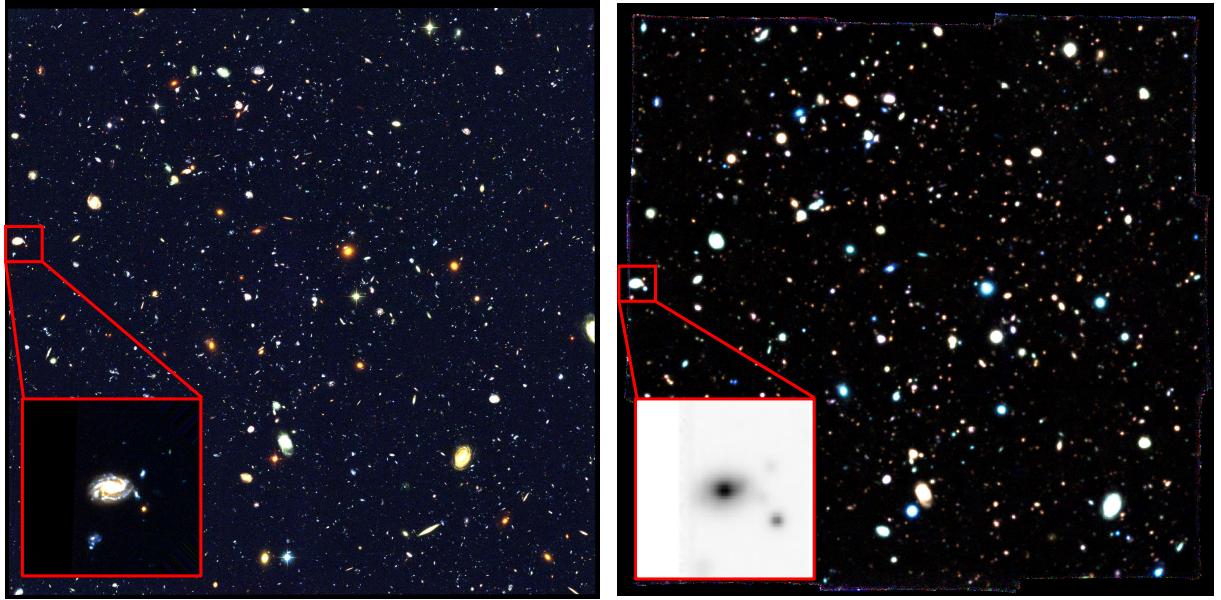


Figure 5. *Left-hand panel:* colour composite image for the HUDF from HST ACS/WFC, Hubble eXtreme Deep Field project data (Illingworth et al. 2013). Frames in three filter bands (F775W, F606W, and F435W) were combined to represent the RGB channels within a colour image. *Right-hand panel:* colour image of the MUSE HUDF region. The spectra wavelength range (4650 Å–9300 Å) of the MUSE cube was divided into three equal regions (4650 Å–6180 Å, 6180 Å–7730 Å, 7730 Å–9300 Å), collapsed, and then combined to create an RGB image. Highlighted in both images is object RAF-24420 (Rafelski et al. 2015), the HST data has a higher optical resolution whereas the MUSE data outclasses in the resolution of the spectroscopic data.

1.5. Project study and 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.

The paper is organised as follows:

In Section 3.3.5, the methodology of galaxy extraction from the MUSE cube is discussed, as well as the subsequent analysis.

3. Discussion

3.1. Galaxy velocity dispersions

3.1.1. [OII] modelling

3.3.2. Faber-Jackson

ysis performed by applying different fitting routines: [OII] Gaussian doublet fittings, and fitting with a penalised pixel-fitting method.

2. Observations and data analysis

2.1. HST HUDF

2.2. MUSE HUDF

After performing the sample reduction methods the final objects shown as *Usable* in Figure 8 can be found in Table [reference].

