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UNIVERSITY OF CALIFORNIA
RIVERSIDE

The Origin and Impact of Broadened Emission Lines in Star-Forming Galaxies at
 $1.4 < z < 3.8$

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

Doctor of Philosophy

in

Physics

by

William Robert Freeman

September 2017

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Dedicated to my parents Tom and Sue Freeman

and

to Tim Ngo

ABSTRACT OF THE DISSERTATION

The Origin and Impact of Broadened Emission Lines in Star-Forming Galaxies at $1.4 < z < 3.8$

by

William Robert Freeman

Doctor of Philosophy, Graduate Program in Physics
University of California, Riverside, September 2017
Dr. Brian Siana, Chairperson

Broadened emission lines have been detected in a small sample of galaxies with high star formation rates (SFR) at $z \sim 2$. However, the impacts and origins of the broad emission have not been quantified for a large sample of galaxies. This work presents results from the MOSFIRE Deep Evolution Field survey on broad emission from the nebular emission lines $H\alpha$, [NII], [OIII], $H\beta$, and [SII]. After removing known AGN, the sample consists of 127 galaxies with $1.37 < z < 2.61$ and 84 galaxies with $2.95 < z < 3.80$. We study broad flux by decomposing the emission lines using narrow and broad components for individual galaxies and stacks. For the $z \sim 2$ sample, the broad flux accounts for 10-50% of the flux in nebular emission lines when detected and in the $z \sim 3.3$ sample the broad component comprises 10-60% of the flux when detected. For individual galaxies, there are no correlations between the broad to narrow flux fraction as a function of mass, SFR, sSFR, or star formation surface density. When placed on the N2-BPT diagram ($[OIII]/H\beta$ vs. $[NII]/H\alpha$) the broad components are shifted towards the higher $[OIII]/H\beta$ and $[NII]/H\alpha$ ratios. We compare the location of the broad components to shock models and find that the broad component could be explained as a shocked outflow. Assuming the broad component is an outflow we estimate the mass loading factor (mass outflow rate/star formation rate) as a function of mass and find generally good agreement with previous observations. We find our galaxies are compatible with simulations only if a large fraction of the outflows are below 275 km s^{-1} for galaxies below $10^{10} M_{\odot}$ stellar mass. We

show that adding shocks to $z \sim 0$ spectra from SDSS shifts galaxies towards the location of $z \sim 2$ galaxies on several emission line diagnostic diagrams and is therefore a plausible candidate for the cause of the offset to the N2-BPT diagram.

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Chapter 1

Introduction

Galaxies have extremely diverse characteristics like their shape, size, structure, stellar mass, gas mass, dust properties, central black hole mass, and metal content. Understanding how such a variety of galaxies came to be is one of the major challenges of modern astronomy. The main motivation behind this work was to try to understand one specific aspect of galaxy evolution: ionized outflows in star-forming galaxies at $1.3 < z < 3.5$.

Outflowing material can be studied in a number of different ways (Veilleux et al. 2005). Neutral material in front of a galaxy can absorb light and create blueshifted absorption profiles (ie. Rupke et al. 2005, Martin 2006, Steidel et al. 2010). Through images, emission from recombining hydrogen can be seen from material moving away from the galaxy (ie. Westmoquette 2007). The method we use in this work is by using spectra of nebular emission lines that have been kinematically broadened because the material is outflowing (Shapiro et al 2009, Newman et al. 2012).

There are a number of potential sources of broad emission and understanding these is important to correctly interpret emission lines at high redshift. We discuss not only outflows, but low luminosity AGN and shocks as possible contributors to the broad emission seen in galaxies.

In Chapter 1, we discuss previous work on the topics of outflows and briefly discuss shocks and AGN to provide context. The data presented in this work are a part of the Mosfire Deep

Evolution Field Survey. We describe the details of the survey, preliminary results, and outreach as well.

In Chapter 2, we discuss the methods we use to analyze the data to separate the broad emission from the intrinsic emission of the galaxy. Outflows, shocks, and AGN are considered as possible origins of the broad emission. Next, we assume that shocks are the primary source of ionization of the broad emission and discuss the implications of shocked emission in emission line diagnostic diagrams (such as $[\text{NII}]/\text{H}\alpha$ vs $[\text{OIII}]/\text{H}\beta$).

In Chapter 3, we discuss the software that was created and used to extract 1D spectra from the reduced 2D images. We also discuss the generalized markov chain monte carlo (MCMC) code used for line fitting.

We conclude in Chapter 4.

1.1 Interpretations of Broad Emission

1.1.1 Outflows

Outflows and inflows of galaxies form a feedback loop that is a crucial part of galaxy formation. This regulates the amount of gas available to form stars and adds chemical enrichment to the intergalactic medium. Outflows from galaxies play a crucial role in their evolution and the formation of their stars. Galaxies are very efficient at cooling gas, and cool, dense gas quickly coalesces to form stars (White & Rees 1978, Balogh et al. 2001, Davé et al. 2001). Forming stars leads to supernovae which heat the interstellar medium (ISM) and push material out of galaxies thus creating a self-regulating feedback loop. In simulations without feedback, star formation rates are much higher than observed (ie. Moster et al. 2010, Hopkins et al. 2014) and too much stellar mass is produced. Feedback heats the interstellar medium and removes mass from the galaxy, thus decreasing the efficiency of star formation (Davé & Oppenheimer 2007, Oppenheimer et al. 2010, Brooks 2010, Hopkins et al. 2014).

Understanding the balance between inflowing gas, outflowing gas, and star formation is crucial to understanding galaxy formation and evolution. Many large simulations often use sub-grid feedback prescriptions based on the circular velocity and star formation rate (SFR) and other factors to ensure galaxies match reality (White & Frenk 1991, Kauffmann et al. 1993, Somerville & Davé 2015 (review)). These prescriptions have tunable free parameters to ensure that simulated galaxies match relationships such as the stellar mass-halo mass, Tully-Fisher, and mass-metallicity relations. This highlights the fact that outflows are critically important and require more study (Somerville & Davé 2015).

For low redshift galaxies, it is possible to study outflows and gas in great detail. Many studies have used absorption from lines in the optical or UV such as Na D, Mg II, or Fe II to trace outflowing interstellar gas. These studies found that the velocity of outflowing material is correlated with SFR (Heckman et al. 2000, Rupke et al. 2005, Martin 2005, Weiner et al. 2009, Rubin et al. 2010, McLean et al. 2012, Chen et al. 2010, Heckman et al. 2015). However, the neutral absorption line must be converted to an H column density. The conversion is nonlinear and depends on the chemical abundance, geometry, dust depletion, and ionization state of the gas (Martin 2006).

Galaxies at high redshift have on average higher SFRs (Reddy & Steidel 2009) and higher gas fractions (Daddi et al. 2010, Swinbank et al. 2011, Tacconi et al. 2013). It is important to understand outflows at high redshifts when the SFR density was at its peak (Madau et al. 1998, Madau & Dickinson 2014). Outflows at $z \sim 1-3$ have been primarily studied using using interstellar absorption lines (Pettini et al. 2002, Weiner et al. 2009, Kornei et al. 2010) and emission lines like $H\alpha$ (Newman et al. 2012). The $H\alpha$ emission line is indicative of star formation within a galaxy (Kennicutt et al. 1994). When viewed edge-on, many galaxies show spatially extended $H\alpha$ emission which is characteristic of outflowing material (Martin 2006, Leroy et al. 2015). When viewed face-on the spectra of galaxies have an intrinsic $H\alpha$ emission line, but in some galaxies there are doppler-broadened emission which has also been attributed to outflowing material (Westmoquette et al. 2007, Rubin et al. 2010, Shapiro et al. 2009, Genzel et al. 2011, Newman et al. 2012, Westmoquette et al.

2012, Förster Schreiber et al. 2014, Newman et al. 2014, Wood et al. 2015). Since the narrow $H\alpha$ flux is proportional to star formation and the broad $H\alpha$ flux is indicative of outflowing material, the ratio between the two (Broad Flux Ratio, BFR) is proportional to the mass loading factor (η =mass outflow rate/SFR) (Genzel et al. 2011). In galaxies with a high signal-to-noise (S/N) emission lines, a single Gaussian is typically a poor fit which indicates the need for a broad component. Of particular interest, Newman et al. (2012) (hereafter N12) measured broad components in the $H\alpha$ spectra of 27 $z \sim 2.3$ galaxies using the SINFONI/VLT integral field spectrograph. In constructing composite spectra for bins of mass, SFR, and SFR surface density (Σ_{SFR}), they find evidence for a critical limit where above a Σ_{SFR} of $1.0 \text{ M}_{\odot} \text{ year}^{-1} \text{ kpc}^{-2}$ outflows have larger η .

As stated previously, many simulations use feedback prescriptions based on a galaxy’s SFR, mass, and/or Σ_{SFR} to determine the impact of outflows. By separating broad and narrow emission in the $H\alpha$, [NII], [OIII], $H\beta$, and [SII] emission lines, we will be able to measure η for these galaxies. With the MOSDEF spectra, we measure η as a function of stellar mass, SFR, sSFR, and Σ_{SFR} . Our goal is to uncover the physical properties of galaxies that may affect their outflow efficiency which will provide a better calibration for current feedback prescriptions. We will compare our measurements to those made by N12 who also measure η as a function of stellar mass, SFR, and Σ_{SFR} . Also, if the broad component is a significant fraction of the flux in an emission line, this could be important to consider when making measurements such as SFR from $H\alpha$. If the BFR for various lines are different, then the broad emission could affect line ratio diagnostic diagrams such as the BPT diagram ($[\text{OIII}]/H\beta$ vs $[\text{NII}]/H\alpha$) (Newman et al. 2014). Galaxies’ position on the BPT diagram depend on ionization parameter, electron density, AGN presence, and metallicity (Kewley et al. 2013) and if broad emission shifts measurements on this diagram, the physical situation in galaxies may be incorrectly interpreted.

1.1.2 Shocks

Most emission lines originate in HII regions within a galaxy and are from photoionization from bright, massive type O and B stars. There have been some recent studies that indicate broad emission from local galaxies may be a result of ionization from shocks (Wood et al. 2015).

If there is some contribution from shocks to emission lines, then the total flux from a given line would be a mix between photoionization and shock ionization. Kewley et al (2013) found that contribution from fast (> 200 km/s) shocks could make galaxies appear as a composite starburst-AGN galaxy. Composite starburst-AGN galaxies have higher [NII]/H α ratios than purely star-forming galaxies.

It is feasible that contributions from shocked emission within galaxies are pushing galaxies at $z \sim 2$ to higher [NII]/H α ratios at a given [OIII]/H β and this could partially explain the offset that has been seen between galaxies at $z \sim 0$ and $z \sim 2$. As we show in Chapter 2, the broad emission in galaxies has higher [NII]/H α than the narrow emission and shocks could explain this offset.

1.1.3 AGN

An AGN outputs a large amount of energy and can drastically change the appearance of a galaxy. AGNs can be detected optically using the N2-BPT diagram because galaxies with AGN are offset from star-forming galaxies. It is possible that low luminosity AGN are contributing to the emission lines of high redshift galaxies. Stacking galaxies might make this emission more apparent.

If there are a large number of low luminosity AGN within galaxies at $z \sim 2$, this could partially explain the offset that has been seen between galaxies at $z \sim 0$ and $z \sim 2$.

1.2 The MOSFIRE Deep Evolution Field Survey

This work is part of a large multi-year project (LMAP) on the Keck telescope called the MOSFIRE Deep Evolution Field (MOSDEF) Survey. In this section we describe the survey design, status, and broader impacts.

1.2.1 Survey Design and Goals

The MOSDEF Survey was designed to study ~ 1500 galaxies between $1.5 < z < 3.5$ using rest-frame optical spectra. MOSDEF used the MOSFIRE (McLean et al. 2010) on the Keck-I telescope for 48 nights between December 2012 and spring of 2016. This program targeted galaxies in the CANDELS (Grogin et al. 2011) fields, where the Hubble Space Telescope, Chandra, Herschel, and many other facilities have already taken data. Observations for MOSDEF began in December 2012 and ended in June 2016.

1.2.2 Current Status and Preliminary Results

The MOSDEF survey has recently finished taking observations on MOSFIRE which totaled 48.5 nights. In total, there are 54 masks with 141 total filter-mask combinations. There are 4956 extracted 1D spectra for 1427 targets and serendips. Of the 1427 targeted spectra, 1178 had measured redshifts and 1160 of those fall between $1.37 < z < 3.80$ which is 81.3%. Including serendips there are 1350 robustly measured redshifts and 1295 of those fall between $1.37 < z < 3.80$.

Figure 1.1 shows the final redshift histogram for the survey. Of the targeted objects 288, 558, and 241 are at redshifts of $1.37 < z < 1.97$, $2.37 < z < 2.7$, and $2.95 < z < 3.75$ respectively. Including serendips, there are 327, 613, and 288 galaxies within those redshift bins. There were 53 galaxies with $z < 1.37$ and 22 at $z < 1.0$. There are 2 galaxies at $z > 3.75$: GOODS-N-17940 at $z=4.4125$ and COSMOS-8144 at $z=4.487$ (Shapley et al. 2017).

Since the data are in the CANDELS fields, there is extensive ancillary data across many

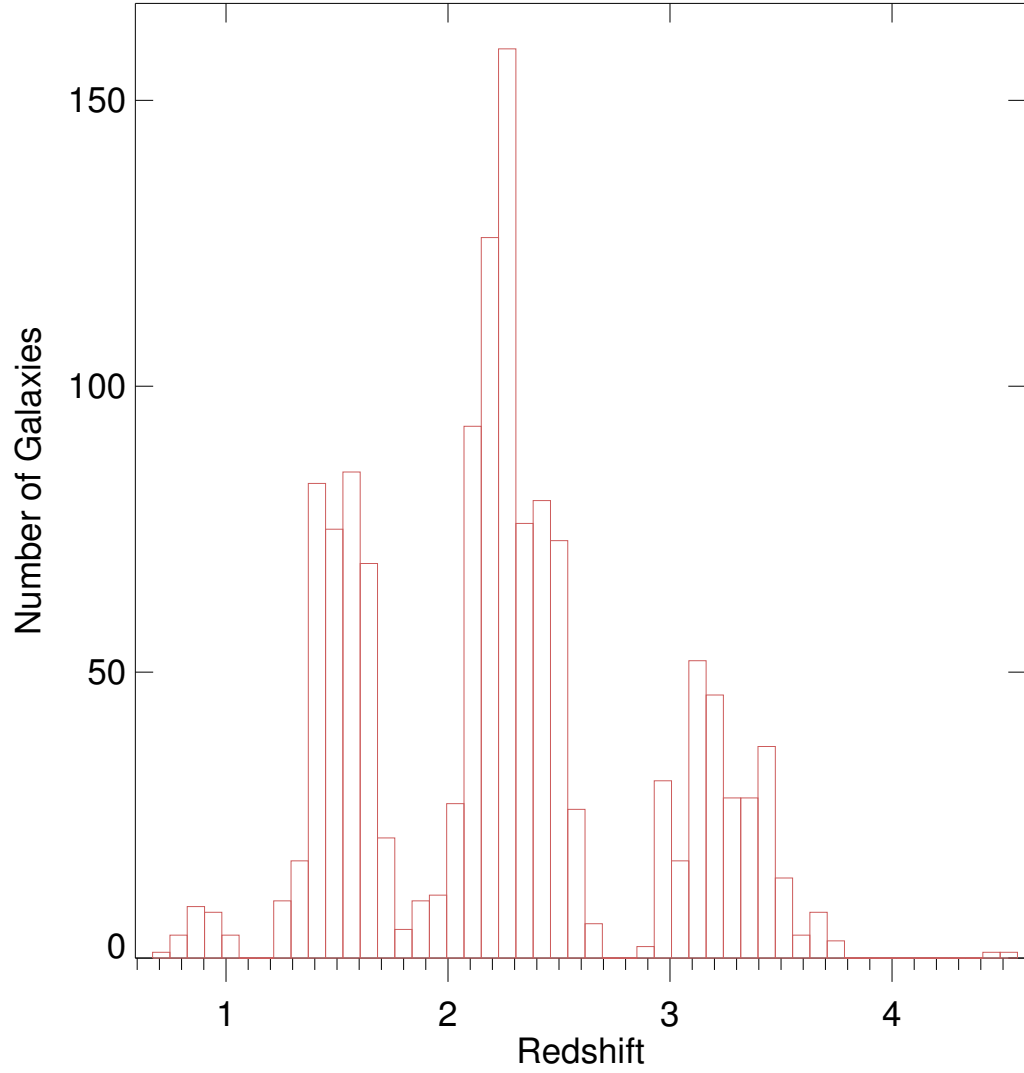


Figure 1.1 Redshift histogram for full MOSDEF sample

wavelengths. These data provide good constraints on physical parameters measured using a technique called Spectral Energy Distribution (SED) fitting. The MOSDEF team used the Fitting and Assessment of Synthetic Templates (FAST) SED fitting code (Kriek et al. 2009, Kriek et al. 2015) to measure properties of the sample. Fast calculates the SED for a grid of input parameters such as SFR, z , age, mass, and star formation history. It then calculates the χ^2 for every model and outputs the lowest.

The science goals of the MOSDEF survey are to understand the star formation, dust attenuation, metallicity, the baryon cycle (inflows and outflows), ISM conditions, and dynamical masses of galaxies at $1 < z < 3$. With only the first half of the total dataset, the MOSDEF team has made many leaps forward in our understanding in these areas of science.

1.2.3 Broader Impacts and Outreach

Scientific Impact

To study galaxy evolution, a large, statistically significant sample is necessary. Large samples have been gathered at low redshifts. The Sloan Digital Sky Survey (SDSS, York et al. 2000) and the 2dF Galaxy Redshift Survey (2dFGRS) have taken images and spectra of 10^6 galaxies in the local universe. These surveys have measured the distributions of luminosity, color, star formation rate, and metallicity (and other properties) of these galaxies. At $z \sim 1$, a number of surveys such as the DEEP Extragalactic Evolutionary Probe 2 (DEEP2, Davis et al. 2003) and The PRISM Multi-object Survey (PRIMUS, Coil et al. 2011) measured similar properties. The MOSDEF Survey is the first to measure the properties of a large number of galaxies at $z \sim 1 - 3$.

The MOSDEF survey has obtained spectra of 2,000 target galaxies and is one of the largest allocations of Keck time. These data have immense legacy value as this survey increases, by an order of magnitude, the number of rest-frame optical spectra of galaxies at these redshifts. The MOSDEF spectra enable additional studies with the wealth of ancillary data that exist in these fields. The redshifts of the galaxies in the survey have been released and the spectra will be made available within two years. Additionally, I have released software to aid in the extraction of faint spectra, which will be useful to others taking data with MOSFIRE or other multi-object spectrographs.

Members of the MOSDEF team have made more than two dozen presentations at scientific conferences. These presentations have shown the astronomical community the results of the project as well as subjected the work to scrutiny.

Public Outreach

The MOSDEF team has created a website that contains many essential resources for K-12 teachers. The section of the website for the public has several pages explaining different aspects of the survey. There is a movie that shows the basics of taking spectra and how we can see emission from hydrogen, oxygen, and stellar light from galaxies billions of light years away. There are pages about how astronomers measure redshift, mass, dust, and star formation rate. These web pages give students an idea of how astronomers use spectra to understand the universe. Learning how actual astronomers study the universe is an exciting way to learn about astronomy.

Software for the Community

The National Science Foundation (NSF) Directorate of Mathematical and Physical Science Division of Astronomical Science encourages investigators to share software created as part of their research and to make the software widely available and usable. The MOSDEF team is making some of the software used for the survey publicly available.

The 2D reduction software will be made publicly available. This code produces 2D reduced spectra automatically by removing sky emission, masking cosmic rays and bad pixels, rectifying the frames, combining the images, correcting for telluric response, and flux calibrating the data. The 2D reduction procedure is discussed in detail in Kriek et al. (2015).

The 2D to 1D extraction software, called BMEP, is already public. The entire source code and extensive documentation is included in the release of BMEP. The documentation covers installation, use, troubleshooting, and output descriptions which will ensure the usability of the code. This code is described in Chapter 3.

A generalized markov chain monte carlo code based on the Metropolis-Hastings algorithm was used to fit each galaxy and stack in this work. This is the only code of its type written in IDL and is described in Chapter 3.

Chapter 2

Broadened Emission from Galaxies at High Redshift

2.1 Chapter Introduction

Rest-frame optical nebular emission lines such as $H\alpha$, $[\text{NII}]$, $[\text{OIII}]$, $H\beta$, and $[\text{SII}]$ are diagnostics of physical properties of galaxies such as star formation rate (SFR) (Kennicutt 1998, Shivaiei et al. 2015), dust extinction (Kashino et al. 2013, Steidel et al. 2014, Reddy et al. 2015), electron density (Osterbrock 1989, Hainline et al. 2009, Bian et al. 2010, Sanders et al. 2016), and metallicity (Pettini & Pagel 2004, Erb et al. 2006, Sanders et al. 2015). A consequence of this is that galaxies fall into well-defined patterns in emission line diagnostic diagrams such as the N2-BPT diagram ($[\text{OIII}]/H\beta$ vs. $[\text{NII}]/H\alpha$) and the S2-BPT diagram ($[\text{OIII}]/H\beta$ vs. $[\text{SII}]/H\alpha$) (Baldwin et al. 1981). The position of a galaxy on these diagrams is determined by its underlying physical conditions such as electron density, hardness of ionizing radiation, AGN presence, and metallicity (Kewley et al. 2013, Shapley et al. 2015, Coil et al. 2014, Sanders et al. 2016). Galaxies at $z \sim 2$ show a systematic offset from local galaxies in the N2-BPT diagram (Shapley et al. 2005, Erb et al. 2006, Liu et al.