3.1.2. Full spectrum modelling

3.1.3. σ results

3.2. Galaxy velocities

3.3. Voronoi tessellation

3.3.1. Tully-Fisher

3.4. Applicability of locally derived scaling relations

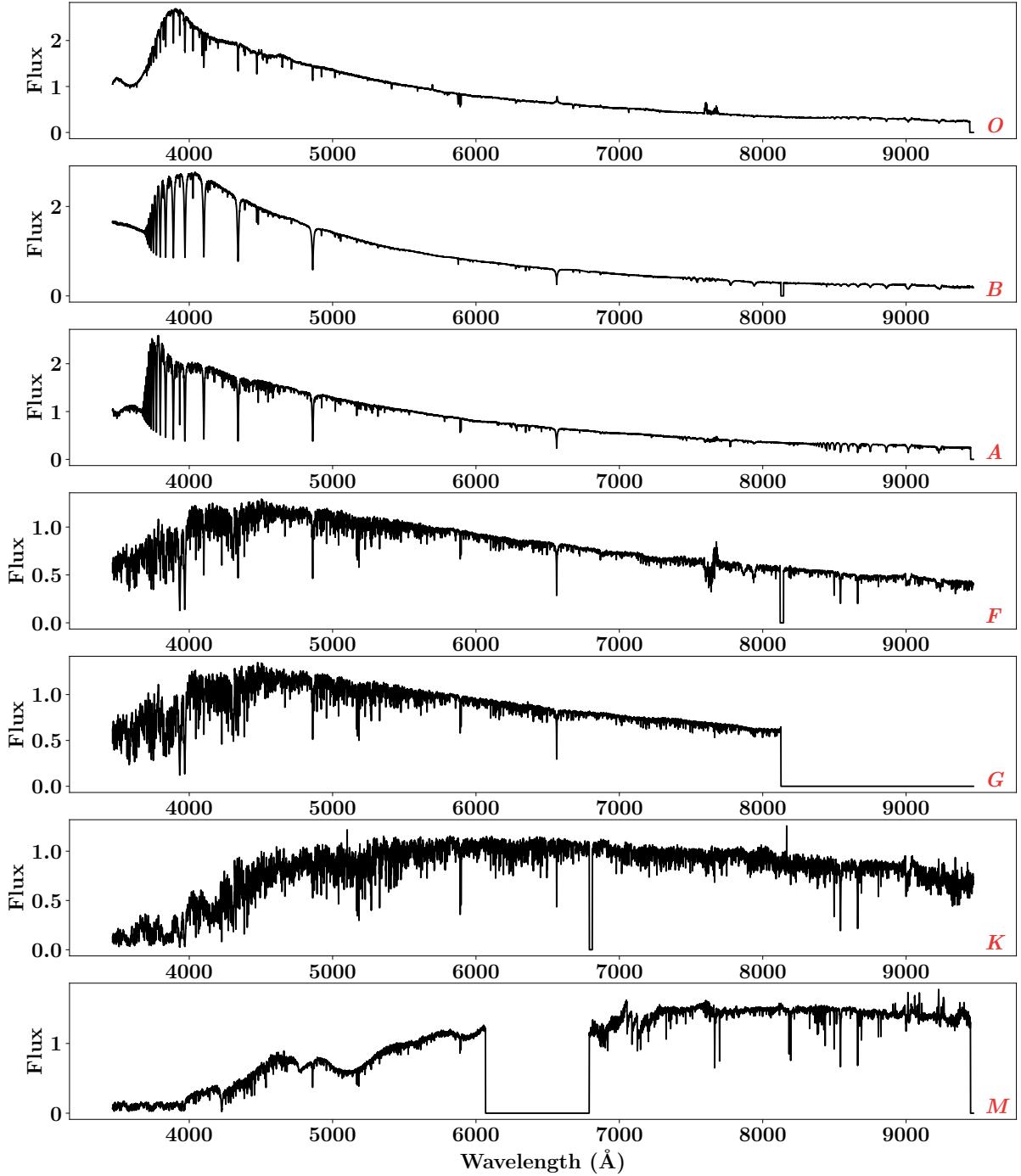


Figure 6. Example spectra for spectral types *OBAFGKM*. Taken from the Indo-US Library of Coudé Feed Stellar Spectra (Valdes et al. 2004), the stars used have metallicities $[\text{Fe}/\text{H}]_{\odot} \approx 0$ and are: 30614 (*O*), 17081 (*B*), 39866 (*A*), 5015 (*F*), G 7-6 (*G*), 5858 (*K*), and G 176-11 (*M*). These spectra demonstrate that older types (*FGKM*) have larger amounts of absorption and emission lines when compared to younger types (*OBA*) as they have spent a greater amount of time undergoing nuclear fusion. Galaxy spectra will contain combinations of these stars which produces a unique profile.

Cube ID	RAF ID	RA (deg)	Dec. (deg)	F606W mag.	z	V_* (km s $^{-1}$)	σ_* (km s $^{-1}$)	V_{OII} (km s $^{-1}$)	σ_{OII} (km s $^{-1}$)
C1804	24420	53.1783773	-27.76824447	21.4864(8)	0.66850(6)	153531(10)	182(25)	153471(24)	147(35)
C1578	22735	53.13064889	-27.79026088	21.880(1)	0.66640(5)	153185(7)	117(12)	153094(18)	139(25)
C849	21651	53.17251203	-27.79636076	22.125(1)	0.347053(5)	89414(8)	3.8(7)	89314(18)	79(24)
C286	24587	53.16992265	-27.77102451	21.1412(9)	0.62169(1)	145050(7)	58(6)	144939(17)	91(16)
C5	20595	53.15639984	-27.81081513	21.5823(8)	0.66459(2)	152807(9)	78(10)	152768(21)	110(24)
C767	21364	53.18023505	-27.79892259	21.958(1)	0.6673(1)	153328(10)	148(21)	153250(24)	141(34)
C414	7253	53.15153909	-27.76201929	22.546(3)	0.42451(5)	106177(10)	106(21)	106076(23)	128(42)
C549	24515	53.15256871	-27.76950996	22.858(3)	0.33644(1)	87049(9)	25(6)	86943(22)	85(32)
C175	8246	53.18480046	-27.777745246	23.570(4)	0.52255(2)	126111(11)	127(25)	126029(28)	82(28)
C1129	9958	53.13928756	-27.78066897	23.677(4)	0.73403(2)	165114(19)	60(15)	165020(46)	95(41)
C765	23794	53.15817553	-27.78109416	22.391(2)	0.619373(2)	144615(12)	65(12)	144512(30)	64(20)
C1075	3630	53.16129898	-27.79547518	23.720(3)	0.30988(3)	80989(11)	143(41)	80925(26)	77(38)
C540	24348	53.16236468	-27.77506443	21.4602(8)	0.41894(2)	105015(8)	60(10)	104899(19)	91(25)
C895	39778	53.14168389	-27.77310068	24.291(6)	0.52461(2)	126561(18)	0.5(2)	126434(43)	73(38)
C554	38260	53.14916378	-27.76363345	23.401(3)	0.737184(4)	165687(12)	123(20)	165565(30)	70(19)
∞	9475	53.18591136	-27.77561507	24.084(4)	1.42553(8)	-	-	-	-
C310	8531	53.16632928	-27.76858816	23.778(5)	1.29533(2)	-	-	-	-
C363	8672	53.16395412	-27.76905273	24.569(7)	0.41891(3)	-	-	-	-
C486	51705	53.18782913	-27.79405589	20.6113(5)	0.345393(8)	-	-	-	-
C254	4686	53.19373778	-27.78787018	24.572(7)	0.43534(3)	-	-	-	-
C688	5773	53.17805845	-27.79274792	25.82(2)	1.4263(1)	-	-	-	-
C759	8949	53.14617923	-27.77103939	24.108(5)	1.3155(2)	-	-	-	-
C1394	2908	53.1525505	-27.80037599	24.99(1)	1.4254(1)	-	-	-	-
C847	21703	53.17365111	-27.7973635	24.218(5)	0.66543(1)	-	-	-	-
C1665	50714	53.15110943	-27.80949195	24.552(4)	1.08753(3)	-	-	-	-
C541	24353	53.16081556	-27.77537746	22.442(2)	0.62149(6)	-	-	-	-

Table II. Parameters for the final reduced sample of 35 galaxies. Columns show the working cube ID, the ID from the UVUDF Catalogs (Rafelski et al. 2015) (RAF ID), the object right ascension (RA) and declination (Dec.), the magnitude of the object in the HST F606W filter, the calculated galaxy redshift (z), the galaxy stellar velocity (V_*) and velocity dispersion (σ_*), and the galaxy gas velocity (V_{OII}) and velocity dispersion (σ_{OII}). Note that only 15 galaxies were analysed for their stellar and gas components as the majority of the sample contained spectra with not enough signal-to-noise. 11 of the non-analysed galaxies are provided here with the rest contained in Appendix A.