2008). There has been a great deal of study on the cause of this offset. Plausible explanations for the offset include higher ionization parameters (Brinchmann et al. 2008, Kewley et al. 2015), elevated N/O ratios at fixed O/H (Masters et al. 2016, Shapley et al. 2015, Jones et al. 2015, Sanders et al. 2016, Cowie et al. 2016), harder stellar radiation fields at fixed nebular metallicity (Steidel et al. 2014, Strom et al. 2017), and different star formation histories (Steidel et al. 2016, Hirschmann et al. 2017).

Information about the dynamics of galaxies can be measured using 2D spectra and the shape of emission lines (Price et al. 2016). The width of an emission line is determined by a combination of factors such as rotation and velocity dispersion of the galaxy. Additionally, broadened emission is seen in some galaxies, which is associated with outflowing material (Veilleux et al. 2005, Heckman et al. 1990, Daddi et al. 2010, Swinbank et al. 2011, Tacconi et al. 2013, Shapiro et al. 2009, Newman et al. 2012, Newman et al. 2014, Förster Schreiber et al. 2014, Genzel et al. 2011). Broad emission is also seen in some AGNs that is not associated with the broad line region, but with outflows (Förster Schreiber et al. 2014, Genzel et al. 2014a, Leung et al. 2017). In the local universe, broad emission is seen in luminous infrared galaxies (Rupke et al. 2005, Westmoquette et al. 2012). Luminous infrared galaxies are typically associated with active or recent mergers and the increased star formation associated with merging could be driving the outflows. Estimates of physical properties of galaxies from emission lines typically assume the emission originates in the HII regions of galaxies. If a significant portion of the flux originates in a broad, outflowing component, this might influence the estimates of galaxy physical properties.

It is important to understand the effects of broad emission on measurements of physical properties of galaxies at $z \sim 2$, where they have higher SFR (Reddy & Steidel 2009, Madau et al. 1998, Madau & Dickinson 2014), higher gas fractions (Daddi et al. 2010, Swinbank et al. 2011, Tacconi et al. 2013), and are more compact (Trujillo & Pohlen 2005; Shen et al. 2003, Barden et al. 2005) compared to galaxies at $z \sim 0$. The higher SFR and smaller sizes leads to a larger star formation surface density (Σ_{SFR}) which may result in an outflow (Ostriker & Shetty 2011, Newman

et al. 2012). Studies of broad emission at $z \sim 2$ have shown that broad emission is more prominent above a star formation surface density (Σ_{SFR}) of $1.0 \text{ M}_{\odot}/\text{yr}/\text{kpc}^2$ (Newman et al. 2012). Previous studies of broad emission at this redshift have a small sample size (Newman et al. 2014), are done on galaxies with high sSFR (Shapiro et al. 2009, Newman et al. 2012), or focus on galaxies with AGN (Förster Schreiber et al. 2014, Genzel et al. 2011, Leung et al. 2017). A study of broadened emission with a large sample of typical galaxies at $z \sim 1 - 3$ is necessary to understand how broad emission affects the average star-forming galaxy.

In the MOSFIRE Deep Evolution Field (MOSDEF¹) survey (Kriek et al. 2015) we obtained near-infrared spectra for ~ 1500 high-redshift galaxies using the MOSFIRE instrument (McLean et al. 2012) on the W. M. Keck telescope. These spectra enable measurements of the rest-frame optical nebular emission lines for galaxies at $1.37 < z < 3.80$. The data in the MOSDEF survey allow for measurements of broad emission on a large sample of star-forming galaxies (as well as AGN, presented in Leung et al. 2017). The goal of this Chapter is to measure or place limits on a broad component in star-forming galaxies in order to determine the amount broad emission in typical $z \sim 1 - 3$ galaxies. We also aim to understand how broad emission affects the location of a galaxy on emission line diagnostic diagrams such as the N2-BPT and S2-BPT diagrams.

This Chapter is structured as follows: Section 2.2 describes the sample, observations, data reductions, and measurements of physical properties. Section 2.3 describes how we fit galaxy spectra to measure the broad emission. We also describe how we make stacks and test the broad fitting technique. In Section 2.4, we show measurements of the broad emission in individual spectra as well as stacks of galaxies. In Section 2.5, we discuss the source of the broad component and consider several possible physical explanations for the broad flux such as low-luminosity AGN and shocks. In Section 2.6, we discuss possible effects on physical measurements from the broad component. Conclusions are summarized in Section 2.7.

Throughout this work we assume a Λ CDM cosmology with $\Omega_m = 0.3$, $\Omega_{\lambda} = 0.7$, and

¹<http://mosdef.astro.berkeley.edu/>

$H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. All magnitudes are given in the AB system (Oke & Gunn 1983). The wavelengths of all emission lines are in vacuum.

2.2 Observations and reductions

One-dimensional spectra were extracted using custom IDL software called **BMEP**², as described in the Appendix. **BMEP** was tested with output from the MOSDEF team’s custom 2D reduction, the MOSFIRE DRP, and the 2D optical spectra from the Keck Low Resolution Imaging Spectrometer (LRIS, Oke et al. 1995, Rockosi et al. 2010). For the MOSDEF data, both optimally weighted and unweighted spectra were extracted for each object, and we use the optimally weighted spectra for this analysis. The optimal extraction algorithm follows Horne (1986) but is modified to be able to extract fractions of pixels (see the Appendix). To determine the weighting profile, center, and width of each object, we fit a Gaussian to the profile of each object in each filter. The profile was determined by summing flux only at those wavelengths with high S/N in either the continuum or emission lines. Using high S/N areas of the spectra creates clean weighting profiles for the optimal extraction since wavelengths with little or no signal are excluded.

Galaxies in the MOSDEF Survey are split into 3 redshift bins, $1.37 < z < 1.70$, $2.09 < z < 2.61$, and $2.95 < z < 3.80$ that were each observed using a different filter set in order to maximize efficiency (see Kriek et al. (2015) for details). When making stacks, we combine the $1.37 < z < 1.70$ and $2.09 < z < 2.61$ galaxies into a single stack (hereafter the $z \sim 2$ stack) because these galaxies have coverage of $\text{H}\alpha$ and $[\text{OIII}]$. There may be some evolution in broad emission between the galaxies at $1.37 < z < 1.70$ and $2.09 < z < 2.61$ but without combining them broad emission is extremely difficult to detect. The $2.95 < z < 3.80$ galaxies do not have coverage of $\text{H}\alpha$ and are stacked separately (hereafter the $z \sim 3$ stack).

The dataset contains 555 galaxies with measured redshifts, and we create a sub-sample where we remove galaxies for which it may be difficult to accurately measure the broad emission

²Source code and installation instructions available at: <https://github.com/billfreeman44/bmep>

or have AGN (discussed below). When cleaning the sample, we consider the $H\alpha$ and [OIII] detections separately except when considering galaxy-wide effects which are mergers and AGN presence. Initially, there are 503 galaxies with [OIII] detections and 394 with $H\alpha$ detections.

- We remove 50 [OIII] and 35 $H\alpha$ detections where the galaxy was an IR, x-ray, or both IR and x-ray detected AGN. AGN are a possible source of outflows (Leung et al. 2017). To isolate the effects of star formation on outflows, we remove galaxies that were identified as AGN. (see Coil et al. 2014 and Azadi et al. 2017)
- We remove 20 [OIII] and 26 $H\alpha$ detections where the galaxy was optical line detected AGN (above the Kauffmann et al. 2003 line). This is a conservative cutoff considering galaxies at $z \sim 2$ are offset compared to $z \sim 0$ galaxies (Shapley et al. 2015).
- We remove 182 [OIII] detections where $S/N < 10$ for [OIII] and 122 $H\alpha$ detections where $S/N < 10$ for $H\alpha$.
- We remove 22 [OIII] and 41 $H\alpha$ detections where the [OIII] or $H\alpha$ emission line was on or near bright sky lines.
- We remove 14 [OIII] and 17 $H\alpha$ detections where the galaxy appears to be undergoing a merger as indicated from the images or spectra of nearby objects. Mergers may have kinematics which complicate the line profile in terms of an outflow. We determined which galaxies were mergers by inspecting both images and spectra by eye. If the galaxy was very misshapen or there was a nearby companion we removed it. In the spectra, if there were two profiles that overlapped then those galaxies were removed.
- We remove 7 [OIII] and 8 $H\alpha$ detections where the [OIII] or $H\alpha$ emission is near the edge of wavelength coverage and the shape of the profile is difficult to determine.
- We remove 5 [OIII] and 7 $H\alpha$ detections for which we measured a $FWHM > 275$ from a single gaussian. Some galaxies have broad lines simply from rotation and velocity dispersion. To isolate the broad emission, we restrict the narrow emission to have a $FWHM < 275 \text{ km s}^{-1}$ as

described in Section 2.3.1. Including galaxies with $\text{FWHM} > 275 \text{ km s}^{-1}$ creates false positives because the narrow component does not properly fit the narrow emission.

The final sample has 203 galaxies with [OIII] detections and 138 galaxies with $\text{H}\alpha$ detections. There are 125 galaxies with both an $\text{H}\alpha$ and [OIII] detection. The stacks at $z \sim 2$ have an additional restriction to contain galaxies that have coverage of $\text{H}\alpha$, [OIII], [SII], [NII], and $\text{H}\beta$ which results in 113 galaxies in the $z \sim 2$ stack. There are 60 galaxies in the $z \sim 3$ stack.

Figure 2.1 shows histograms of redshift for the full sample of galaxies in blue, the remaining galaxies after the S/N rejection in red, and the the final sample in green. There is no clear bias against any particular redshift or mass, however more galaxies with $\text{SFR} < 10 M_{\odot} \text{ yr}^{-1}$ have been removed. The right side of Figure 2.1 shows the SFR vs. mass for our sample along with the star-forming main sequence from Shivaie et al. (2015). Because we removed galaxies that have an $\text{H}\alpha$ or [OIII] $\text{S/N} < 10$, our sample may be incomplete for galaxies below the main sequence and at low stellar mass.

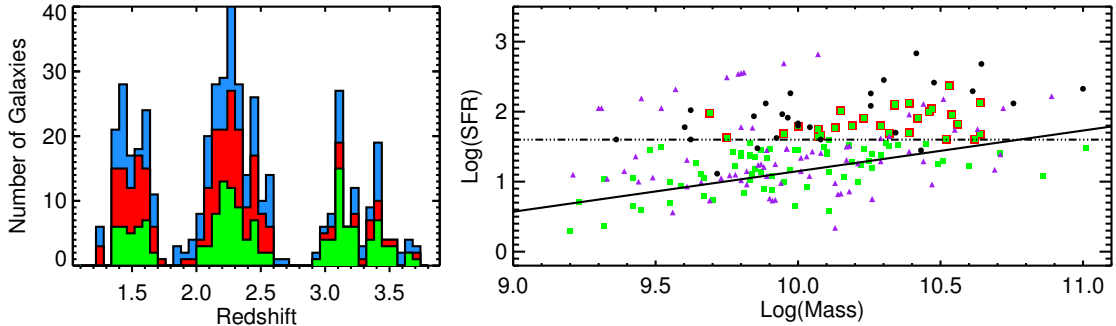


Figure 2.1 Left: Histograms of galaxies in the MOSDEF survey. The solid blue histogram is the full sample, the red is the sample after removing all galaxies with a $\text{S/N} < 10$ in $\text{H}\alpha$ (for $z < 2.3$) or in [OIII] (for $z > 2.3$), and the green histogram is the final sample which removes galaxies where $\text{H}\alpha$ or [OIII] line is too close to the edge of the detector, there was evidence of a merger, or there were bad skylines. Right: SFR vs. mass for the final sample. The green squares are $z \sim 1.5$ and $z \sim 2.3$, purple triangles are $z \sim 3.3$ galaxies, and black circles are galaxies from N12. The solid black line is the star-forming “main sequence” measured from the MOSDEF data (Shivaie et al. (2015)). The horizontal triple dotted line indicates an SFR of $40 M_{\odot} \text{ yr}^{-1}$. Galaxies in the N12-like subsample (see Section 2.3.2) are above this line and have red borders.

2.2.1 Stellar Population Properties

We estimate the physical parameters for our sample, including stellar mass, SFR and age, using the stellar population fitting code FAST (Kriek et al. 2009) to compare the photometric SEDs with stellar population synthesis models (Conroy et al. 2009). We assume a Chabrier (2003) initial mass function (IMF) and the dust reddening curve from Calzetti et al. (2000). We use spectroscopic redshifts from the MOSDEF survey and broadband and mediumband photometric catalogs assembled by the 3D-HST team (Skelton et al. 2014) spanning observed optical to mid-infrared wavelengths. We include a template error function to account for the mismatch in less constrained sections of the spectrum. For a full description of the stellar population modeling procedure see Kriek et al. (2015).

When available, we derive SFRs based on the $H\alpha$ emission line by correcting for Balmer absorption (using the SED) and dust extinction (using the Balmer decrement of $H\alpha/H\beta$), then converting the $H\alpha$ luminosity into a SFR (Kennicutt, 1998), adjusted for a Chabrier (2003) IMF (see Shivaee et al. 2015 for more details). Because galaxies in the $z \sim 3.3$ bin do not have coverage of $H\alpha$, we use SED fitting to determine their SFRs.

2.3 Measuring the Broad Component

In this section, we describe the technique for measuring the broad emission line components for individual galaxies. We also describe how we create stacks.

We aim to measure an underlying broad component of emission lines of galaxies. As discussed in Section 2.1, we will assume emission lines are composed of narrow and broad components with Gaussian profiles. This section describes the fitting process as well as constraints on parameters.

Because of our observing strategy, the $H\alpha$, [NII], and [SII] lines are in the same filter (H if at $z \sim 1.5$ and K if at $z \sim 2.3$) while [OIII] and $H\beta$ fall into a different filter (J if at $z \sim 1.5$, H if at $z \sim 2.3$, and K if at $z \sim 2.3$). We do not simultaneously fit lines that are in different filters

because the spectral resolution is slightly different in each filter³. Additionally the seeing may vary between different filters on one mask because they were not always observed on the same day or were observed during variable seeing. We do not include [SII] in fits of individual galaxies because it is too faint, however it is included in fits of stacks (see Section 2.3.2). For individual galaxies at $1.37 < z < 2.61$ we fit $H\alpha$ and [NII] $\lambda\lambda 6549, 6583$ simultaneously. For individual galaxies at $1.37 < z < 3.8$ we fit [OIII] $\lambda 5008$, [OIII] $\lambda 4959$, and $H\beta$ simultaneously.

For each set of lines, we do two preliminary fits and one final fit. The first preliminary fit uses a single Gaussian to fit each emission line using **MPFIT**, a non-linear least squares fitting code (Markwardt, 2009). We use this single Gaussian fit to subtract off a linear background and normalize the data so the fitted flux density of the peak of the brightest line for each set of lines ($H\alpha$ or [OIII]) is unity, respectively. Next, we fit the data again using **MPFIT** but this time each emission line is fit with two Gaussians, one broad and one narrow. We use the resulting values and errors of this second fit as initial values for the final fit which is done with a custom Markov Chain Monte Carlo (MCMC) code **MPMCMCFUN**⁴ that uses the Metropolis-Hastings algorithm (Metropolis et al. 1953, Hastings 1970). The errors in the second preliminary fit are used as the parameter jump amplitudes for the final fit. In what follows, we use the subscripts S, B, and N to distinguish parameters for the single, broad, and narrow components, respectively.

When fitting multiple emission line components, we constrain the FWHM_B , FWHM_N , broad component shift (Δv), constant background, and the narrow component redshift to be the same for each line. This leaves each single emission line with two free parameters, broad amplitude (A_B) and narrow amplitude (A_N). Two exceptions to this are the [NII] $\lambda 6585$ / [NII] $\lambda 6550$ and [OIII] $\lambda 5008$ / [OIII] $\lambda 4959$ flux ratios which are set to 2.93 and 2.98 respectively according to atomic physics (Osterbrock 1989). Therefore, each fit has five free parameters shared by each line (FWHM_B , FWHM_N , Δv , narrow component redshift, and constant background) and two free parameters for each line (A_N and A_B).

³www2.keck.hawaii.edu/inst/mosfire/grating.html

⁴Source code and installation instructions available at: <https://github.com/billfreeman44/mpmcmcfun>

The resulting best-fit parameters are likely to depend on the chosen limits. For instance, not placing a minimum on the FWHM_N can result in an unphysically narrow emission line. Also, not placing a minimum on the FWHM_B can result in the broad component not being representative of broadened emission. Therefore, we place physically motivated restrictions on all free parameters. For individual galaxies, we restrict the FWHM_N so that it cannot be lower than the average FWHM of skylines in that particular filter and mask. For galaxies smaller than the slit width, it is possible that the FWHM of the narrow component is smaller than that of skylines. However, because the seeing is never far below the width of the slit ($0.''7$), and the line width is broadened by both the spatial extent of the galaxy and the velocity distribution therein. Therefore, we do not expect FWHM_N to be much lower than the width of the sky lines. We also restrict the FWHM_N to be less than 275 km s^{-1} . For this sample, we have removed galaxies where FWHM_S is larger than 275 km s^{-1} (see Section 2.1).

In order to properly study outflows, we must be certain that the broad components measure a kinematically distinct feature from the rotation of the host galaxy. In other words, the broad flux must not be an artifact from a better fit to the narrow emission by using two Gaussian components. Therefore, we restrict the minimum FWHM_B to be a larger value than could be reasonably fit using only a single Gaussian component. Accordingly, we set the minimum FWHM_B to be 300 km s^{-1} which provides some separation in the velocities of the narrow and broad components. Typical FWHMs for ionized outflows from star-forming galaxies are $300\text{-}600 \text{ km s}^{-1}$ (Newman et al. 2012, Genzel et al. 2011, Wood et al. 2015).

Some studies have measured galactic outflow speeds $> 1000 \text{ km s}^{-1}$, but these are typically associated with AGN (Shapiro et al. 2009, Genzel et al. 2014a, Förster Schreiber et al. 2014). Since we have removed known AGN, we do not expect outflows of such high velocity. The upper limit of FWHM_B is set to 850 km s^{-1} which is the typical maximum velocity deduced by the blue-shifted interstellar absorption lines in the rest frame UV of $z \sim 2$ galaxies (Steidel et al. 2010).

When the amplitude of the broad component is consistent with zero, the center and width

become unconstrained. Therefore it is important to restrict these parameters so they do not stray to unrealistic values. The centroid of the broad component is allowed to be anywhere within ± 100 km s⁻¹ of the expected value. The broad component shift is the same for each line. No objects that had significant detections of the broad component ran into this limit. Other studies typically find shifts of < 100 km/s (Newman et al. 2012, Wood et al. 2015).

The amplitude of the narrow H α and [OIII] components are constrained to be between 0.2 and 1.05 (the peak of these lines were normalized to unity from the single Gaussian fit) and the broad component amplitude is constrained to -0.3 and 0.8. Since some galaxies do not show any signs of broad emission, the best value for the FWHM_B could be at or near zero for these galaxies. In these cases, it is still useful to put limits on the broad emission. Therefore, we allow the FWHM_B to be negative to fully sample the parameter space and set proper upper limits on the FWHM_B. In cases where the best value for the FWHM_B is less than zero, we interpret this galaxy as having no significant broad emission but still show the upper limit. For [NII], [SII], and H β we scale the restrictions to the relative peak of each line. All of the constraints are listed in Table 2.1.

Figure 2.2 shows fits for four galaxies that show the strongest evidence for the broad component. It is clear that a single Gaussian does not fit these galaxies well as evidenced by the “wave” pattern that is present in the residuals. The pattern shows the single fits underestimate flux at the peak, overestimate the wings, and underestimate the base. This pattern is particularly evident in the [OIII] lines of 12015, and 13015 and in the H α lines of 12024 and 7231.

The broad flux only dominates a small fraction of the line at high velocities. If the broad flux component is not approximately gaussian, then the fitted broad flux might be different than what we measure. Other studies that analyze galaxies with higher signal to noise find that the broad emission is typically well fit by a gaussian (Newman et al. 2012, Shapiro et al. 2009, Genzel et al. 2011).