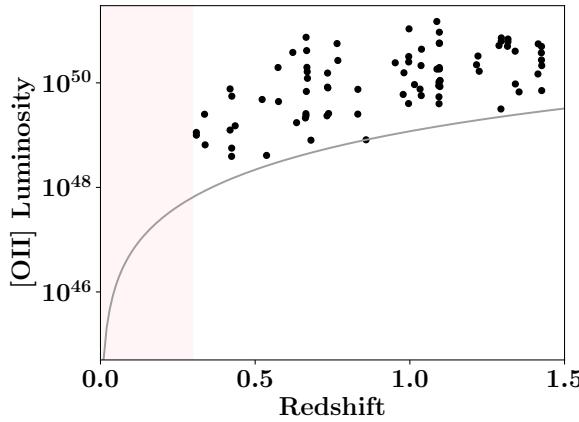


Figure 7. [OII] luminosity against redshift for 84 galaxies. Lower-limit of this sample (grey) was calculated using the object with the smallest flux. All galaxies appear above this limit and approximately follow the luminosity-redshift trend. Note that objects with $z < 0.3$ were not analysed as high-redshift galaxies were desired.

3.5. Future studies

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.

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.

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

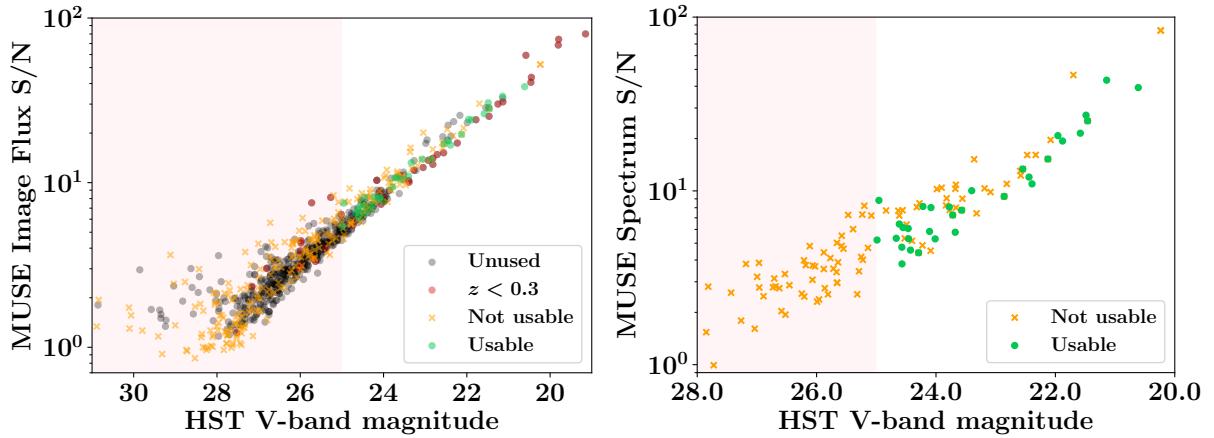


Figure 8. *Left-hand panel*: MUSE image flux signal-to-noise (S/N) versus HST V-band magnitude for the first 300/837 extracted cubes which were ranked by redshift z . *Right-hand panel*: MUSE spectrum signal-to-noise (S/N) versus HST V-band magnitude for reduced sample of extracted objects. *Both*: the red area indicates an imposed magnitude limit of 25.0 mag. The reduction of the cubes to produce the final sample was highly dependent on whether an object was actually a galaxy, if an [OII] feature was present, and whether there was enough S/N for visible absorption features. This gave rise to the “Not usable” classification as shown. From the total sample of 837 objects, this was reduced down to 35 potentially usable galaxies.