Table 2.1. Constraints of the Fits

Parameter	Minimum	Maximum
FWHM_S^{a}	varies ^b	275
A_S^{c}	0	1.05
Δv_S^{d}	-100	+100
FWHM_N	varies ^b	275
A_N	0.2	1.05
Δv_N	-100	+100
FWHM_B	300	850
A_B	-0.3	0.8
Δv_B	-100	+100

^aFWHM in units of km s^{-1}

^bSet to the average FWHM of skylines in each mask

^cRelative to the maximum flux of the line

^dCenter shift in units of km s^{-1} . Negative values imply blueshifts

2.3.1 Making Stacks of Spectra

The broad component is difficult to separate from the narrow emission. The galaxies in Figure 2.2 were chosen because they show the strongest evidence for broad emission. The faint, high velocity wings of the broad component are difficult to distinguish from the noise for the majority of the individual galaxies. In order to achieve a higher S/N, we create stacks of galaxies in bins of stellar mass such that each stack has approximately the same number of galaxies. To create each stack, we interpolate the flux for each galaxy to a common rest-frame wavelength grid, subtract off any continuum, convert each spectrum from flux density to luminosity density, and divide by the total luminosity of either $\text{H}\alpha$ or $[\text{OIII}]$ depending on the wavelength coverage of the stack. To avoid adding significant noise from sky line subtraction residuals, we remove pixels associated with sky lines where the error spectrum is above $1.5\times$ the median error. The error in the stacked spectrum is calculated by making the stack 200 times but using input spectra with added Gaussian noise; the

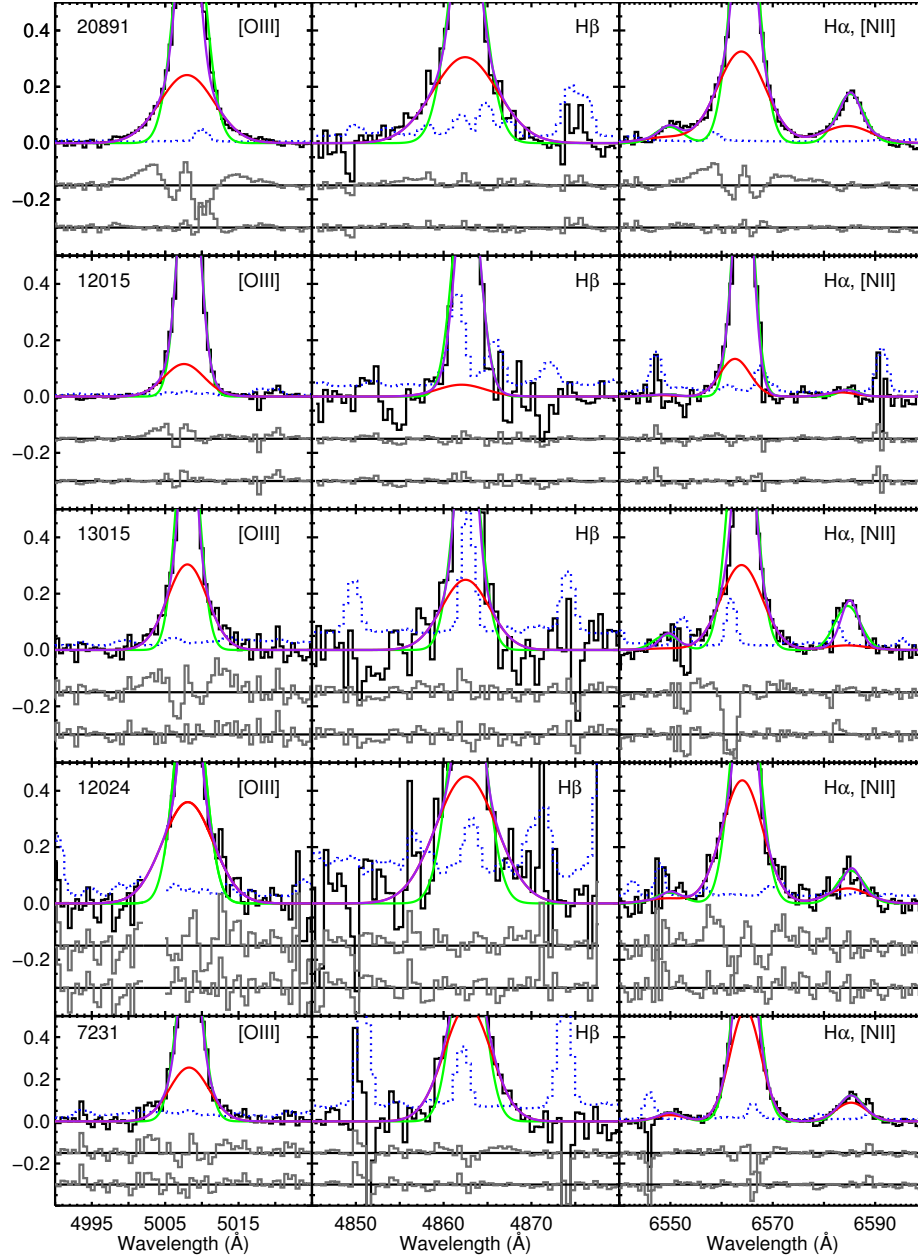


Figure 2.2 Five example fits for individual spectra. Each row is one object and each column from left to right is [OIII], H β , and H α . The 3D HST v4.1 catalog ID is in the upper left and the line is shown in the top right. Each line is normalized such that the strongest line peak is unity. The single Gaussian fit is shown in green. The overall fit for the narrow+broader fits for each stack is shown in purple with the broad component for this fit shown in red. The error spectrum is shown as a dotted blue line. The two gray lines show the residuals for the single Gaussian fit (top) and the narrow+broader fit (bottom). Solid black lines show the amount each residual is offset by for convenience. A skyline has been masked for object 12024 at 5004 Å and at 4877 Å.

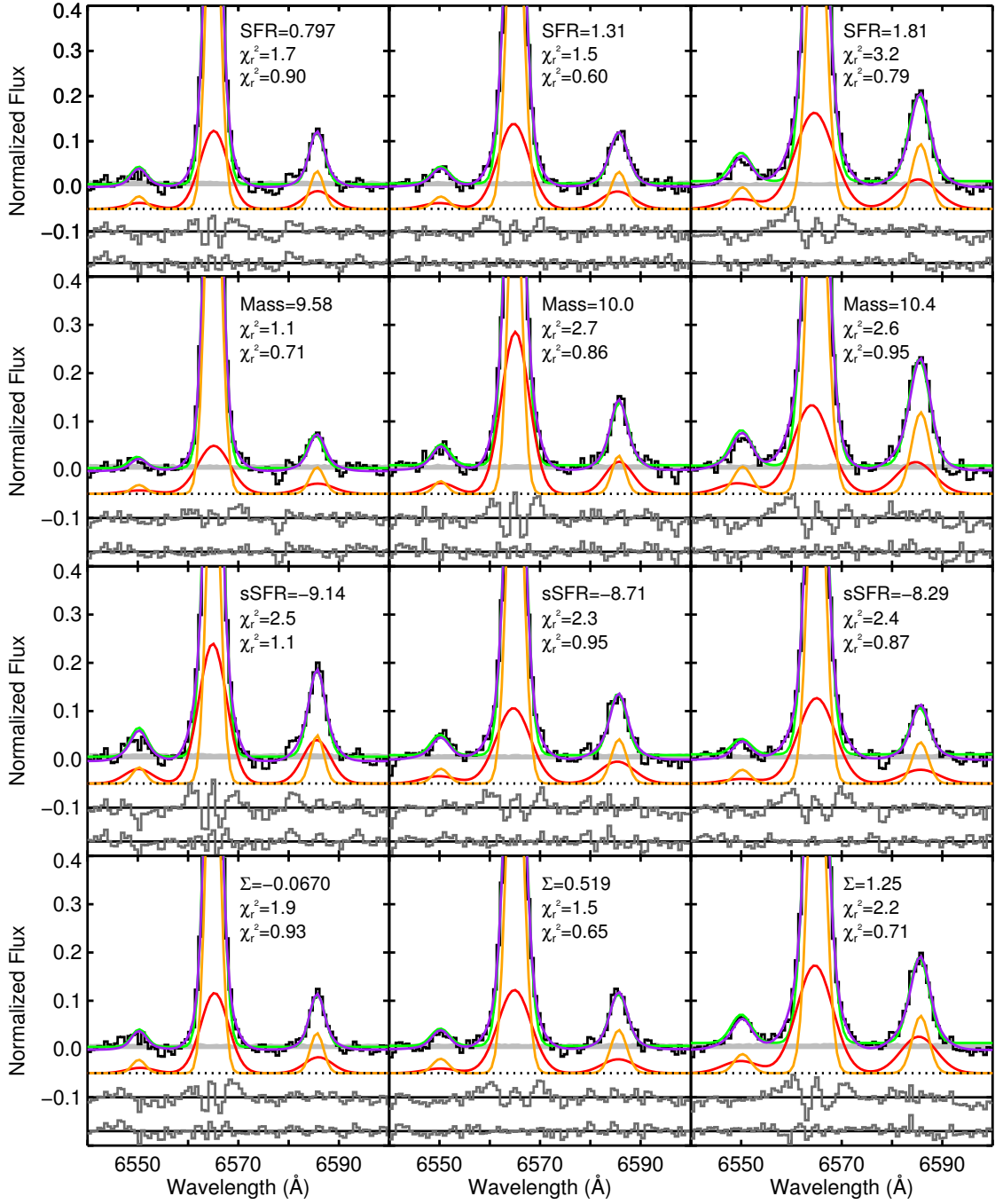


Figure 2.3 Stacks of galaxies showing both the single Gaussian only and narrow+broader component fits for the H α and [NII] lines. The line colors have the same meaning as Figure 2.2 except for the error bars which are shown as shaded gray and the narrow components of the narrow+broader fit which are shown in orange.

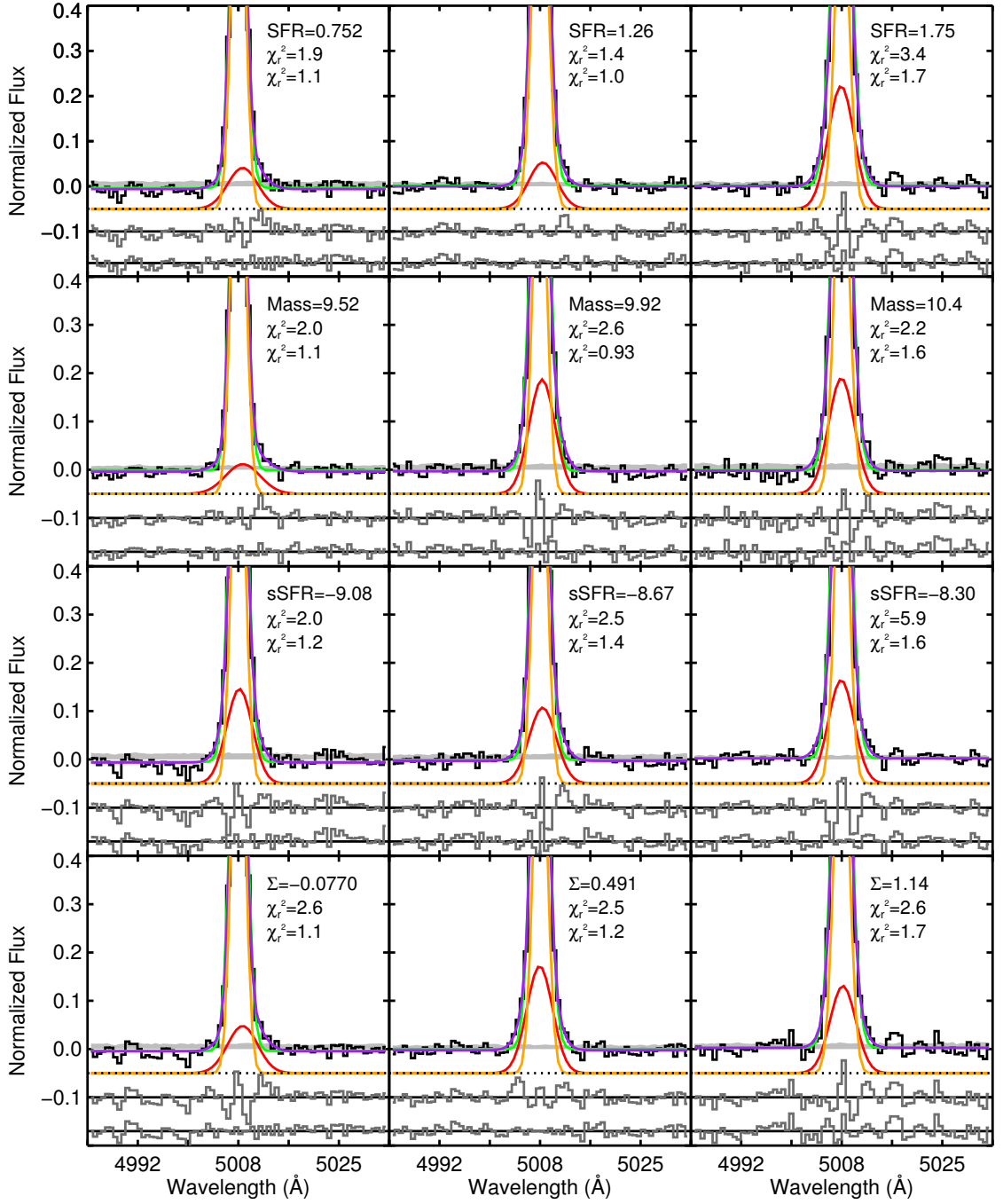


Figure 2.4 Stacks of galaxies showing both the single Gaussian only and narrow+broads component fits for the $z \sim 2.3$ [OIII] lines. Colors and labels are the same from Figure 2.3.

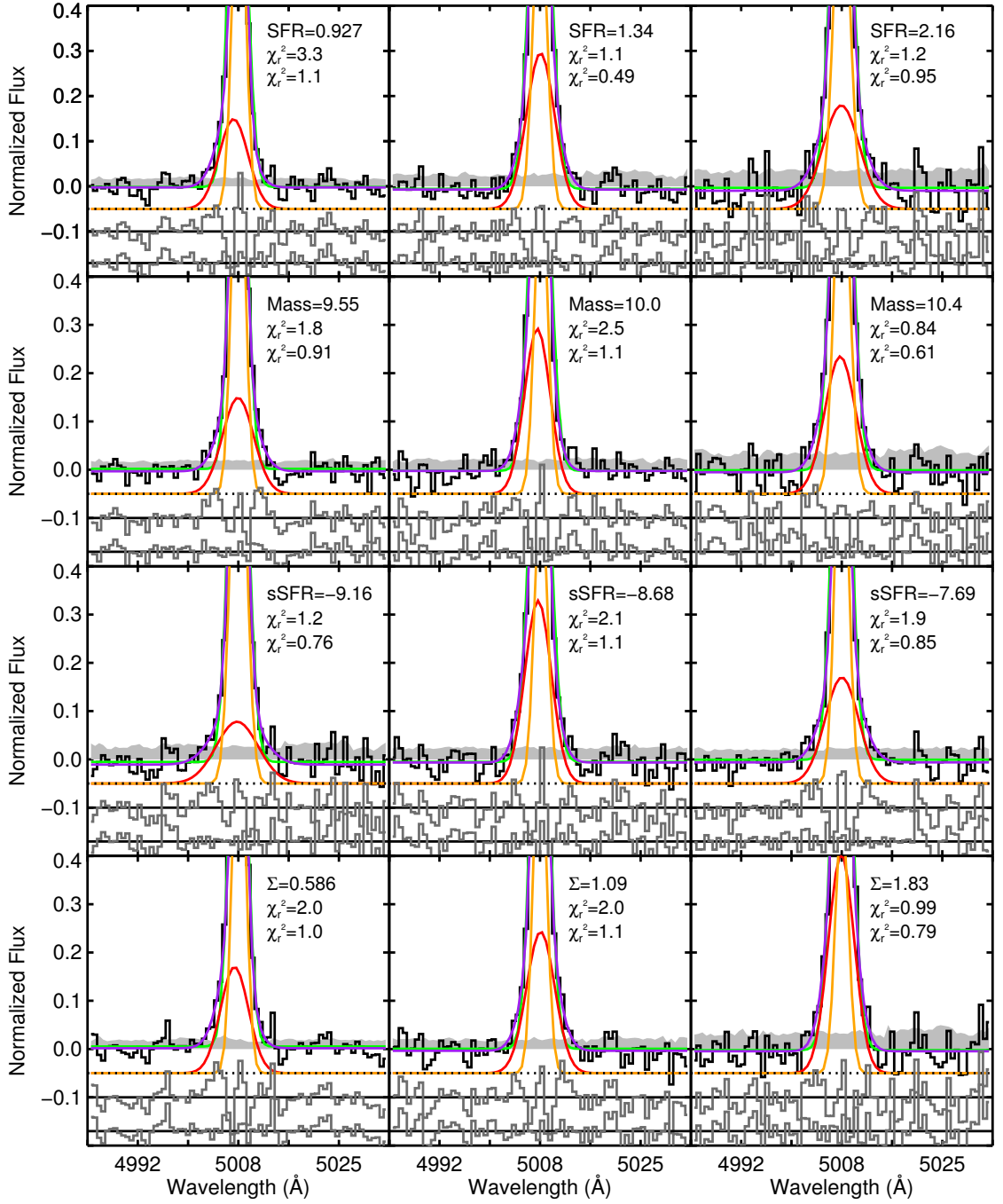


Figure 2.5 Stacks of galaxies showing both the single Gaussian only and narrow+broad component fits for the $z \sim 3.3$ [OIII] lines. Colors and labels are the same from Figure 2.3.

error is calculated by taking the standard deviation of the 200 stacks at each wavelength. The $z \sim 2$ stacks by $\text{H}\alpha$ are shown in Figure 2.3, the $z \sim 2$ stacks by $[\text{OIII}]$ are shown in Figure 2.4, and the $z \sim 3$ stacks by $[\text{OIII}]$ are shown in Figure 2.5.

With this sample, it is also possible to create stacks in bins of SFR, sSFR, and Σ_{SFR} . These stacks are not truly independent from the stacks by mass because these properties correlate with mass. We chose to use mass for the primary analysis in this work because, of the physical parameters we considered, mass is the only parameter that does not depend on the $\text{H}\alpha$ emission line which may be influenced by broad emission. The results from stacks in bins of SFR, sSFR, and Σ_{SFR} are in the Appendix.

The line fitting process for stacks is the same as described in Section 2.3.1 with some exceptions. The line $[\text{SII}] \lambda\lambda 6718, 33$ is included when fitting $\text{H}\alpha$ and $[\text{NII}]$. For the lower limit of FWHM_{N} , we use the average skyline FWHM for each galaxy, which is 80 km s^{-1} . The fit to each stack is shown in Figure 2.3. This figure shows $\text{H}\alpha$ and $[\text{NII}]$ for the stacks at $1.37 < z < 2.61$. For both $\text{H}\alpha$ and $[\text{OIII}]$ in all stacks, the amplitude of the broad component is significant at the $> 3\sigma$ confidence level.

2.3.2 Assessment of False Positives

The broad component dominates the line only at the highest velocities, which is also where the S/N is the lowest. Here we test the fitting process to show that measured broad line parameters are consistent with simulated input parameters.

For this test, we take a single Gaussian, add noise, and fit the Gaussian using the method described in Section 2.3.1. Since this idealized Gaussian has no actual broad component, any broad component that we measure is a false positive. We did this test on 200 simulated emission lines, each with 10 different FWHMs between 75 and 275 km s^{-1} , which spans the range of measured narrow components from the MOSDEF sample. We used the same resolution and wavelength as for an $\text{H}\alpha$ line for a $z \sim 2.3$ galaxy. We add a constant amount of noise to each spectrum such that the

S/N of the H α line ranges between 10 and 300. The assumption of constant noise is an appropriate approximation of the error for a single emission line in the actual spectra because we are limited by the bright sky rather than Poisson noise from the object. The noise does increase as a function of wavelength, particularly in the K band, but this test was only on a single emission line and the error does not change much over the span of a single emission line.

We find that only 11%, 1%, and 0.05% of simulated galaxies have a false positive of 1 σ , 2 σ , or 3 σ respectively. These are lower than the expected rates based on Gaussian statistics, which are 16%, 2%, and 0.1%. The slightly lower values of the test result are because we allow the narrow peak to exceed 1.0 (the max is 1.05). The average broad component is slightly less than 0 which creates an offset in the number of 1 σ , 2 σ , or 3 σ detections. Another result of this test is that the fraction of false positives did not change as a function of width or noise added.

In addition to false positives in individual spectra, there is a possibility of creating an artificial broad component when making the stacks. We performed several tests to ensure that in creating the stacks, we did not also create an artificial broad component. The first test takes 50 Gaussians of random FWHM between 75 and 250 km s $^{-1}$, adds noise, and creates a stack as described in Section 2.3.2. Each added Gaussian has a constant amount of noise across each wavelength element which is similar to the actual spectra except for skylines which are not included in these simulated stacks. We found no evidence of introducing false positives when creating stacks. We repeat this test and add a random shift between ± 1 Å to the centroid of the Gaussian which simulates imperfect redshift estimates. The average redshift error for this sample is 6×10^{-5} which is ~ 0.13 Å at these redshifts. These stacks also failed to produce false positives.

These test have shown that we do not expect false positives to be an issue when using the fitting method described in Section 2.3.1. We have also shown that creating stacks of galaxies does not introduce a broad emission signature.

2.4 Results

In this section, we discuss the broad flux measured in individual and stacked spectra. We discuss the physical interpretation of these measurements in the subsequent section.

2.4.1 Broad Flux Ratio

After fitting each galaxy and stack, we parameterize the broad emission we measured as a broad to narrow flux ratio (broad flux / narrow flux, BFR). We chose this parameterization because other studies have used this and allow for easy comparison (Newman et al. 2012, Shapiro et al 2009, Genzel et al 2011). The BFR is also used to estimate the mass loading factor (Section 2.5.3). Note that $\text{broad flux}/\text{total flux} = 1/(1 + \text{BFR}^{-1})$.

Figures 2.6 and 2.7 show the BFR measured from the $\text{H}\alpha$ line as a function of mass. For individual galaxies, there are 10 detections with $> 3\sigma$ significance out of 138 galaxies (7%). For the stacks and most of the galaxies with detections, the broad flux accounts for 15-40% of the total flux in nebular emission lines. The MOSDEF measurements for BFR are consistent with the measurements from Newman et al. (2012) who did a similar analysis for galaxies at the same mass range. The details of the fits are in Table 2.4.2. The small differences in the number of significant detections in this study and Leung et al. (2017) for the same sample can be attributed to slight differences in codes used to fit the data.

Figures 2.9 and 2.10 show the BFR measured from the $[\text{OIII}]$ line as a function of mass. For $[\text{OIII}]$ there are 21 detections with $> 3\sigma$ significance out of 201 galaxies (10%). For the stacks and galaxies with detections, the broad flux accounts for 20-50% of the total flux in nebular emission lines. For the $z \sim 3$ stacks the broad component comprises 30-60% of the flux and the BFR is slightly higher than in the $z \sim 2$ stacks.

At first glance, the stacks in Figure 2.7 appear to show a correlation between the BFR with mass. Measuring the broad flux in the lowest mass stack is difficult because most of the broad

emission may be at $\text{FWHM} < 275 \text{ km s}^{-1}$ and reliably detecting low velocity broad emission is difficult (discussed in detail in Section 2.5.3). Additionally, the [OIII] broad emission at $z \sim 2$ does not show any increase above $7 \times 10^9 M_{\odot}$, and the $z \sim 3$ stacks show no change with mass (Figure 2.10). There is also no correlation between the detected broad emission in individual galaxies and mass. For these reasons, we cannot confirm a correlation between the BFR and mass.

Figure 2.8 shows the BFR measured from the $\text{H}\alpha$ line as a function of S/N. Galaxies with detections tend to also be at higher S/N. For $\text{H}\alpha$, 66% of galaxies with $\text{S/N} > 70$ have broad component detections but only 1.6% of galaxies with $\text{S/N} < 70$ have detections.

Figure 2.11 shows the BFR measured from the $\text{H}\alpha$ line as a function of S/N. For [OIII], 32% of galaxies with $\text{S/N} > 45$ have broad component detections but only 5% of galaxies with $\text{S/N} < 45$ have detections. It is easier to detect broad emission in [OIII] than in $\text{H}\alpha$ because we include the [OIII] $\lambda 4959$ emission when fitting [OIII] $\lambda 5007$. Using both lines in the fit provides a better constraint on the shape of the broad and narrow emission profiles than using only one line.

The dependence of the detection on S/N implies that the 10% rate is a lower limit. Because outflows are supposedly ubiquitous at $z \sim 2$ we would likely see more broad component detections with deeper data. A dependence on S/N and a broad component detection was also seen in Leung et al. (2017) for AGN in the MOSDEF sample.

2.4.2 Broad and Narrow Component Line Ratios

As described in Section 2.3.1, we fit narrow and broad components to the [OIII], $\text{H}\beta$, $\text{H}\alpha$, [NII], and [SII] emission lines. From this, we are able to calculate the [NII]/ $\text{H}\alpha$, [SII]/ $\text{H}\alpha$, and [OIII]/ $\text{H}\beta$ ratios and place each component on the N2-BPT and S2-BPT diagrams. Figure 2.14 shows the N2-BPT and S2-BPT diagram for the low, medium, and high mass stacks. We do not

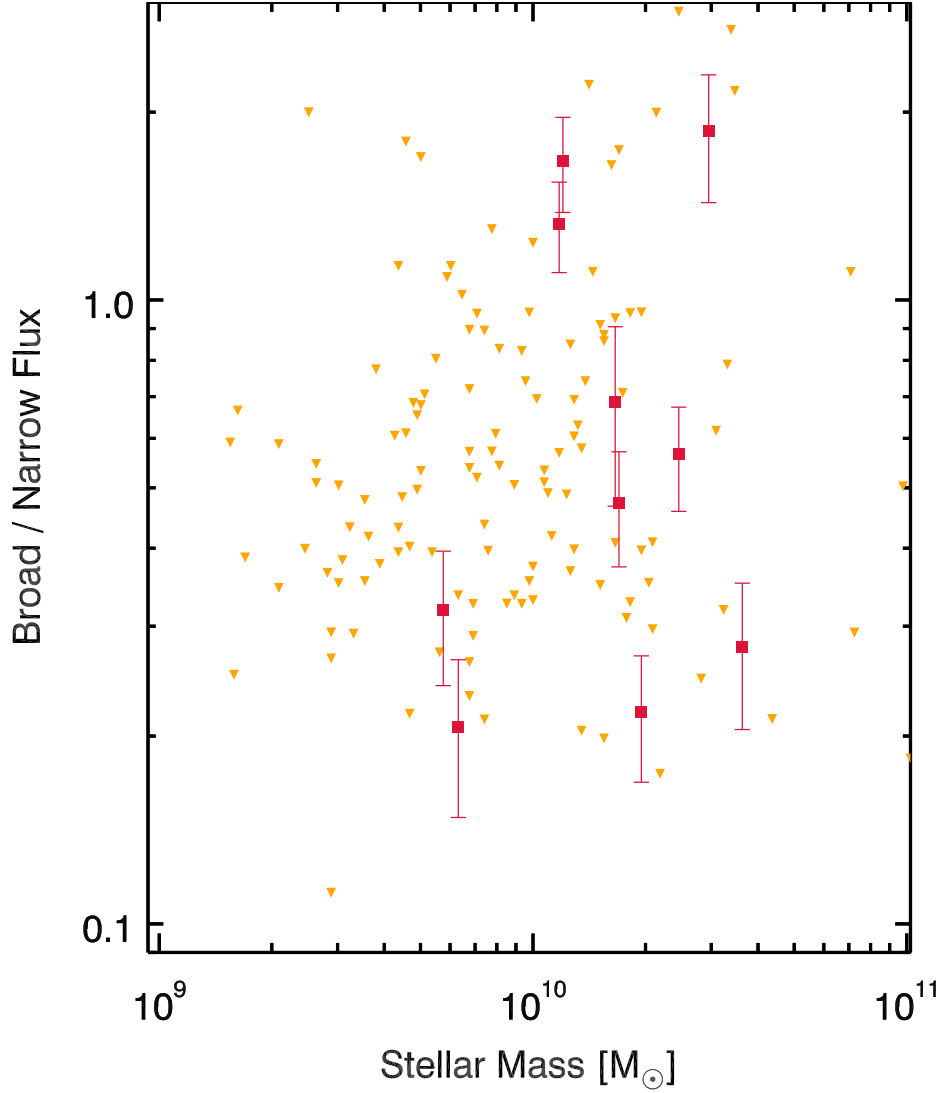


Figure 2.6 BFR as a function of stellar mass for $H\alpha$. Red squares are galaxies with a detection of $> 3\sigma$ significance with one sigma error bars plotted. Orange triangles are 3σ upper limits for galaxies with $< 3\sigma$ significance. The vertical error bars are one-sigma error bars from the fit.

include individual galaxies here because the S/N is too low to create robust line ratios. In this figure, we show trends measured from other studies. The blue dotted line is measured from Kewley et al. (2013) for local galaxies. The orange dashed line is measured from Shapley et al. (2015) for $z \sim 2.3$ galaxies in the MOSDEF survey. The dashed black line is the line from Kauffmann et al. (2003) that separates star forming galaxies and AGN for local galaxies. The dotted black line is

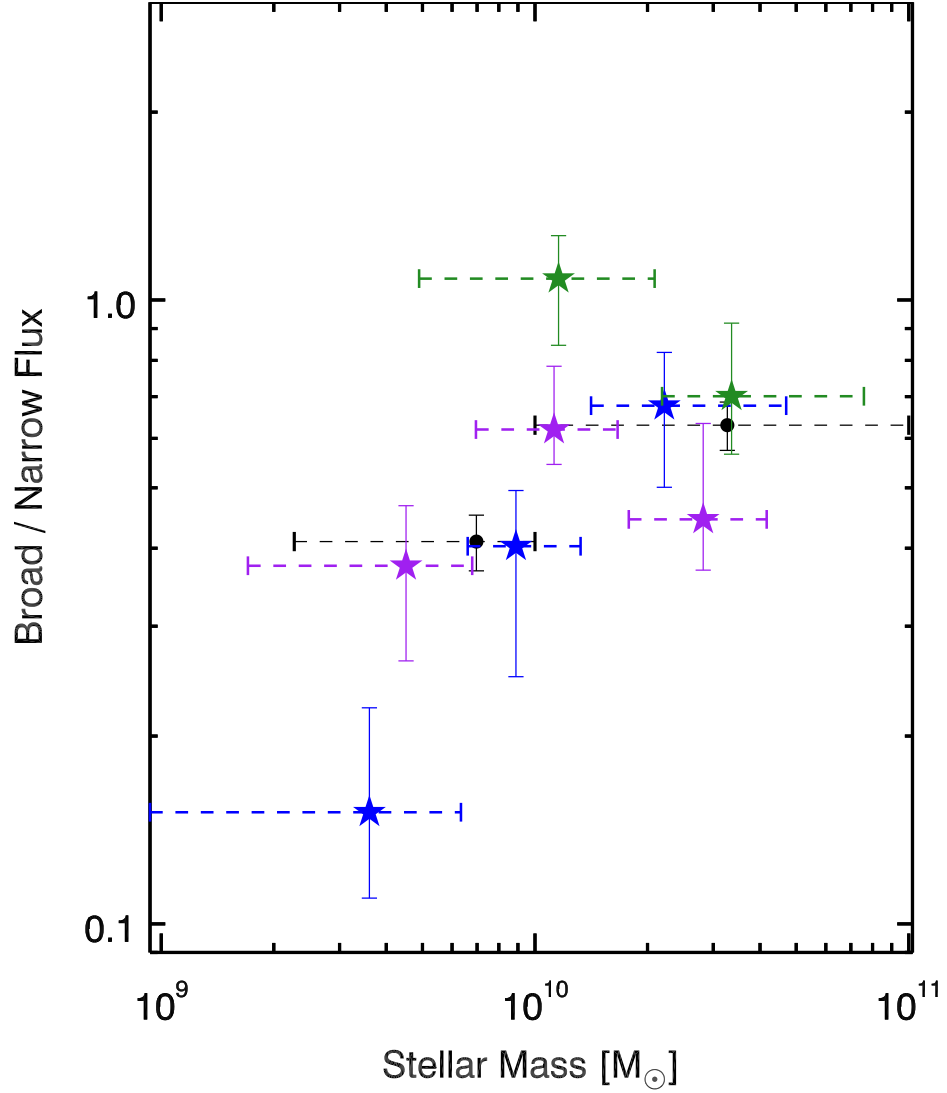


Figure 2.7 BFR as a function of stellar mass from stacks for $H\alpha$. Blue stars show the BFR of the stacks. The purple stars are the stacks galaxies with high inclination. Black points are stacks from Newman et al. (2012). The green stars are a high-SFR sub sample that includes all galaxies with an $SFR > 40 M_{\odot} \text{ yr}^{-1}$. The vertical error bars are one-sigma error bars from the fit and the horizontal dashed lines show the domain of points included.

from Kewley et al. (2001) and is the “maximum starburst” line where galaxies containing AGN lie above this line.

For individual galaxies, Balmer emission-line fluxes can be corrected for underlying stellar absorption based on the equivalent widths of stellar Balmer features as estimated from the stellar

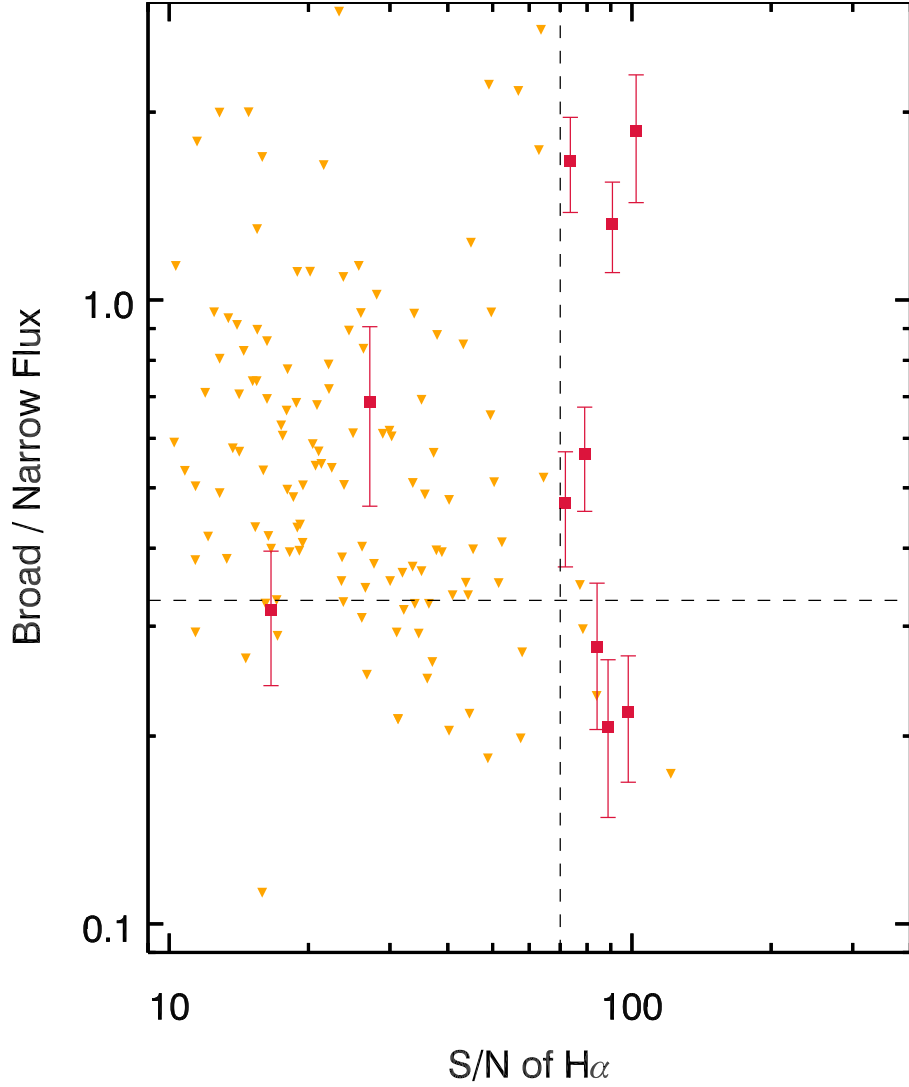


Figure 2.8 BFR as a function of S/N for $H\alpha$. S/N is measured by the flux of the emission line fit with a single Gaussian function. The dashed lines mark a S/N of 70 and a BFR of 0.33 (corresponding to a broad to total flux fraction of 25%). In the MOSDEF sample, 66% of galaxies with $S/N > 70$ have broad component detections but only 1.6% of galaxies with $S/N < 70$ have detections.

population synthesis model fit to the SED of each galaxy (Reddy et al. 2015). For each stack, we estimate the Balmer absorption by calculating the average absorption for each galaxy in the stack. This gives us an estimate for the total fraction of flux that was absorbed but no information about the shape. However, without knowing the exact shape/width of the absorption feature, we do not know how much of the correction should be applied to the narrow line and how much should be applied

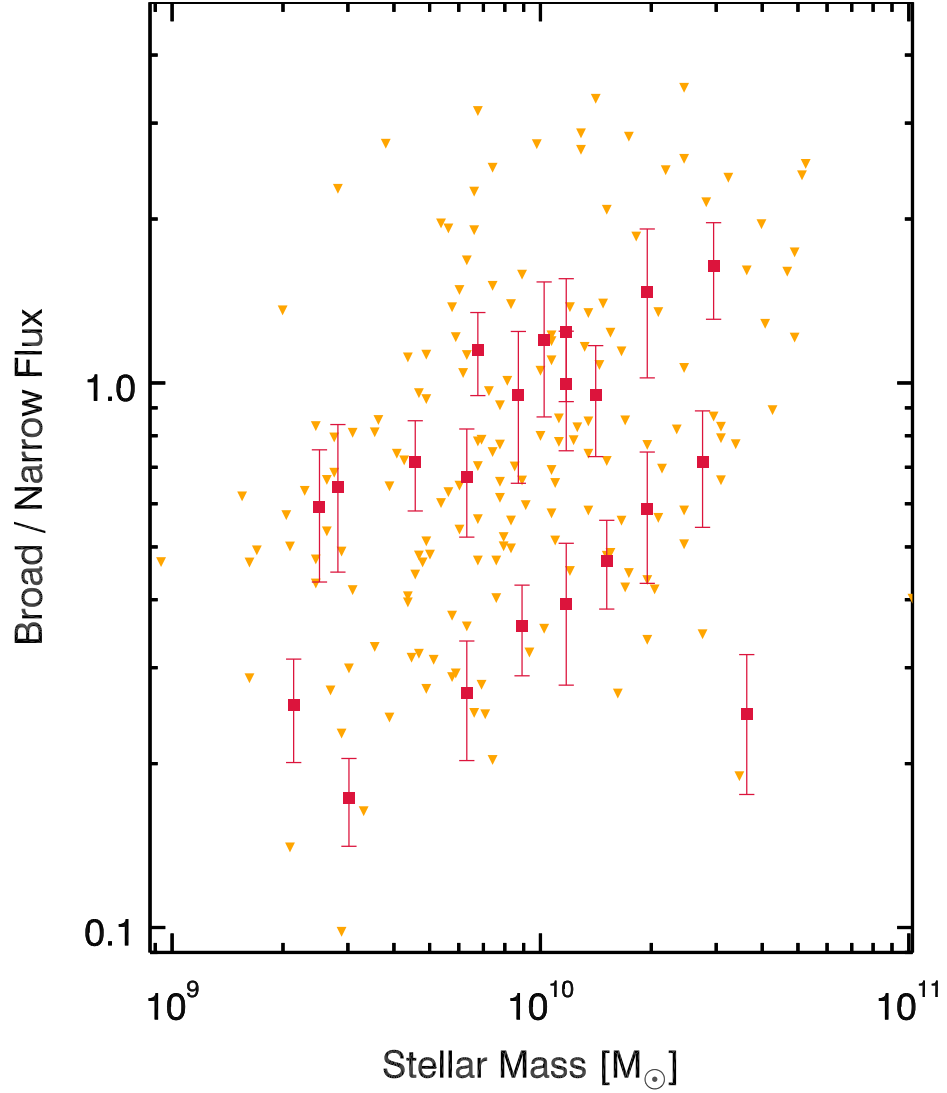


Figure 2.9 BFR as a function of stellar mass for [OIII]. Symbols are the same as Figure 2.6

to the broad line. Therefore, we calculate the Balmer absorption correction assuming the broad component is affected by 0, 33, 66, and 100% of the Balmer absorption and the narrow component is affected by 100, 66, 33, and 0% respectively. In Figure 2.14, the 0% and 100% absorption cases correspond to the hollow point and the solid point furthest from the hollow point, respectively. These corrections allow us to look at the extremes for Balmer absorption corrections in each component. For the single gaussian fits (square points) there is only one solid point because the Balmer emission

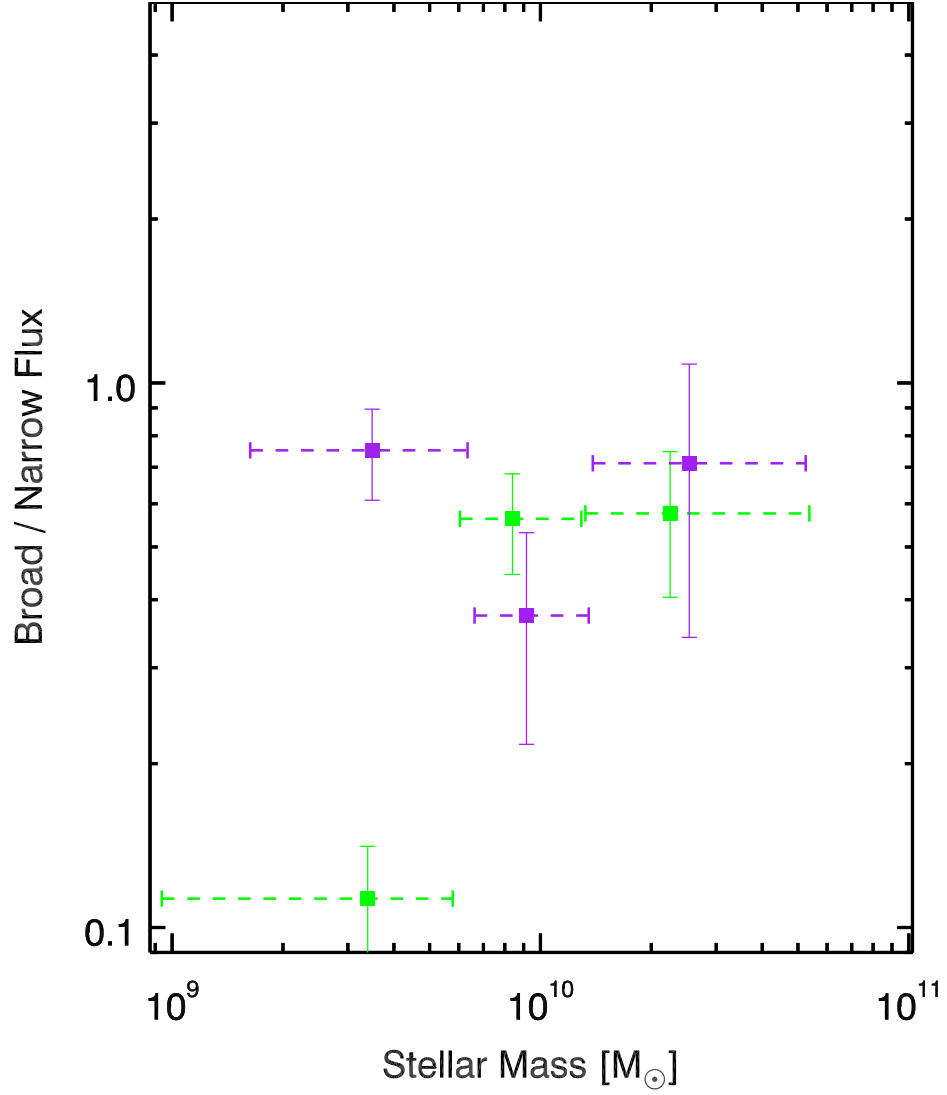


Figure 2.10 BFR as a function of stellar mass for stacks of [OIII]. Symbols are the same as Figure 2.7

is not split between narrow and broad components and the magnitude of the Balmer absorption correction is unambiguous.