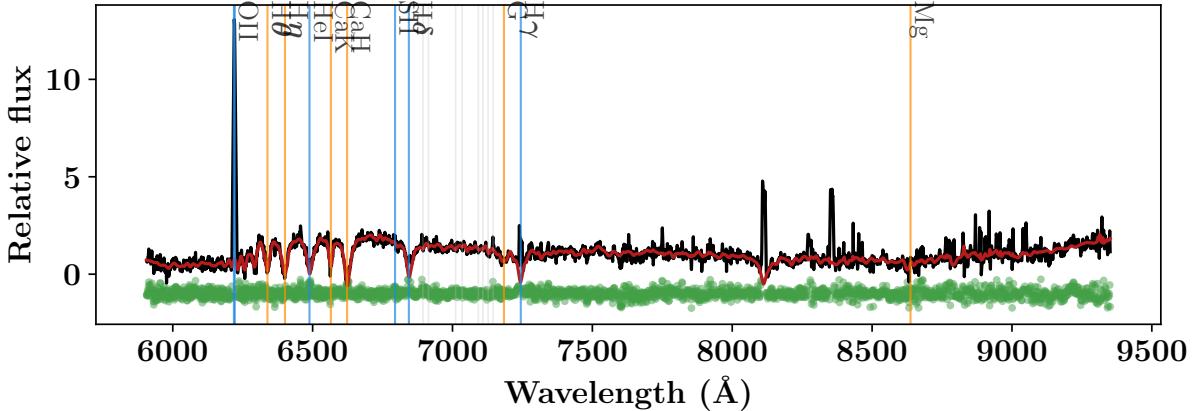


Figure 9. Example spectra and the pPXF analysis performed for C1804. The galaxy integrated spectra (black) would be passed to the pPXF fitting routine which would normalise the data and return a best fitting model (red) plus values for galaxy velocity and velocity dispersion. The residuals between the data and model (green) are shown in addition to some highlighted emission (blue), absorption (orange), and iron (grey) spectra features. For C1804 in particular, pPXF provided a reduced $\chi^2 \approx 1.69$ which is an indication of a good fit.

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 disc. Then take the IMF, there is disagreement on the exact form it takes, some model

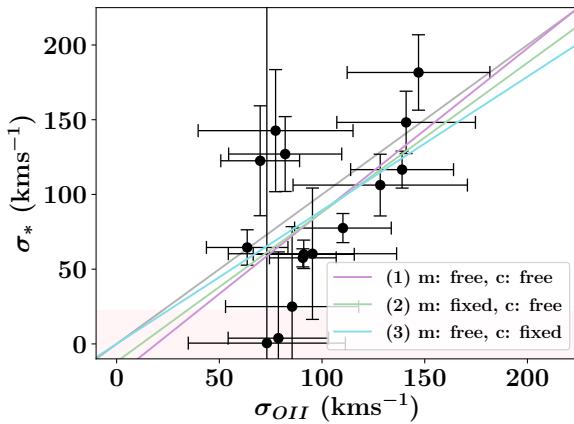


Figure 10. Stellar velocity dispersions (σ_*) versus [OII] gas velocity dispersions (σ_{OII}) for a sample of 15 galaxies. Three linear models were fitted to the data: (1) free gradient and free intercept, $\chi^2_\nu = 9.43$; (2) fixed gradient and free intercept, $\chi^2_\nu = 9.62$; and (3) free gradient and fixed intercept, $\chi^2_\nu = 5.87$. Model 3 is the best fit, and from the data a linear model appears to be the best consideration. σ_* values are limited by the instrumental resolution of MUSE and values within this range ($< \sigma_{inst}/2 = 22.7 \text{ kms}^{-1}$) should be considered with caution.

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.

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.

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.