In Figure 2.14, the ratios from the single Gaussian fits (squares) are lower than results from previous MOSDEF studies (Shapley et al. 2015). This can be explained by the fact that we required a $S/N > 10$ for the $H\alpha$ and [OIII] lines. This requirement preferentially removed lower mass galaxies which are typically more offset from the local relation.

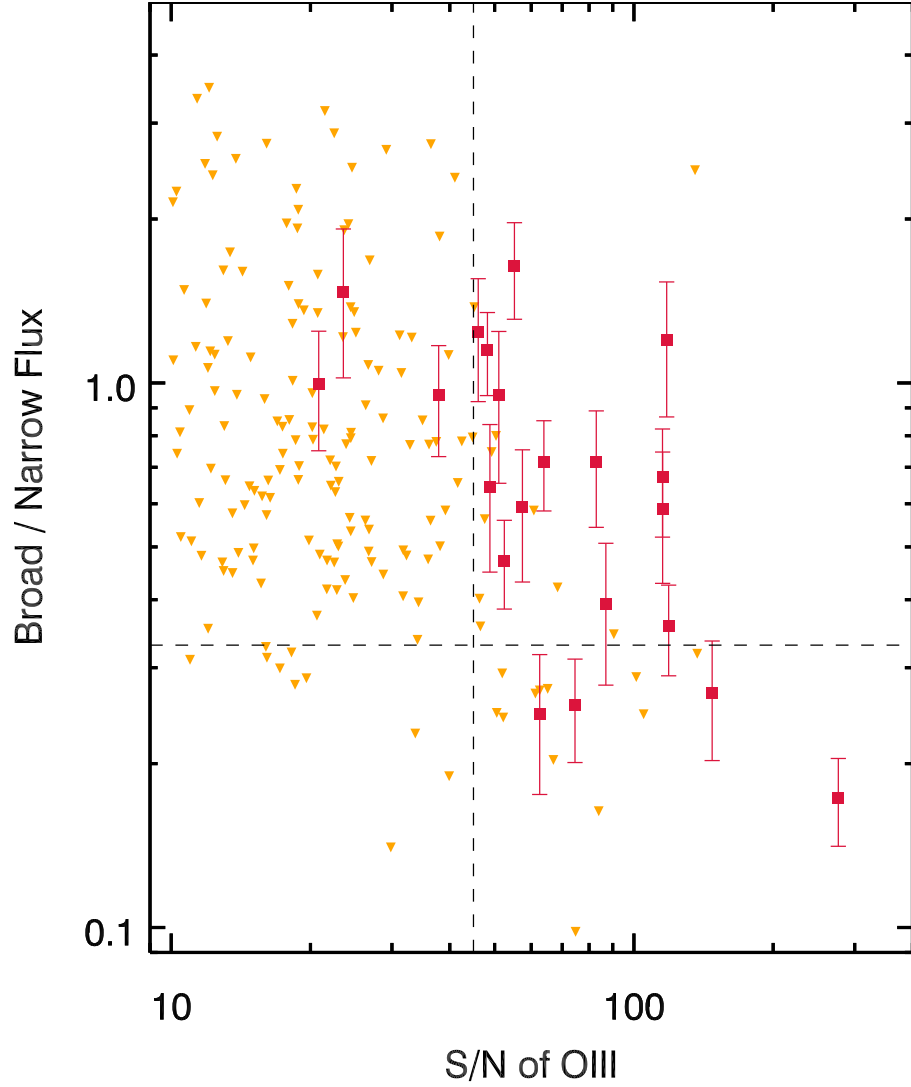


Figure 2.11 BFR as a function of S/N for [OIII]. S/N is measured by the flux of the emission line fit with a single Gaussian function. The dashed lines mark a S/N of 70 and a BFR of 0.33 (corresponding to a broad to total flux fraction of 25%).

The narrow component ratios tend to lie more towards the $z \sim 0$ relationship (blue dotted line, Kewley et al. 2013) than other measurements at $z \sim 2.3$. The broad components of the narrow+broad fits (diamonds) lie in the composite region or above the Kewley et al. (2001) line. After Balmer correction the broad components are less offset in $[\text{OIII}]/\text{H}\beta$ but still have higher $[\text{NII}]/\text{H}\alpha$.

The right side of Figure 2.14 shows the S2-BPT diagram for each stack and for each component. The [SII] line typically has less flux than the [NII] line making measuring the broad component more difficult. We are only able to place 1σ limits on the broad components of the [SII] line in stacks.

The results from the non-parametric fits are shown in Figure 2.13. The high velocity points are typically higher than the Kauffmann et al. (2003) line which is a similar trend to the broad component ratios in Figure 2.14. This shows that the results from the fits are not likely from an incorrect fit to the data, and that the results presented here do not particularly depend on the model for measuring the broad flux. Other emission profiles may be able to measure the broad component (ie. Voigt), but a test of different models for measuring broad emission are beyond the scope of this work.

2.4.3 Non-parametric Line Ratio Measurements

It is possible that the narrow line profile may not be Gaussian shape and could be more complicated (van der Marel & Franx 1993). Inspection of the residuals of galaxies with high S/N shows no clear pattern and the reduced χ^2 are typically close to unity.

Up to this point we have assumed the broad flux is Gaussian in shape. The kinematics may be more complicated and produce non-Gaussian shapes. Additionally, the Balmer absorption could also change the shape of the emission lines. Balmer absorption is broader than emission lines and could affect the broad emission more than the narrow emission. To measure broad emission regardless of shape, we calculate line ratios using the flux at different velocities from the centroid of each line for stacks from Figure 2.14 as well as galaxies with > 10 S/N in all four lines (8 galaxies).

Figure 2.13 shows the numerical integration results for the highest S/N galaxies and the stacks. Overall the high velocity points (where the broad emission dominates) show similar trends to higher [NII]/H α as the fitted broad emission components in Figure 2.14. It is reasonable to use

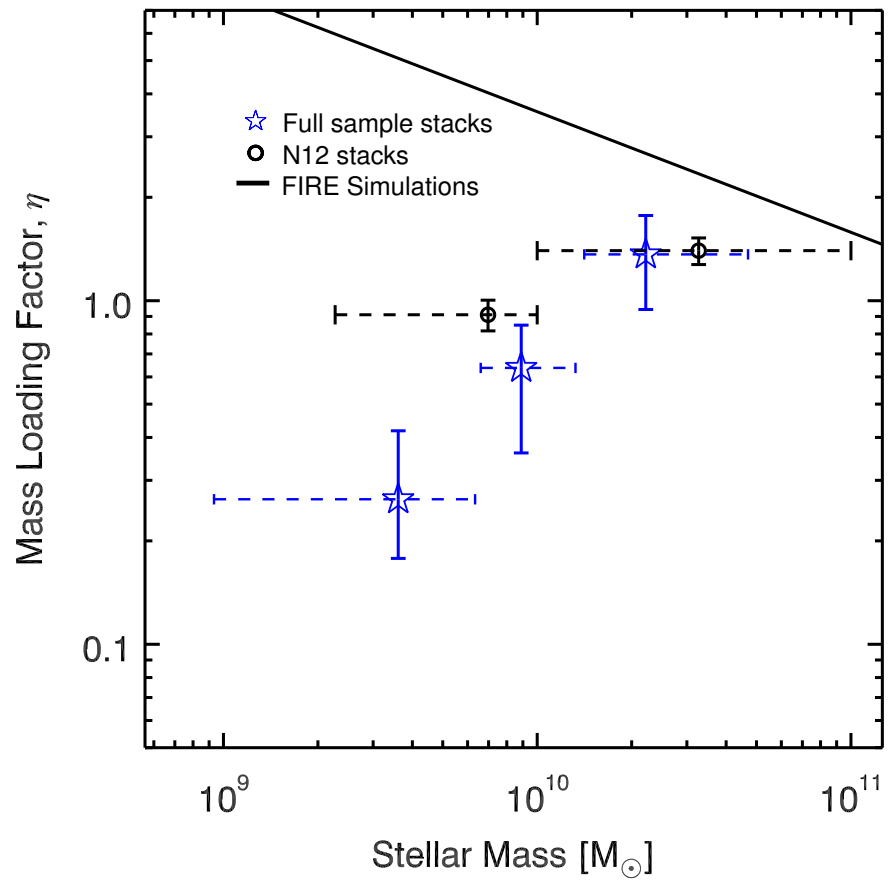


Figure 2.12

Par. ^a	Stack avg ^b	Stack range ^c	BFR ^d	BFR _n ^e	BFR _x ^f	FWHM ^g	vel. off. ^h
SFR	0.794	0.360 — 1.05	0.24 ± 0.067	0.035	0.44	300 ± 80	-51. ± 20
SFR	1.28	1.05 — 1.47	0.28 ± 0.085	0.021	0.53	300 ± 50	-11. ± 10
SFR	1.76	1.48 — 2.23	0.65 ± 0.15	0.19	1.1	300 ± 30	17. ± 7
Mass	9.53	8.97 — 9.76	0.11 ± 0.028	0.029	0.20	390 ± 100	-83. ± 40
Mass	9.92	9.78 — 10.1	0.56 ± 0.12	0.21	0.92	300 ± 20	-18. ± 8
Mass	10.4	10.1 — 10.7	0.58 ± 0.17	0.060	1.1	300 ± 30	8.5 ± 9
sSFR	-9.04	-10.2 — -8.81	0.31 ± 0.098	0.020	0.61	300 ± 90	-31. ± 10
sSFR	-8.64	-8.81 — -8.46	0.34 ± 0.12	-0.012	0.70	300 ± 50	-6.1 ± 10
sSFR	-8.29	-8.45 — -7.74	0.45 ± 0.081	0.21	0.69	310 ± 30	11. ± 6
Σ	-0.0470	-0.742 — 0.290	0.21 ± 0.048	0.062	0.35	330 ± 60	-49. ± 20
Σ	0.507	0.313 — 0.692	0.44 ± 0.095	0.15	0.72	300 ± 40	-3.6 ± 7
Σ	1.15	0.719 — 1.92	0.18 ± 0.046	0.046	0.32	840 ± 1000	9.1 ± 20
SFR*	0.94	0.34 — 1.1	0.73 ± 0.16	0.24	1.2	300 ± 20	41. ± 10
SFR*	1.3	1.1 — 1.4	0.29 ± 0.16	-0.19	0.77	300 ± 100	-27. ± 30
SFR*	2.1	1.6 — 2.7	0.92 ± 0.33	-0.076	1.9	390 ± 60	-26. ± 20
Mass*	9.5	9.2 — 9.8	0.75 ± 0.14	0.32	1.2	340 ± 30	-13. ± 9
Mass*	10.	9.8 — 10.	0.37 ± 0.16	-0.097	0.85	300 ± 100	27. ± 20
Mass*	10.	10. — 11.	0.71 ± 0.37	-0.40	1.8	320 ± 80	25. ± 20
sSFR*	-9.1	-9.8 — -8.9	0.54 ± 0.29	-0.33	1.4	300 ± 90	24. ± 20
sSFR*	-8.7	-8.8 — -8.6	0.56 ± 0.25	-0.17	1.3	300 ± 60	11. ± 20
sSFR*	-7.8	-8.4 — -7.3	0.77 ± 0.19	0.20	1.3	350 ± 50	-17. ± 10
Σ*	0.59	-0.082 — 0.82	0.72 ± 0.19	0.15	1.3	300 ± 40	36. ± 10
Σ*	1.1	0.88 — 1.3	0.65 ± 0.21	0.010	1.3	300 ± 50	-12. ± 10
Σ*	1.8	1.5 — 2.3	1.1 ± 0.45	-0.29	2.4	320 ± 40	15. ± 10

Table 2.2 Parameters from the stack fits. a: Parameter by which the stack was created. The * indicates a $z \sim 3.3$ stack. b: The geometric mean of the galaxies included. c: Range of galaxies included. d: Broad Flux Fraction of the stack and $1\text{-}\sigma$ errors. e: The $3\text{-}\sigma$ lower limit on the Broad Flux Fraction (negative value means a $< 3\sigma$ significance of the measurement). f: The $3\text{-}\sigma$ upper limit on the Broad Flux Fraction. g: The FWHM of the broad component (km s^{-1}) and the $1\text{-}\sigma$ error. h: The velocity offset between the peaks of the broad and narrow components (km s^{-1}). A negative value indicates a blueshift. The $1\text{-}\sigma$ error in the velocity offset is included.

the fits since the non-parametric measurements show similar results and the double-gaussian models are good fits to the data.

2.5 Discussion

In this section we discuss possible origins of the broad flux emission that can explain the offset line ratios of the broad component compared to the narrow component. We consider shocks (Section 2.5.1) and low luminosity AGN (Section 2.5.2). We also interpret the broad emission as an

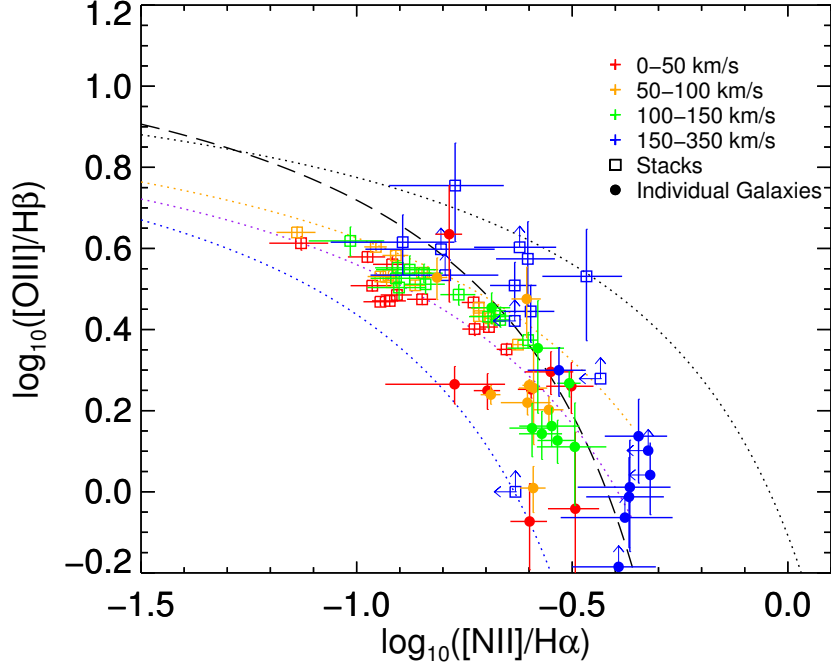


Figure 2.13 N2-BPT diagram calculated by integrating the emission within several velocity bins. The higher velocity bins are more offset than the lower velocity bins. This may show that the larger velocity parts of an emission line are dominated by a broad emission component that is also offset.

outflow and estimate the mass loading factor for the stacks (Section 2.5.3).

2.5.1 Shocks

Emission line ratios from shocks differ from ratios in purely photoionized gas. Shock-heated gas can become ionized by high-energy photons from the shock or by collisional excitation. Emission line ratios shift in the presence of shocks and the magnitude and direction of the shift depends on the metallicity, electron density, magnetic field, and shock velocity (Allen et al. 2008). Shocked emission tends to have higher $[\text{NII}]/\text{H}\alpha$ and $[\text{SII}]/\text{H}\alpha$ ratios relative to what is produced in photoionized HII regions (Allen et al. 2008). Since the broad components in Figure 2.14 have higher $[\text{NII}]/\text{H}\alpha$ ratios than the narrow components or single Gaussian fits, this may indicate the presence of shocks. In this section, we investigate if the broad emission can be explained by shocks by creating the N2-BPT

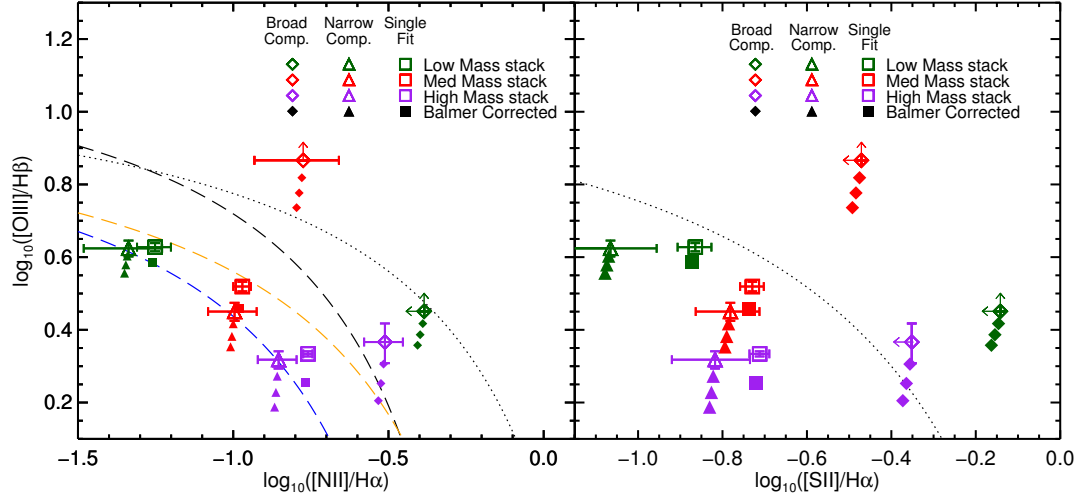


Figure 2.14 The N2-BPT and S2-BPT diagram for $z \sim 2.3$ stacks of data by mass. The ratios for each stack were calculated using the narrow component, broad component, and single gaussian fits. The broad component ratios, narrow component ratios, and single Gaussian fit ratios are the diamonds, triangles, and squares respectively. The solid points are corrected for Balmer absorption. For the narrow and broad line ratios, the three points show if 33, 66, and 100% of the Balmer absorption is in that particular component. Error bars are $1-\sigma$ and galaxies with $S/N < 3$ are plotted at $1-\sigma$ limits and are marked by arrows. The blue dotted line is measured from Kewley et al. (2013) for local galaxies. The orange dashed line is measured from Shapley et al. (2015) for $z \sim 2.3$ galaxies in the MOSDEF survey. The dashed black line is the line from Kauffmann et al. (2003) that separates star forming galaxies and AGN. The dotted black line is from Kewley et al. (2001) and is the “maximum starburst” line where above this line lie AGN.

and S2-BPT diagrams using data from the shock models by Allen et al. (2008)⁵ and comparing these models to the broad emission line ratios.

The shock models simulated emission line ratios for shocked gas, the precursor to the shock, and a shock+precursor which combines the shock and precursor components. Because we do not spatially resolve the emission from these galaxies, we are unable to separate the different components of the shock. Therefore, we compare our measurements of the broad emission to the combined shock+precursor ratios.

Allen et al. (2008) measured shock+precursor emission line ratios for two sets of models, one at a fixed electron density and varying metallicity ($n_e = 1 \text{ cm}^{-3}$ at $\log(O/H)+12$ of 8.03, 8.35, 8.44, and 8.93), and another at fixed metallicity and varying electron density ($\log(O/H) + 12 = 8.93$

⁵<http://cdsweb.u-strasbg.fr/~allen/shock.html>

at $n_e = 1, 10, 100, 1000 \text{ cm}^{-3}$). We restrict the models shown to those that have a magnetic field strength at pressure equipartition. The shock velocity for the models range from $100 - 1000 \text{ km s}^{-1}$, but we only show shock velocities of $200-500 \text{ km s}^{-1}$ based on the velocities measured in Table 2.4.2.

In Figures 2.15 and 2.16 we show the shocked models for the N2-BPT and S2-BPT diagrams respectively. The top row shows the effect of changing metallicity on shocked ratios, and the bottom row shows the effect of changing density. The galaxies in this sample (with S/N of $[\text{NII}] > 3$) have a median metallicity of $\log(\text{O}/\text{H})+12 = 8.43$ with 80% of galaxies between $8.27 < \log(\text{O}/\text{H})+12 < 8.59$ calculated using the $[\text{NII}]/\text{H}\alpha$ ratio as in Sanders et al. (2015). The electron density of the MOSDEF galaxy sample is $290^{+169}_{-88} \text{ cm}^{-3}$ (Sanders et al. 2015). Since none of the simulations span exactly the range of metallicities and densities of the MOSDEF galaxies, we are forced to extrapolate between the effects of metallicity and density. We highlight the point that is the best match to the metallicity, electron density, and shock velocity in green. This green point corresponds to the shock model which has ($v = 300 \text{ km s}^{-1}$, $\log(\text{O}/\text{H})+12 = 8.44$, $n_e = 1 \text{ cm}^{-3}$) in the top row and ($v = 300 \text{ km s}^{-1}$, $\log(\text{O}/\text{H})+12 = 8.93$, $n_e = 100 \text{ cm}^{-3}$) in the bottom row.

In Figure 2.15, there is a strong metallicity dependence on the $[\text{NII}]/\text{H}\alpha$ ratio and there is almost no change as a function of electron density except at the highest density ($n_e = 1000 \text{ cm}^{-3}$) where $[\text{NII}]/\text{H}\alpha$ decreases. The broad lines measured from stacks are consistent with the $[\log(\text{O}/\text{H})+12=8.44$, $n_e = 1 \text{ cm}^{-3}]$ and $[\log(\text{O}/\text{H})+12=8.35$, $n_e = 1 \text{ cm}^{-3}]$ points. The shock model that best matches the physical parameters is very near the broad emission line ratios. Therefore, it is feasible that the positions of the broad components in the N2-BPT diagram can be explained by shocks.