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

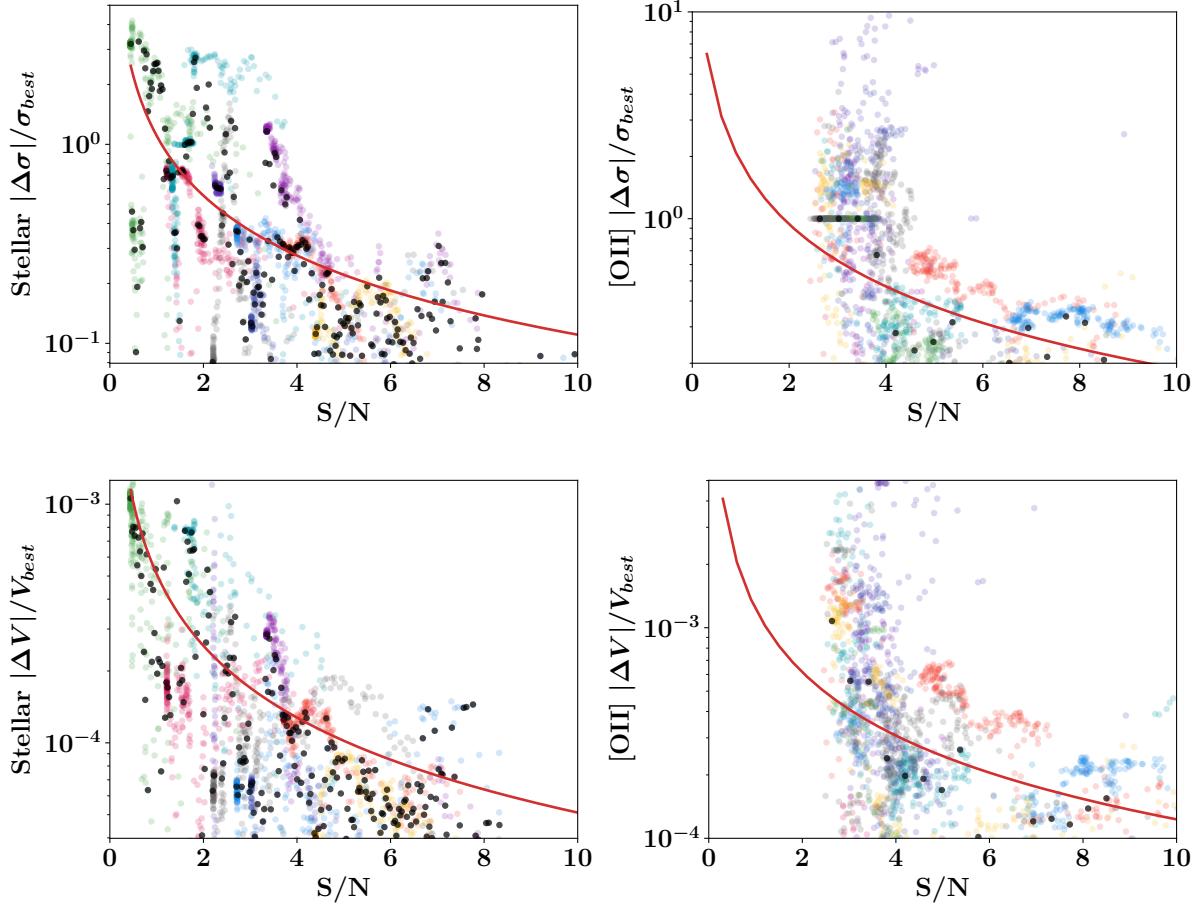


Figure 11. *Top panel:* fractional error versus signal-to-noise for stellar and [OII] gas velocity dispersions. *Bottom panel:* fractional error versus signal-to-noise for the stellar and [OII] gas velocities. *All:* the a/x models (red) provided alternative uncertainties on acquired V and σ values. The fitting routines would produce their own errors but their reliability was questioned and their methodology unknown.

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 (Beck-

with 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.

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 Survey was performed over a two year time-

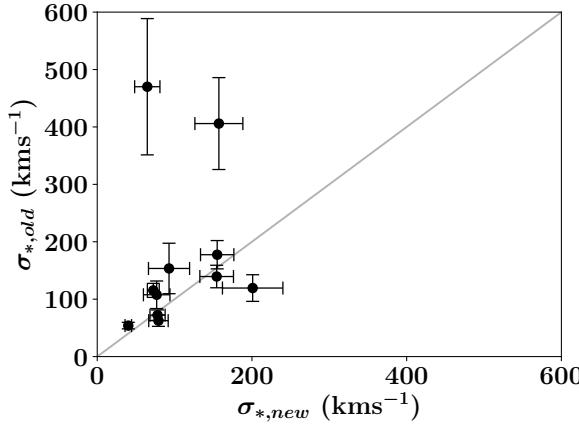


Figure 12. Velocity dispersions for old stellar types (*GK*) versus those for new (young) stellar types (*OA*). 11 galaxy spectra were isolated into overlapping regions of $3700 \times (1+z)$ Å to $4200 \times (1+z)$ Å for young stars, and $4000 \times (1+z)$ Å to $4500 \times (1+z)$ Å for old stars. If a linear trend is considered then two spiral galaxies (C1129 and C175) strongly deviate from this line. This could be attributed to the difficulty in fitting for smaller wavelength regions or to problems with high noise.

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 5), 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.