In the top row of Figure 2.16, the model that best matches the MOSDEF data has a higher $[\text{SII}]/\text{H}\alpha$ ratio than any of the broad emission. This may be due to the limitation that the models with varying metallicity have an electron density of 1 cm^{-3} . The models in the bottom row show that $[\text{SII}]/\text{H}\alpha$ decreases as electron density increases. Since the electron density of the MOSDEF galaxy sample is $290^{+169}_{-88} \text{ cm}^{-3}$ the models in the top row would likely shift to lower $[\text{SII}]/\text{H}\alpha$ ratios at higher electron densities. Therefore, it is feasible that the positions of the broad components in

the S2-BPT diagram can be explained by shocks.

From these line ratios, we conclude that it is feasible that the broad emission is a result of shocked emission. This does not rule out other sources of emission such as AGN (discussed in Section 2.5.2) and photoionized outflows (discussed in Section 2.5.3).

2.5.2 AGN

When creating the sample presented in this work, we removed all X-ray, IR, and optically identified AGN from this sample because our goal is to study star formation driven outflows, and AGN are known to drive outflows at $z \sim 2$ (Förster Schreiber et al. 2014, Leung et al. 2017). However, there may be low luminosity AGN that were not detected with these methods and were inadvertently included in the sample. There is an observational bias against identifying AGNs at all wavelengths in low-mass galaxies (Azadi et al. 2017). This bias may lead to some galaxies that host AGN being included in the sample and stacks despite removing any optical, IR, or X-ray detected AGN. AGN typically have higher $[\text{NII}]/\text{H}\alpha$ and $[\text{OIII}]/\text{H}\beta$ ratios because of harder ionization coming from the accretion disk, which is consistent with the line ratios we find in the broad component.

With integral field spectroscopy it is possible to create spatially resolved line ratios (Newman et al. 2014, Wright et al. 2010), which can be used to determine if a galaxy in the “composite” region of the N2-BPT diagram has an AGN. Using an IFU, Newman et al. (2014) found some galaxies that lie in the composite region of the BPT diagram host AGN. The cores of these galaxies lie in the AGN region while the outer edges lie in the star-forming region. The high $[\text{NII}]/\text{H}\alpha$ and $[\text{OIII}]/\text{H}\beta$ ratios of the core indicated the presence of an AGN that would not be detected in spectra of low spatial resolution.

It is unlikely that we are detecting outflows driven primarily by AGN because AGN driven outflows have more extreme kinematics compared to star-formation driven outflows. AGN driven outflows are typically 500-5000 km/s (Genzel et al. 2014a, Förster Schreiber et al. 2014, Leung

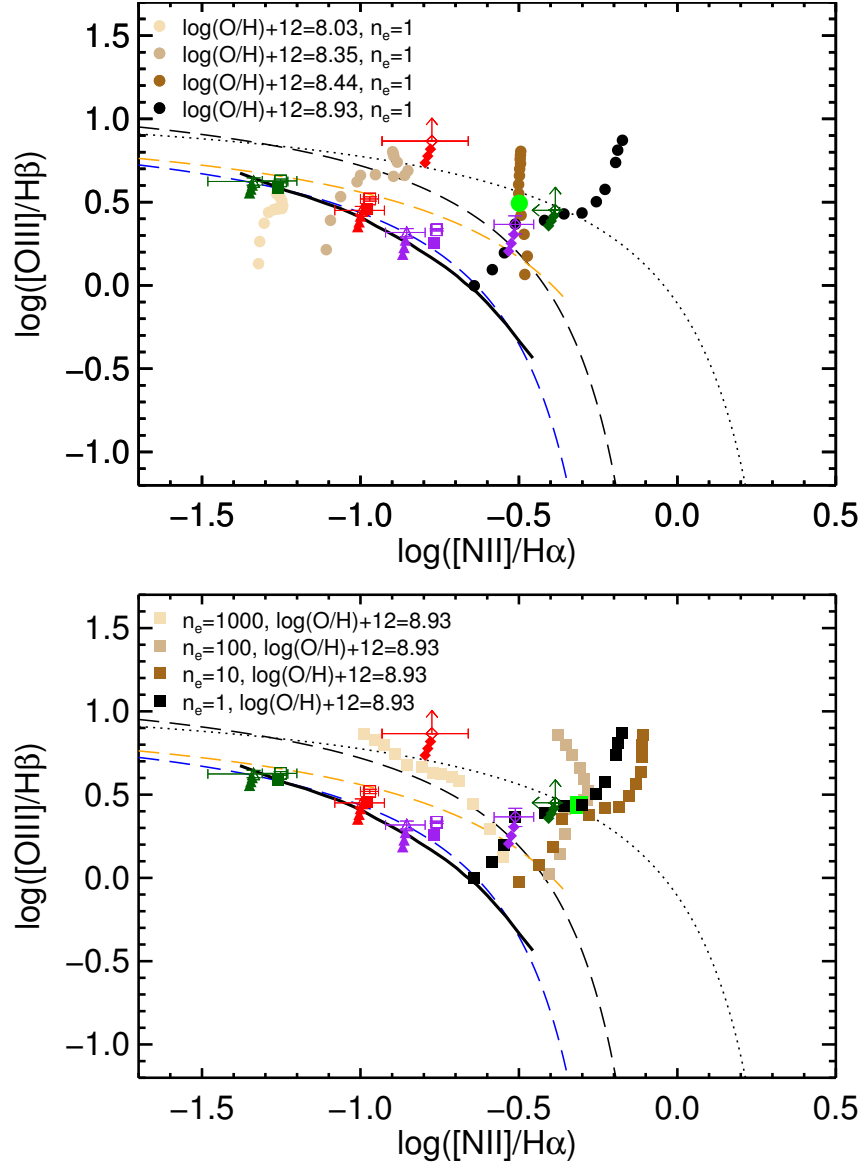


Figure 2.15 The N2-BPT diagram with shock models and SDSS. The black line are SDSS galaxies measured by Sanders et al. (2016). The tan circles are shock models from Allen et al (2008) that have an electron density of 1 cm^{-3} and metallicities of $\log(O/H) = 8.03, 8.35, 8.44$, and 8.93 . The tan squares are shock models from Allen et al (2008) that have a metallicity of $\log(O/H) = 8.93$ and an electron density of 1 cm^{-3} . The green points are the model with a shock velocity of 300 km s^{-1} at a metallicity and electron density similar to the average MOSDEF galaxy. The broad and narrow fits are also show with the same symbols as Figure XX.

et al. 2017) which is much faster than typical outflow velocities from star-forming galaxies which are $300\text{-}550 \text{ km/s}$ (Shapiro et al. 2009, Newman et al. 2012, Table 2.4.2). The velocity difference

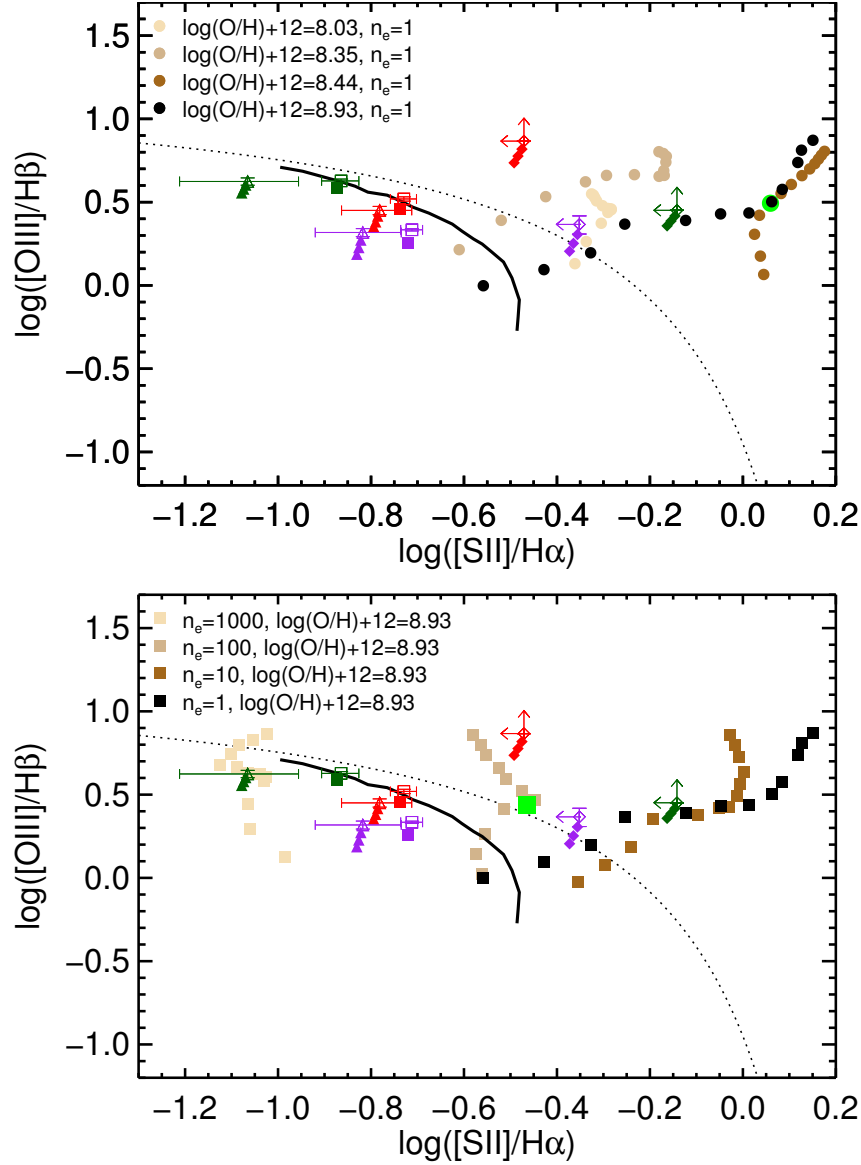


Figure 2.16 The S2-BPT diagram with shock models and SDSS.

between the narrow and broad components in AGN driven outflows is 100-500 km/s (Leung et al. 2017) while star-formation driven outflows typically have velocity offsets of < 100 km/s (Newman et al. 2012, Table 2.4.2)

Although we have removed all X-ray, IR, and optically identified AGN from this sample, we can't completely rule out some contribution to the broad (and narrow) lines from broad line regions

around low mass, low luminosity black holes. We used an extremely conservative cutoff for optically identified AGN and AGN driven outflows have very different kinematics compared to star-formation driven outflows. If there is any AGN contribution it is likely a small factor.

2.5.3 Outflows

One interpretation of the broad component is that it traces ionized outflowing materials (Bland & Tully 1988, Heckman et al. 1990, Gergeev 1992, Phillips 1993, Lehnert & Heckman 1996, Veilleux et al. 2001, Colina et al. 2004, Westmoquette et al. 2007, Westmoquette et al. 2008, Shapiro et al. 2009, Newman et al. 2012, Rupke & Veilleux 2013, Genzel et al. 2014b, Feruglio et al. 2015, Leroy et al. 2015). In this section, we interpret the broad component as a photoionized ionized outflow, calculate the mass loading factor η (outflow mass rate/SFR), and compare to other observations as well as simulations.

Using some assumptions about the outflow velocity, radius, temperature, and density we can convert the BFR into an estimate of η . We adopt the outflow model from Genzel et al. (2011). In order to compare our results to those of Newman et al. (2012) (hereafter N12), we use the same model which assumes the broad component to be photoionized and the emission of $H\alpha$ to be a result of case-B recombination.

The model assumes a spherical outflow with a constant velocity (cf. Steidel et al. 2010). The mass outflow rate, $\dot{M}_{\text{out}}$ can be calculated as:

$$\dot{M}_{\text{out}} = \frac{1.36m_H}{\gamma_{H\alpha}n_e} \left(L_{H\alpha} \frac{F_{\text{broad}}}{F_{\text{narrow}}} \right) \frac{V_{\text{out}}}{R_{\text{out}}} \quad (2.1)$$

where m_H is the atomic mass of hydrogen, V_{out} is the velocity of the outflow, R_{out} is the radius, $\gamma_{H\alpha}$ is the $H\alpha$ emissivity, n_e is the electron density in the outflow, $L_{H\alpha}$ is the total extinction corrected $H\alpha$ luminosity, and $F_{\text{broad}}/F_{\text{narrow}}$ is the BFR.

The electron density for the outflow could be measured using the broad [SII] $\lambda 6718$ /[SII] $\lambda 6733$

ratio (Osterbrock 1989, Newman et al. 2012, Sanders et al. 2016). We attempt to measure this ratio for the broad components for the stacks. The flux in the [SII] lines is low which results in a large measurement uncertainty in the ratio. We are unable to constrain the density using the broad component from this work. We adopt the value used by N12 of $50^{+50}_{-50} \text{ cm}^{-3}$.

The term $V_{\text{out}}/R_{\text{out}}$ is the characteristic timescale of the outflow. In an attempt to measure the radius of the outflow we made a stack of the 2D spectra and attempted to find broad flux in the spatial direction (e.g. Martin 2006, Leung et al. 2017). We were unable to measure a spatially extended component in the stacked spectrum. For R_{out} we adopt the value of 3 kpc as measured by N12. This value is reasonable given the angular size at this redshift is $\sim 8 \text{ kpc arcsec}^{-1}$ and our best seeing is $\sim 0.''6$. For V_{out} , we use the “maximum” velocity of the outflow defined as $V_{\text{max}} = |\Delta v_{\text{B}} - 2\sigma_{\text{B}}|$ (Genzel et al. 2011, Wood et al. 2015). This value represents the velocity of the outflow if one assumes the outflow is spherically symmetric with a constant velocity.

We use an $\text{H}\alpha$ emissivity of $3.56 \times 10^{-25} \text{ erg cm}^3 \text{ s}^{-1}$ which assumes an electron temperature of $T_e = 10^4 \text{ K}$ and density of $n_e = 10^2 \text{ cm}^{-3}$.

If we use the Kennicutt (1998) relation between SFR and $\text{H}\alpha$ luminosity corrected for a Kroupa IMF ($\text{SFR}[\text{M}_{\odot} \text{ yr}^{-1}] = 7.9 \times 10^{-42} L_{\text{H}\alpha}[\text{ergs s}^{-1}]$), we can divide Equation 1 by SFR and simplify to:

$$\eta \approx 2.0 \left(\frac{50 \text{ cm}^{-3}}{n_e} \right) \left(\frac{V_{\text{out}}}{300 \text{ km s}^{-1}} \right) \left(\frac{3 \text{ kpc}}{R_{\text{out}}} \right) \left(\frac{F_{\text{b}}}{F_{\text{n}}} \right) \quad (2.2)$$

where $F_{\text{b}}/F_{\text{n}}$ is the BFR.

Figure 2.17 shows η calculated for each stack and the values are listed in Table 2.4.2. The error calculation includes measurement uncertainties from the BFR and the FWHM_{B} . We do not include errors in the radius, electron density, and temperature assumed, and including these errors would increase the error on the mass loading factor by at least an order of magnitude. Figure 2.17 also includes the mass loading factor measured by N12. The measurements from N12 are higher

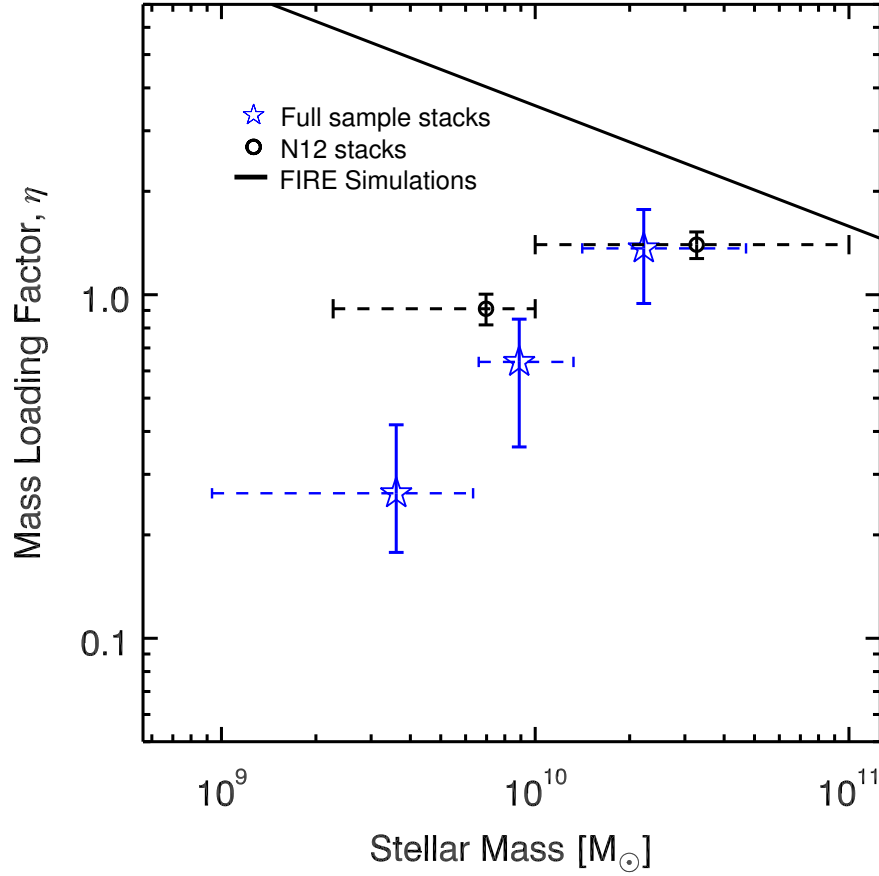


Figure 2.17 The mass loading factor as a function of mass. The $z \sim 2$ stacks from Figure 2.12 are shown as blue stars. Measurements of η from Newman et al. (2012) are shown as black circles. We also include the η vs mass relationship found from the FIRE simulations (Muratov et al. 2015). The conversion from BFR to η is described in detail in Section 2.5.1.

than the MOSDEF stacks despite having similar BFR measurements. N12 use $V_{\text{out}} = 400 \text{ km s}^{-1}$ but we use $V_{\text{out}} = |\Delta v_B - 2\sigma_B|$ which results in a lower velocity compared to N12 by 50-100 km s^{-1} .

Interestingly, η increases as a function of mass which is contrary to what we expect from the FIRE simulations (Muratov et al. 2015). This is likely explained by our inability to detect low velocity outflows. The speed of outflows increases as a function of SFR from observations (Martin 2005, Weiner et al. 2009) and simulations (Muratov et al. 2015, Christensen et al. 2015). At low outflow speeds ($\text{FWHM}_B < 275 \text{ km s}^{-1}$), the emission from the outflow may be indistinguishable from the emission from the HII regions. To quantify the detectability of low velocity outflows we

created two tests using simulated spectra where we can control the BFR and FWHM_B of galaxies used to make stacks. We then can measure the BFR and FWHM_B of the stacks and check if they are representative of the input galaxy parameters.

In the low velocity test (Test 1), the input FWHM_B s increase from 100 to 800 km s^{-1} as a function of mass. For Test 1, galaxies below $10^{10} M_*$ have velocities below 300 km s^{-1} . In the high velocity test (Test 2), the input FWHM_B s vary from 275 to 550 km s^{-1} . Both tests use the same distribution of BFRs. The slope of this distribution has the same slope of BFR vs. M_* from the FIRE simulations if one converts their η vs. M_* slope using Equation 2.2 (Equation 8 from Muratov et al. (2015)) and assuming $n_e = 50 \text{ cm}^{-3}$ and $V_{\text{out}} = 300 \text{ km s}^{-1}$. The input BFRs are offset to be in alignment with the highest mass stack (BFR=0.68 at $M_*=10.4$) where the effects of low velocity outflows should be minimized.

The results of these tests are shown in Figure 2.18. In Test 1, stacks underestimated the BFR for galaxies in the low/medium mass stacks. These stacks contain 100 and 55% galaxies with $\text{FWHM}_B < 275 \text{ km s}^{-1}$. The FWHM measured for these stacks is too large compared to the input galaxy values although this is expected because we do not allow the FWHM_B parameter to go below 300 km s^{-1} (see Section 2.3.4).

Figure 2.19 plots the fraction of mass flux above 275 km s^{-1} versus stellar mass in the FIRE simulations. At stellar masses below $< 10^{10} M_\odot$ more than half of the mass flux is below 275 km s^{-1} . An exact comparison to the FWHM_B measured from this work and the velocities measured in FIRE is difficult because of projection effects but it shows that outflow velocity is decreasing as a function of stellar mass. The mass loading factor in the low mass galaxy stack in Figure 2.17 is still compatible with the results from the FIRE simulations but only if the outflows for low mass galaxies ($< 10^{10} M_\odot$) have low velocities ($\text{FWHM}_B < 275 \text{ km s}^{-1}$).

The mass loading factor for the highest mass stack ($\eta = 1.4^{+0.41}_{-0.42}$) is lower than the predicted value from FIRE at that mass ($\eta = 2.6$). The FWHM_B measured for this stack is $340 \pm 30 \text{ km s}^{-1}$ so the difficulty of detecting low velocity outflows should not be a factor (Table 2.4.2). Using a

smaller electron density or smaller radius in Equation 2.2 would bring these into better alignment however there is no evidence to justify this change. An alternate explanation for why η in Figure 2.17 is lower than expected is that some fraction of the outflow is neutral and not visible as a broad $H\alpha$ component. Outflows measured in the $H\alpha$ line are a measure of the ionized component of the outflow, but outflows are multi-phase and have neutral, ionized, and dusty components (Leroy et al. 2015, Wood et al. 2015, Feruglio et al. 2015). Some studies of a small number of local galaxies have measured the neutral phase to have $9 - 14\times$ as much mass as the ionized phase (Wood et al. 2015, Martín-Fernández et al. 2016). Additionally, Martin (2006) measured both Na I absorption and $H\alpha$ emission in 18 ultra-luminous infrared galaxies and found that there was no correlation between the strength of the Na I absorption and the extended $H\alpha$ emission. An undetected neutral component may account for the factor of 2 difference between what is measured here and the FIRE simulations.