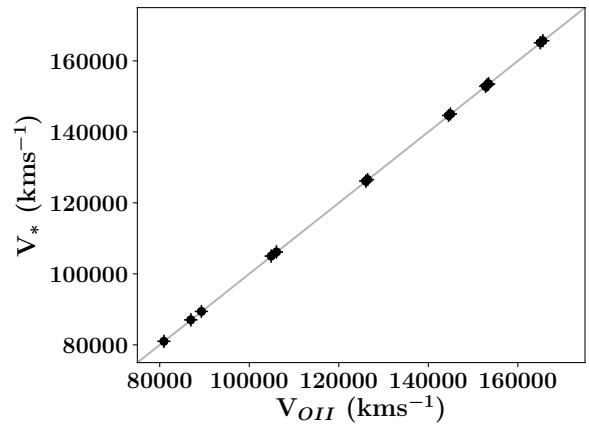


Figure 13. Stellar and [OII] gas velocities for 15 galaxies. The calculated velocities appear to be well in agreement with each other with a 0.0757% fractional difference. It would be expected that both components move at the same relative velocity.

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.

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 vari-

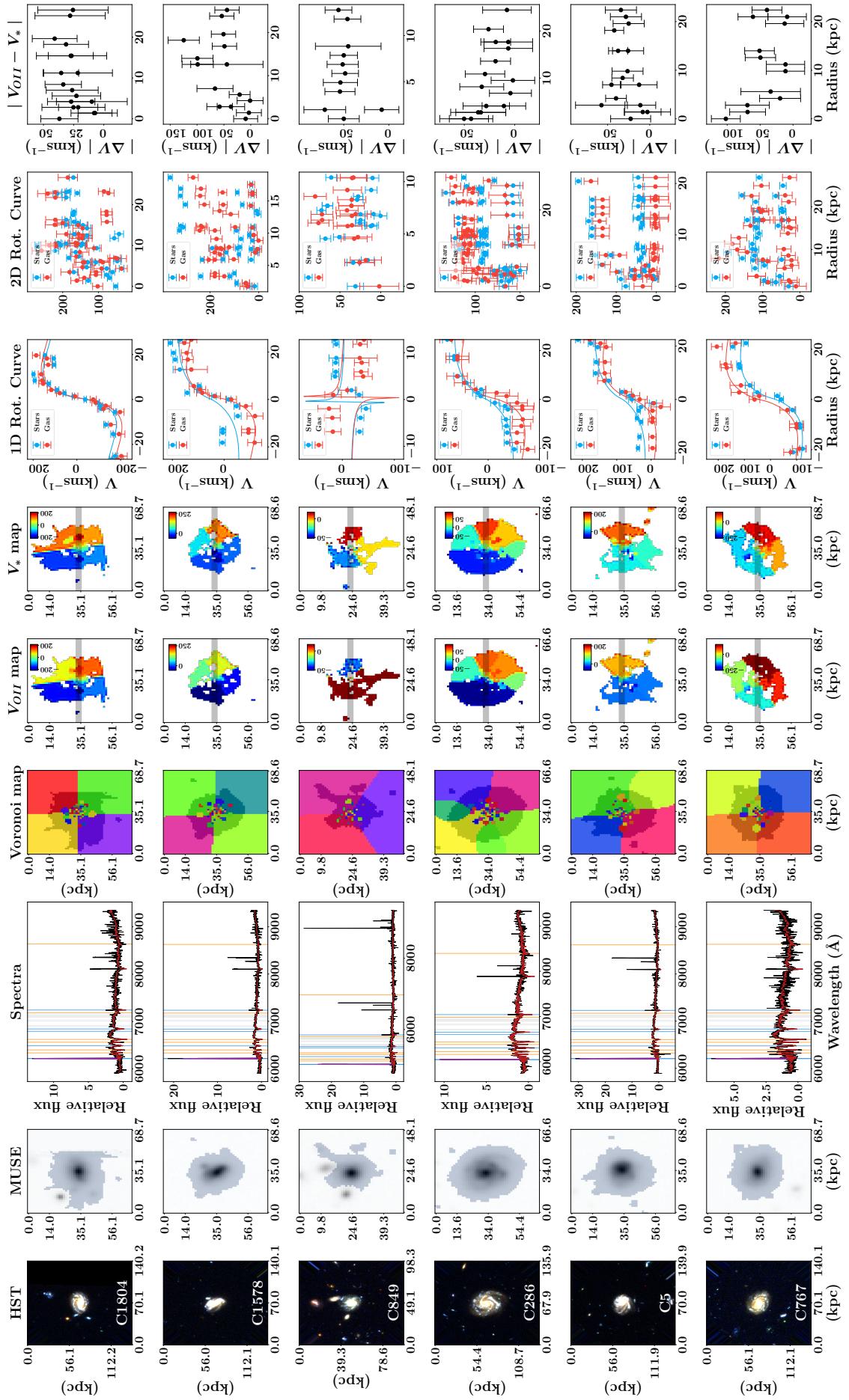


Figure 14. Voronoi tessellation analysis for 6 galaxies. *HST*: HST colour image and galaxy cube ID. *MUSE*: collapsed optical image from MUSE spectroscopic data and segmentation map (grey). *Spectra*: galaxy data (black); pPXF model (red); and emission (blue), absorption (orange), and iron (grey) spectral lines. *Voronoi map*: Voronoi tessellated MUSE map and segmentation area. V_{OII} , V_* maps: velocity fields for galaxy. *1D Rot.* *Curve*: rotation curve as defined by grey strips on velocity maps. *2D Rot. Curve*: rotation curves from galaxy inclined-corrected map. $|V_{OII} - V_*|$: stellar and gas velocity difference versus galaxy radius with data from 1D rotation curves.

ous 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 8(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 8(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.

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.

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 9). 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,

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

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.

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 7). 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.

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*.

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 9), *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.

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 15) 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.

The Coudé library has yet to be fully tested as other limitations of pPXF were explored. One question which arose was

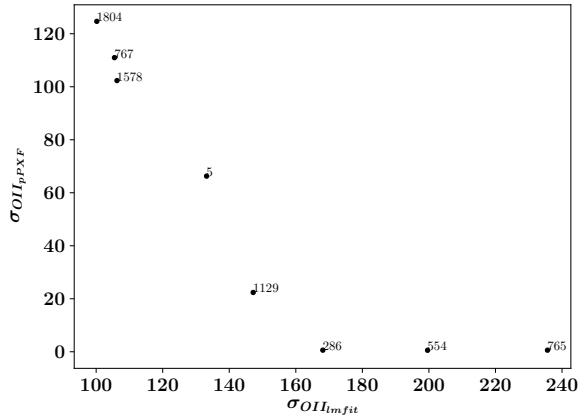


Figure 15. The widths of the [OII] doublets obtained from the Gaussian modelling (labelled *lmfit*) plotted against the widths found from the gas population fitter in pPXF. A linear trend is expected, however a failure in the set-up of pPXF has produced the illogical results as shown in the plot.

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 ??). 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.

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.

4. 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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Appendices

A. Remaining galaxies from sample

The remaining 9 objects from the final reduced sample of 35 galaxies are presented in Table III. These 9 are part of 20 which could not be analysed due to lack of signal-to-noise or lack of a prominent [OII] emission feature.

Cube ID	RAF ID	RA (deg)	Dec. (deg)	F606W mag.	z
C1411	20647	53.16431016	-27.81082586	24.465(4)	0.73503(6)
C943	6028	53.16620903	-27.7939202	24.427(7)	1.036159(9)
C1559	20306	53.16418209	-27.81846837	25.402(7)	1.09406556(0)
C543	22939	53.18402132	-27.79150708	24.956(5)	1.22018(3)
C1423	20544	53.16311572	-27.81360388	24.459(3)	1.42504(2)
C606	9791	53.1648948	-27.77873099	25.17(1)	0.98091(1)
C627	8908	53.15398319	-27.77098973	24.666(8)	0.83200(4)
C400	8559	53.15986702	-27.76684123	24.615(7)	1.03670(3)
C1134	2795	53.16638743	-27.80182796	25.17(1)	0.6820(1)
C1225	1742	53.16803964	-27.80741481	24.014(4)	0.30996(3)

Table III. Remaining 9 objects from the 20 non-analysed galaxies which were not shown in Table II. Columns show the working cube ID, the ID from the UVUDF Catalogs ([Rafelski et al. 2015](#)) (RAF ID), the object right ascension (RA) and declination (Dec.), the magnitude of the object in the HST F606W filter, and the calculated galaxy redshift (z). Total sample contained 35 objects, 15 of which had high enough signal-to-noise in their spectra for the gas and stellar components to be analysed.