The assumptions that the broad component is an outflow and the broad component is shocked are not mutually exclusive. The broad component could be a shocked outflow. If we assume a 100% collisionally-ionized outflow, the mass loading factor would be smaller by a factor of ~ 2 (see the appendix of Genzel et al. 2011).

In conclusion, we estimate the mass loading factor using Equation 2.2 (Genzel et al. 2011) and find generally good agreement with other measurements of η at this redshift (Newman et al. 2012). We assumed the electron density and geometry of the outflow were the same as those of other studies (Newman et al. 2012) since we were not able to measure these parameters with our sample. At low masses, η increases as a function of mass which is contradictory to the results of the FIRE simulations (Muratov et al. 2015, Hopkins et al. 2014) where a decrease with mass is predicted. This difference is best explained by our inability to detect contributions from low velocity ($\text{FWHM} < 275 \text{ km s}^{-1}$) broad components as shown in Figure 2.18. Another feasible explanation is that the outflows have a large neutral component which is not detected because broad $H\alpha$ emission is sensitive to the ionized component of the outflow.

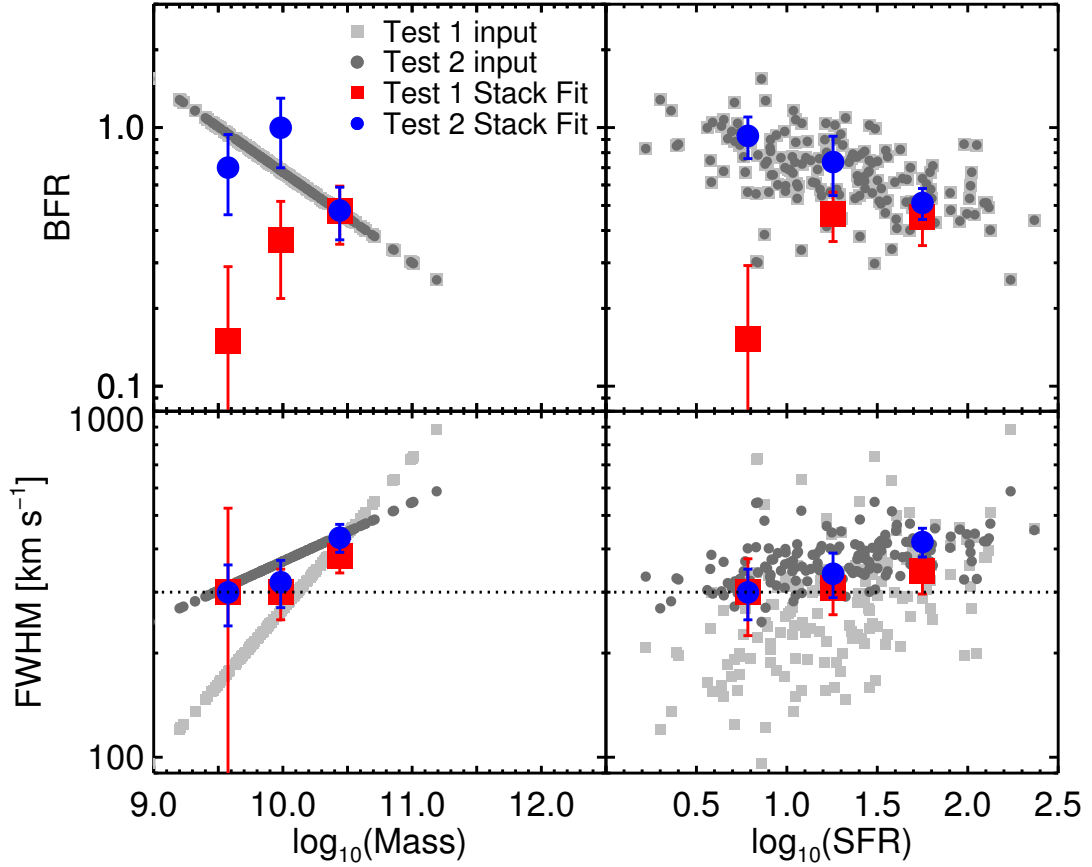


Figure 2.18 Results from two tests where we added broad components to simulated spectra, created stacks, and fit the stacks using the method described in Section 2.3.1. The BFR for both tests are identical, but the FWHM_B for Test 1 ranges from 100-900 km/s and for Test 2 ranges from 260-500 km/s. The input BFR and FWHM_B are linear with respect to mass. The left column shows fits to stacks by mass and the right column shows fits to stacks by SFR. When the FWHM of the broad component is below 275 km/s the BFR is underestimated.

There have been some recent studies that suggest the broad flux from emission lines does not trace bulk motions of galactic outflows but instead traces outflows at the base of the galactic wind, on scales similar to those of the star-forming regions. Wood et al. (2015) study the local galaxy NGC 7552 using both broad $\text{H}\alpha$ (which traces ionized material) and absorption from Si II and C II absorption lines (which traces neutral material). They find the mass absorption lines is $8.5\times$ the mass measured using broadened $\text{H}\alpha$ emission. Wood et al. (2015) measured the maximum blueshift of the absorption lines to be 1000 km/s which is much greater than the maximum blueshift of the

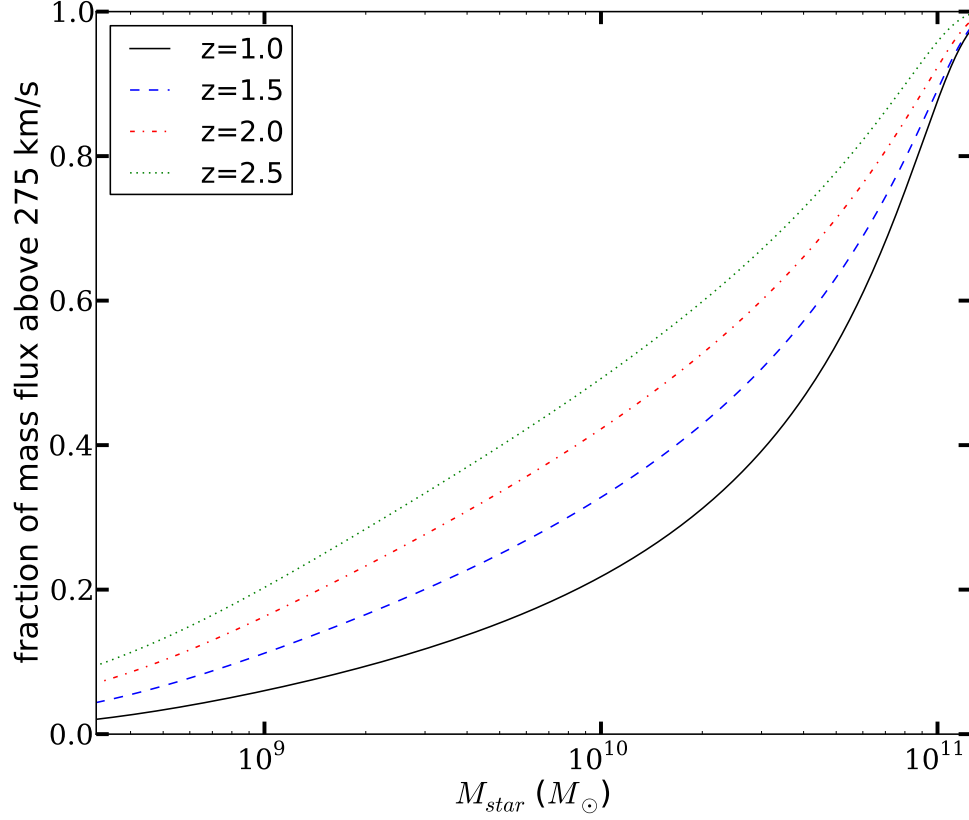


Figure 2.19 The fraction of mass flux above 275 km s^{-1} measured at $0.25 \times R_{virial}$ from galaxies in the FIRE simulations.

$\text{H}\alpha$ (290 km s^{-1}). Martín-Fernández et al. (2016) find similar results in NGC 5394 using absorption from Na I D and emission from $\text{H}\alpha$. Additionally, Martin (2006) measured both Na I absorption and $\text{H}\alpha$ emission in 18 ultra-luminous infrared galaxies and found that there was “no obvious correlation with the strength of the Na I absorption [and the extended $\text{H}\alpha$ emission]”. These studies are only for small samples of local galaxies and it is unclear if these results apply to higher redshifts.

2.6 Implications of Broadened Emission on Estimating Physical Properties of Galaxies

Nebular emission lines provide a means of estimating physical properties of galaxies such as dust extinction, metallicity, electron density, and ionization parameter. However, most of the calculations assume the emission is coming from photoionized HII regions within the galaxy. If the broad component we have measured here is a result of shocks, then the inclusion of this flux will affect line ratios and measurements. In Section 2.5, we showed that a plausible explanation for the location of the broad component line ratio in the N2-BPT diagram is shocks. In this section, we aim to answer the question: Is it possible that the changes in line ratios between $z \sim 0$ and $z \sim 2$ are caused by the addition of shocked emission?

2.6.1 The O32, R23, O3N2, and N2 line ratios

The abbreviations introduced in this section are:

$$N2 = [NII]/H\alpha$$

$$O32 = [OIII]\lambda\lambda 4959,5007 / [OII]\lambda\lambda 3726,3729$$

$$O3N2 = ([OIII]\lambda\lambda 4959,5007) / ([NII]/H\alpha)$$

$$R23 = ([OIII]\lambda\lambda 4959,5007 + [OII]\lambda\lambda 3726,3729) / H\beta$$

For the MOSDEF sample, Shapley et al. (2015) and Sanders et al. (2016) showed that the $z \sim 2$ galaxies are offset from the $z \sim 0$ galaxies in diagnostic diagrams that include [NII]. Specifically, the galaxies were offset in the N2-BPT, O32 vs. O3N2, and O32 vs. N2 diagrams and did not show any significant offset in the O32 vs. R23 and S2-BPT diagrams. While there is much

speculation, there is no definitive explanation for the offset. In this section, we test if the offsets in the diagnostic diagrams could be caused only by adding the emission from shocks to the $z \sim 0$ spectra.

Figures 2.20, 2.21, and `iono32o3n2` show the O32 vs. R23, O32 vs. O3N2, and O32 vs. N2 diagrams respectively. Each has the data at $z \sim 0$ from SDSS in black and at $z \sim 2$ from Sanders et al. (2016). We overlay the same shock models shown in Figure ???. The shock models in Figure ??? show the same general trend as the $z \sim 2$ data when compared to the SDSS data: no clear offset in O32 vs. R23, a slight offset in O32 vs. O3N2, and a large offset in O32 vs. N2.

To add the flux from shocks to local data, we select two shock models that are closest to the mean electron density, metallicity, and shock velocity of the MOSDEF sample ($290^{+169}_{-88} \text{ cm}^{-3}$ Sanders et al. 2016, $\log(\text{O}/\text{H}) + 12 = 8.43$, Sanders et al. 2015, and shock velocity of 300 km s^{-1}). These models are shown as green points. We then add the SDSS distribution and shocked data point together assuming a BFR of 0.4 (which is the average BFR for the stacks by $\text{H}\alpha$ and corresponds to 29% of the total flux being shocked) and plot the result as a green line. These SDSS+shocks models represent what local galaxies would look like with the addition of the best fitting shock model from Figure ???.

Figures 2.20, 2.22, and 2.21 shows the O32 vs. R23, O32 vs. O3N2, and O32 vs N2 diagrams, respectively, with data at $z \sim 0$ from SDSS in black and at $z \sim 2$ from Sanders et al. (2016). We overlay the same shock models shown in Figures 2.15 and 2.16. The shock models in these figures show the same general trend as the $z \sim 2$ when compared to the SDSS data: no clear offset in O32 vs R23, a slight offset in O32 vs O3N2, and a large offset in O32 vs N2. To add the flux from shocks to local data, we select two shock models that are closest to the mean electron density, metallicity, and shock velocity of the MOSDEF sample ($290^{+169}_{-88} \text{ cm}^{-3}$ Sanders et al. 2016, $\log(\text{O}/\text{H})+12 = 8.43$, Sanders et al. 2015, and shock velocity of 300 km s^{-1}). These models represent the closest shock models to the entire MOSDEF sample and are shown as green points. We then

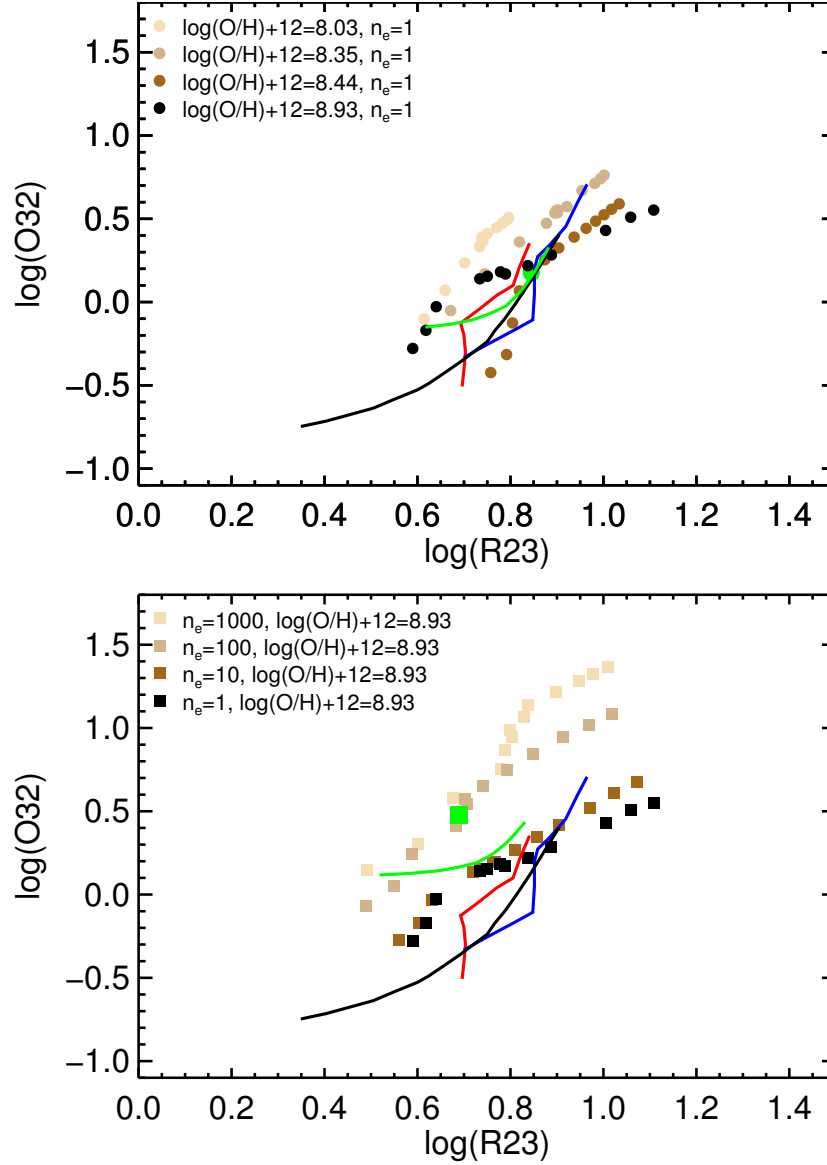


Figure 2.20 O32 vs. R23 for SDSS data, MOSDEF galaxies, shock models, and SDSS+shock models. The red and blue lines are from Sanders et al. (2016) who measure these ratios for galaxies that are more offset (blue) and less offset (red) from the local relation in the N2-BPT diagram. The remaining colors and symbols are the same as in Figure 2.15

add the SDSS distribution and shocked data point together assuming a BFR of 0.4 (which is the average BFR for the stacks by H α and corresponds to 29% of the total flux being shocked) and plot the result as a green line. These SDSS+shocks models represent what local galaxies would look like with the addition of the best fitting shock model from Figure 2.15.

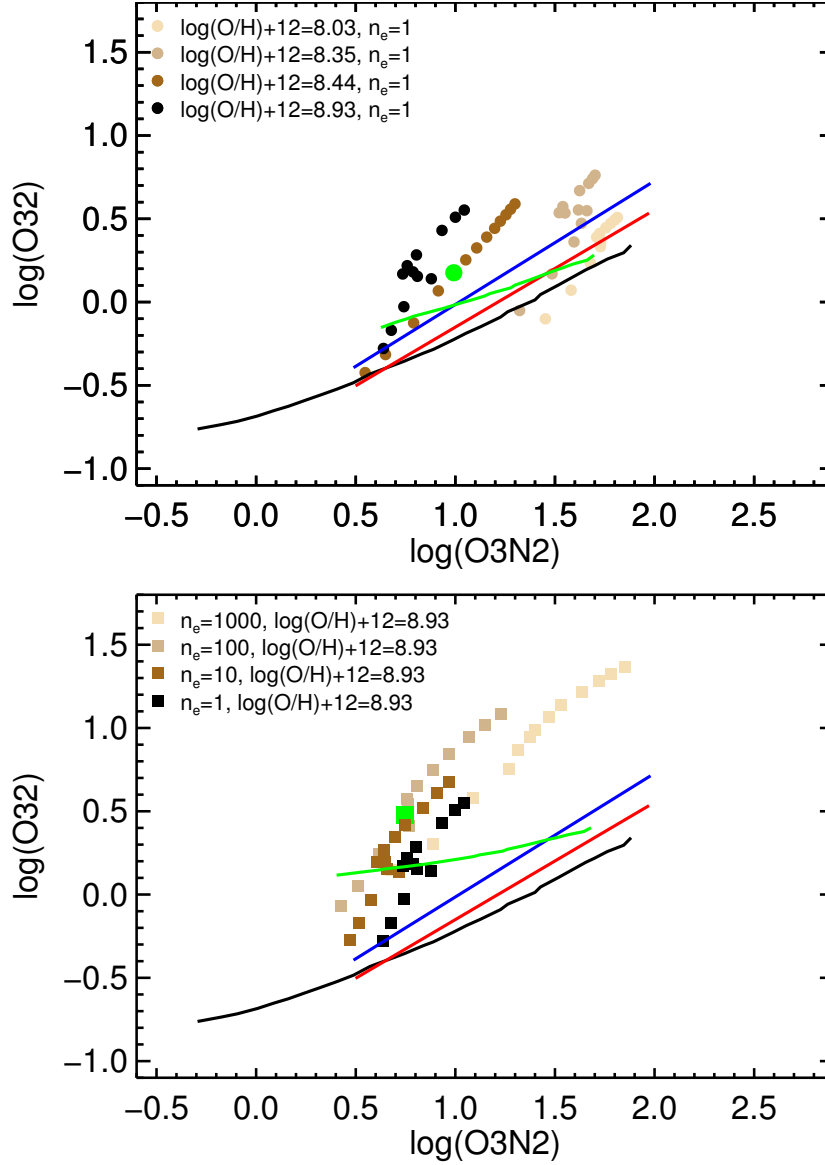


Figure 2.21 O32 vs. O3N2 for SDSS data, MOSDEF galaxies, shock models, and SDSS+shock models. The colors and symbols are the same as in Figure 2.20.

In Figure 2.20, the low metallicity (top row) SDSS+shock models in the O32 vs R23 diagram show no clear offset from the SDSS data or the trendlines from Sanders et al. (2016). The high electron density, high metallicity SDSS+shock models are slightly higher than the SDSS data but agree with the red line for $R23 > 0.7$.

In Figure 2.21, the SDSS+shock models in the O32 vs O3N2 diagram show a slight offset

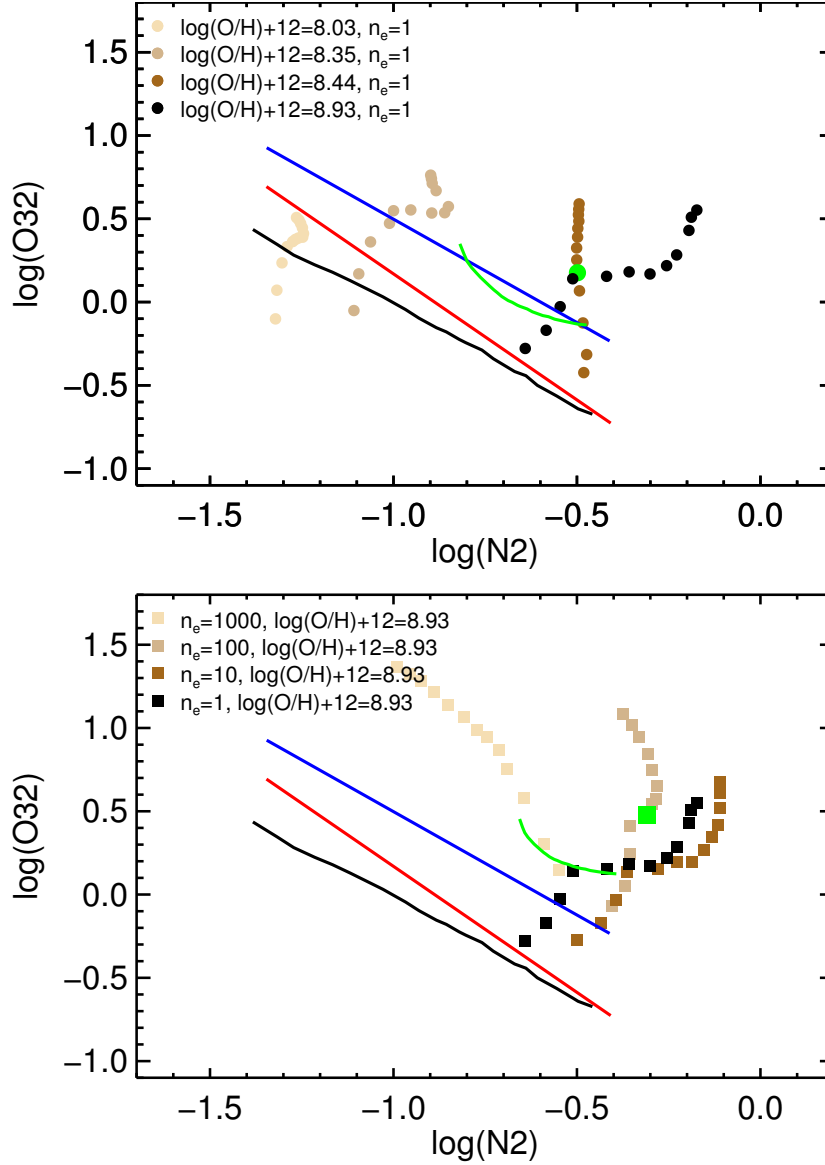


Figure 2.22 O32 vs. N2 for SDSS data, MOSDEF galaxies, shock models, and SDSS+shock models. The colors and symbols are the same as in Figure 2.20.

from the SDSS data. The SDSS+shock models agree with the trendlines from Sanders et al. (2016) except for the high electron density (bottom row) model for $\text{O3N2} < 1.0$. This is likely because the high electron density models use a metallicity of 8.93 which is higher than most galaxies in the MOSDEF sample. Lowering metallicity shifts the shock models to the right (top row)

In Figure 2.22, the SDSS+shock models in the O32 vs N2 diagram are highly offset from

the SDSS data. The SDSS+shock models agree with the trendlines from Sanders et al. (2016) but do not match the data range. This is because of the strong dependence on metallicity in the shocks and on N2. Lower values of N2 indicate a lower metallicity. For the lower values, it would be more appropriate to use the lower metallicity shock model. Using the lower metallicity point would shift the range to lower N2 values and into better agreement with the low metallicity data.

For the O32 vs. R23, O32 vs. O3N2, and O32 vs N2 diagrams adding shocks to SDSS data at $z \sim 0$ could shift the line ratios towards the values measured at $z \sim 2$. This does not prove that the offset is caused by shocks, only that they are a possibility. We have not shown that this is not a contribution from AGN, as they have similar line ratios to shocks.

2.6.2 The N2-BPT diagram

A great deal of study has been done on the cause of the offset of $z \sim 2$ galaxies from the $z \sim 0$ galaxies in the N2-BPT diagram (Shapley et al. 2005, Erb et al. 2006, Liu et al. 2008, Masters et al. 2016, Steidel et al. 2014, Shapley et al. 2015, Strom et al. 2017). Here, we calculate the same shock+SDSS models for the N2-BPT diagram and calculate where the broad component should lie if it is due to shocks.

Figure 2.23 shows the SDSS+shock model along with the location of the $z \sim 2$ galaxies from Shapley et al. (2015). The SDSS+shock model lines show generally good agreement with the line from Shapley et al. (2015). This implies that adding shocks to the spectra of local galaxies could, in part, explain the offset of the $z \sim 2$ galaxies. This conclusion comes with the caveat that we are unable to completely rule out some contribution from AGN in our stacks. Since AGN have similar line ratios to shocks the same argument holds that low-luminosity AGN (instead of shocks) could explain the offset of the $z \sim 2$ galaxies.

The SDSS+shock models show that adding shocks to the spectra of local galaxies could reproduce the offset of the $z \sim 2$ galaxies. This assumes a single shock velocity, electron density, and metallicity for the whole sample. The MOSDEF sample has a wide range of metallicities (Sanders

et al. 2015), electron densities (Sanders et al. 2016), and shock velocities (Table 2.4.2). If shocks are the cause of the offset and the broad components are due to shocked emission, then the broad components should occupy some region of the N2-BPT diagram, not just a single point.

2.6.3 Speculation Where Broad Emission May Lie at $z \sim 3$

We can estimate where this distribution should be when making the following assumptions:

1. Emission lines are the sum of the intrinsic emission from HII regions (corresponding to the narrow component) and a broadened, shocked emission (corresponding to the broad component). **2.** Measuring the emission with a single Gaussian is equal to the sum of the narrow and broad fluxes. This was generally true to within 5% for the fits in Figures 2 and 3. **3.** The broad component has the same $[\text{OIII}]/\text{H}\beta$ as the narrow component and only $[\text{NII}]/\text{H}\alpha$ changes. The shock models shown in Figure 2.15 occupy the same range in $[\text{OIII}]/\text{H}\beta$ as the SDSS galaxies. Also, Sanders et al. (2016) and Masters et al. (2016) both show little to no change between $z \sim 0$ and $z \sim 2$ for emission line diagrams that only involve hydrogen, oxygen, and sulfur.

The second assumption results in the following relationship:

$$\frac{[\text{NII}]_S}{\text{H}\alpha_S} = \frac{[\text{NII}]_N + [\text{NII}]_B}{\text{H}\alpha_N + \text{H}\alpha_B} \quad (2.3)$$

Where the S, N, and B subscripts refer to single, narrow, and broad components respectively. The broad flux ratio is defined as: $\text{BFR} = \text{H}\alpha_B / \text{H}\alpha_N$. We use this to rearrange Equation 2.3 into terms measured in Section 2.4:

$$\frac{[\text{NII}]_S}{\text{H}\alpha_S} = \frac{[\text{NII}]_B}{\text{H}\alpha_B} \frac{1}{1 + \text{BFR}^{-1}} + \frac{[\text{NII}]_N}{\text{H}\alpha_N} \frac{1}{1 + \text{BFR}} \quad (2.4)$$

This equation relates the single, broad, and narrow ratios with the broad flux fraction. We use this to calculate how far offset the broad component must be to account for the offset between

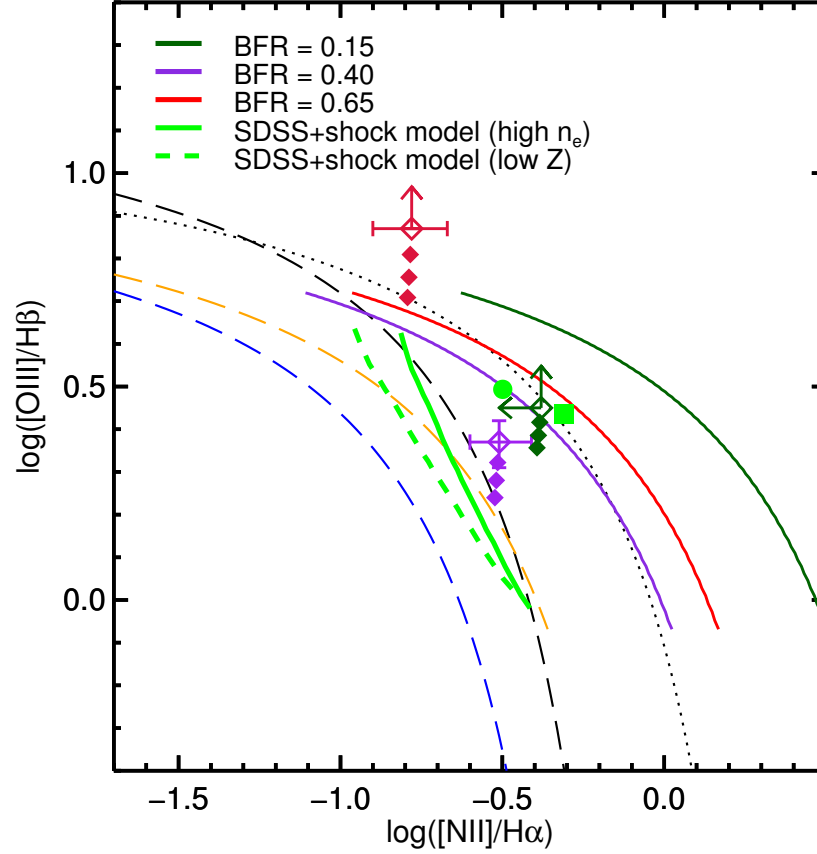


Figure 2.23 The N2-BPT diagram with the SDSS+shock and broad component predictions. The blue dashed, orange dashed, black dashed, and black dotted line have the same meaning as Figure 2.14. The diamonds are the broad components from Figure 2.14. The thick green lines are the SDSS+shock models with the high electron density line on the left and the low metallicity line on the right. The solid lines are a prediction as to where the broad components should lie if they are the cause of the offset between galaxies at $z \sim 0$ and $z \sim 2$. To calculate this, we use Equation 4 and the values of the BFR from Figure 2.12 to predict where the broad component line ratios should lie. The colors of each line match the broad component color for each BFR. The magenta dashed line is a prediction for where galaxies would lie at $z \sim 3.4$ if measured with a single Gaussian. Details for this calculation are in Section 2.6.2.

$z=0$ and $z=2$ data in the N2-BPT diagram. First, we use the $z=0$ relation from Kewley et al. (2013) (blue dashed line) as the input narrow line ratio. Next, we use the $z=2$ relation from Shapley et al. (2015) (orange dashed line) as the input single line ratio. Finally, we calculate the broad line ratio for the BFRs show in Figure 2.12 (0.15, 0.4, 0.65). If we were to measure a large number of broad components in individual spectra this is where they would lie if the assumptions going into Equation

2.4 are true.

We can use Equation 2.4 to calculate where galaxies would lie on a $z \sim 3.4$ N2-BPT diagram if we make the following assumptions: **1.** The average BFR at $z \sim 2$ is 0.5 and the average BFR at $z \sim 3.4$ is 0.8. This comes from the right side of 2.12. **2.** The broad emission ratios are the same between $z \sim 2$ and $z \sim 3.4$

First, we use the $z=0$ relation from Kewley et al. (2013) (blue dashed line) as the input narrow line ratio. Next, we use the $z=2$ relation from Shapley et al. (2015) (orange dashed line) as the input single line ratio. We then calculate the location of the broad emission if the BFR is 0.5. This gives us the location of the broad emission for typical $z \sim 2$ galaxies. Then we use the curve of the broad emission at $z \sim 2$ as an input to Equation 2.4. We again assume the relation from Kewley et al. (2013) (blue dashed line) as the input narrow line ratio. We use 0.8 as the BFR which is the average BFR at $z \sim 3.4$ from Figure 2.12. From these inputs, we calculate the location of where galaxies would be on the N2-BPT diagram at $z \sim 3.4$.

$$\log\left(\frac{[\text{OIII}]}{\text{H}\beta}\right) = \frac{0.670}{\log([\text{NII}]/\text{H}\alpha) - 0.465} + 1.11 \quad (2.5)$$

2.6.4 The S2-BPT diagram

As shown in Figure ??, the shocked $[\text{SII}]/\text{H}\alpha$ ratios that best match the properties of the MOSDEF galaxies are offset to higher values than the SDSS data. If shocks are the cause of the offset in the N2-BPT diagram, then one might also expect an offset in the S2-BPT diagram as well. However, there is no measured offset between the SDSS and the $z \sim 2$ data in the S2-BPT diagram (Shapley et al. 2015). We have two possible explanations: the electron density dependence on the shocked $[\text{SII}]/\text{H}\alpha$ ratio and contribution from diffuse ionized gas.

The electron density of the MOSDEF sample is $290^{+169}_{-88} \text{ cm}^{-3}$, and the shocked line ratios for that particular density would lie between the 100 and 1000 cm^{-3} shock models. The SDSS galaxies also lie between the 100 and 1000 cm^{-3} shock models (see Figure ??). It is possible that

the shocked $[\text{SII}]/\text{H}\alpha$ ratio for an electron density of 290 cm^{-3} lies close to the SDSS distribution. If this is the case, including the shocked emission would not change the $[\text{SII}]/\text{H}\alpha$ ratios of the $z \sim 0$ galaxies much. The small difference between the shocked $[\text{SII}]/\text{H}\alpha$ ratio and the photoionized $[\text{SII}]/\text{H}\alpha$ ratio could explain the lack of an offset in the S2-BPT diagram.

Another explanation for no offset in the S2-BPT diagram could be because of less contribution from diffuse ionized gas at $z \sim 2$ compared to $z \sim 0$. The fraction of $\text{H}\alpha$ emission from diffuse ionized gas decreases as $\Sigma_{\text{H}\alpha}$ increases (Oey et al. 2007). As emission from diffuse ionized gas decreases, the $[\text{SII}]/\text{H}\alpha$ ratio decreases while $[\text{OIII}]/\text{H}\beta$ stays the same (Zhang et al. 2017, Sanders et al. 2017). Since galaxies at $z \sim 2$ have higher SFR (Reddy & Steidel 2009, Madau et al. 1998, Madau & Dickinson 2014) and are more compact (Trujillo & Pohlen 2005, Shen et al. 2003, Barden et al. 2005) they have higher $\Sigma_{\text{H}\alpha}$ which implies they will have less contribution from diffuse ionized gas if these local relations hold at $z \sim 2$. Local galaxies with high Σ_{SFR} do lie lower than those with low Σ_{SFR} on the S2-BPT diagram (Masters et al. 2016). If $z \sim 2$ galaxies follow these same trends, then we should expect a lower $[\text{SII}]/\text{H}\alpha$ ratio at a given $[\text{OIII}]/\text{H}\beta$ ratio. Therefore, the lack of an offset in the S2-BPT diagram could be because less contribution from diffuse ionized gas causes the narrow emission to lie at lower $[\text{SII}]/\text{H}\alpha$ than average $z \sim 0$ galaxies while the broad emission is higher $[\text{SII}]/\text{H}\alpha$ due to shocks. These effects compete with each other and ultimately cancel each other out.

2.6.5 Measuring SFR from $\text{H}\alpha$

The presence of shocks can also affect measurements made from single emission lines such as SFR from $\text{H}\alpha$. If the broad emission should be removed when calculating SFR then not doing so would overpredict the SFR. Given the measured BFRs, SFRs would be overpredicted by 15, 40, and 68%, respectively in our three mass bins. However, given the large number of systematic uncertainties in these calculations (extinction curves, nebular vs. continuum extinction, initial mass functions, and star formation histories), a 15-70% offset could go undetected. Furthermore, despite

only detecting a BFR of 0.15 in the lowest mass bin, the contribution from broad emission may be higher because of our inability to detect broad emission with $\text{FWHM} < 300 \text{ km/s}$.

2.7 Conclusions About Broad Emission

We present results from the MOSFIRE Deep Evolution Field (MOSDEF) survey on broad emission from the nebular emission lines $\text{H}\alpha$, $[\text{NII}]$, $[\text{OIII}]$, $\text{H}\beta$, and $[\text{SII}]$. After removing known AGN, merging galaxies, and lines affected by skylines, we study broad flux by fitting the emission lines of individual galaxies and stacks using narrow and broad Gaussian components. For the $1.37 < z < 2.61$ sample, the broad flux accounts for 10-50% of the flux in nebular emission lines when detected and in the $2.95 < z < 3.80$ sample the broad component comprises 10-60% of the flux when detected. For individual galaxies, there are no correlations between the BFR as a function of mass, SFR, sSFR, or Σ_{SFR} , but there is a strong correlation with higher S/N galaxies and a broad component detection.

We calculate $[\text{SII}]/\text{H}\alpha$, $[\text{NII}]/\text{H}\alpha$, and $[\text{OIII}]/\text{H}\beta$ line ratios for the narrow components, broad components, and the single Gaussian fits. Compared to what one would obtain using a single Gaussian, the broad components have higher $[\text{NII}]/\text{H}\alpha$ and $[\text{OIII}]/\text{H}\beta$ line ratios. When placed on the BPT diagram (Figure 2.14) the broad components for stacks lie within the composite star-forming/AGN region. We compare the locations of the broad component line ratios to shock models from Allen et al. (2008) and conclude that the broad emission could be explained by shocks. The locations of the broad components could also be explained by contribution from low-luminosity AGN that may have been included in the stack.

We estimate the mass loading factor using Equation 2.2 (Genzel et al. 2011) and applying some assumptions about the electron density and geometry of the outflow (Newman et al. 2012). We find generally good agreement with other measurements of η at this redshift (Newman et al. 2012). At low masses, η increases as a function of mass. This result is contradictory to the results

of the FIRE simulations (Muratov et al. 2015, Hopkins et al. 2014) where a decrease with mass is predicted. This difference is best explained by our inability to detect contributions from low velocity ($\text{FWHM} < 275 \text{ km s}^{-1}$) broad components as shown in Figure 2.18. Another feasible explanation is that the outflows have a large neutral component which is not detected because broad $\text{H}\alpha$ emission is sensitive to the ionized component of the outflow.

We combine the shock models from Allen et al. (2008) with local line ratios from SDSS and calculate where these galaxies would lie on several emission line diagnostic diagrams. We compare these SDSS+shock models to the emission line properties of $z \sim 2$ galaxies to test if only the addition of shocks could account for the shifts in emission line diagrams between $z \sim 0$ and $z \sim 2$. If we add a 29% shocked component to SDSS data at $z \sim 0$, the N2-BPT, O32 vs. O3N2, and O32 vs. N2 diagrams have similar offset line ratios to the observed $z \sim 2$ data from Sanders et al. (2016) and Shapley et al. (2015). There is no offset in the O32 vs. R23 diagram which is also seen in Sanders et al. (2016) at $z \sim 2$. The lack of an offset in the S2-BPT diagram seen at $z \sim 2$ may be due to the strong dependence of shocked emission on electron density or from decreased contribution from diffuse ionized gas. Since AGN have similar ratios to shocked emission, it is also possible that AGN contribution could explain the positions of $z \sim 2$ galaxies instead of shocks.

If the offsets between $z \sim 0$ and $z \sim 2$ galaxies in emission line diagnostic diagrams are caused by outflowing, shocked gas, then the contribution from the shocks can be subtracted to isolate emission from HII regions when calculating star formation rate, for instance. Given the measured BFRs, SFRs would be overpredicted by 15, 40, and 68%, respectively in our three mass bins. However, given the large number of systematic uncertainties in these calculations (extinction curves, nebular vs. continuum extinction, initial mass functions, and star formation histories), a 15-70% offset could go undetected.

In this work, we have shown that galaxies at $z \sim 1 - 3$ have a broad component and that the origin of this emission is likely shocks or AGN. In either case, the broad emission may complicate how we interpret galaxy properties measured from emission lines (Kewley et al. 2013, Newman et al.

2014). Additionally, a better estimate of the electron density of the outflows would be beneficial because the uncertainty in this measurement dominates our error in calculating the mass loading factor. Future studies on outflows at $z \sim 2$ would greatly benefit from spatial information. High spatial resolution integral field unit maps aided by adaptive optics (e.g., with Keck/OSIRIS) will enable us to disentangle if the broad component is from AGN or is truly due to outflows (Newman et al. 2014).

Chapter 3

Reduction and Scientific Software

3.1 BMEP: 2D to 1D Reduction Software for the MOSDEF Survey

The MOSDEF team has written software to handle the 2D and 1D reduction process. The 2D code is described in Kriek et al. (2015) and the 1D extraction code, BMEP¹, is described here. The MOSDEF observing strategy uses an ABA'B' dither pattern and when the first data were taken, the standard MOSFIRE Data Reduction Pipeline (DRP, Konadaris 2014?) was unable to reduce data taken in this pattern.

The 2D reduction code outputs images that are combined, flat-corrected, cleaned of cosmic rays, and rectified. Each output image has 6 extensions: the science image, two variance images, a pixel weighting map, a response curve, and a telluric correction. One variance image is calculated using the read noise and the exposure time and stuff like that and the other variance image is calculated using the standard deviation of each input pixel in the stack. We use the variance calculated from first principles.

The MOSDEF survey has taken spectra for ~ 1500 galaxies at redshifts of $z \sim 1 - 3$.

¹Source code and installation instructions available at: <https://github.com/billfreeman44/bmep>

Extracting 1D spectra from 2D images in the Y, J, H, and K bands is challenging because of the large number of sky lines, high background noise, and nearly no continuum for most galaxies. The usual method to extract spectra would be to bin the data in the wavelength axis to create a profile. Doing this for MOSFIRE data would add in a large amount of noise to the profile because there is almost no stellar continuum for most of the galaxies and high background noise. Most galaxies have only significant flux from emission lines. This produced a unique challenge in that only select wavelength regions should be used to create the weighting profile for extracting spectra.

To solve this problem, I have written the 2D to 1D extraction code called **BMEP**. This code reads in data from the 2D MOSDEF reduction program and allows the user to interactively select the wavelengths to sum together to create the weighting profile. **BMEP** also has a “continuum mode” that automatically removes skylines from the wavelength range selected for galaxies with continuum. Seven members of the MOSDEF team used **BMEP** and reduced 4900+ spectra with it. Figure 3.2 shows an example spectrum displayed while using **BMEP**.

3.1.1 Features of **BMEP**

Many galaxies at high redshift have extremely bright emission lines compared to their continuum (Kennicutt 1998). In most of the spectra, the continuum is too faint to be detected and the only signal is from emission lines. This makes it impossible to trace a spectrum as a function of wavelength. **BMEP** assumes the rectification was perfect and does not attempt to find a trace as a function of wavelength.

One of the benefits of **BMEP** is when binning columns in the wavelength direction to calculate the profile, one can easily include areas of the spectrum that have emission lines. The interactivity of profile creation is one of the features of **BMEP** that allows for quick and accurate extractions (~ 1 minute per object). Also, if there is continuum, there is a “continuum mode” that rejects areas of the spectrum that contain bright skylines when adding many columns of data together.

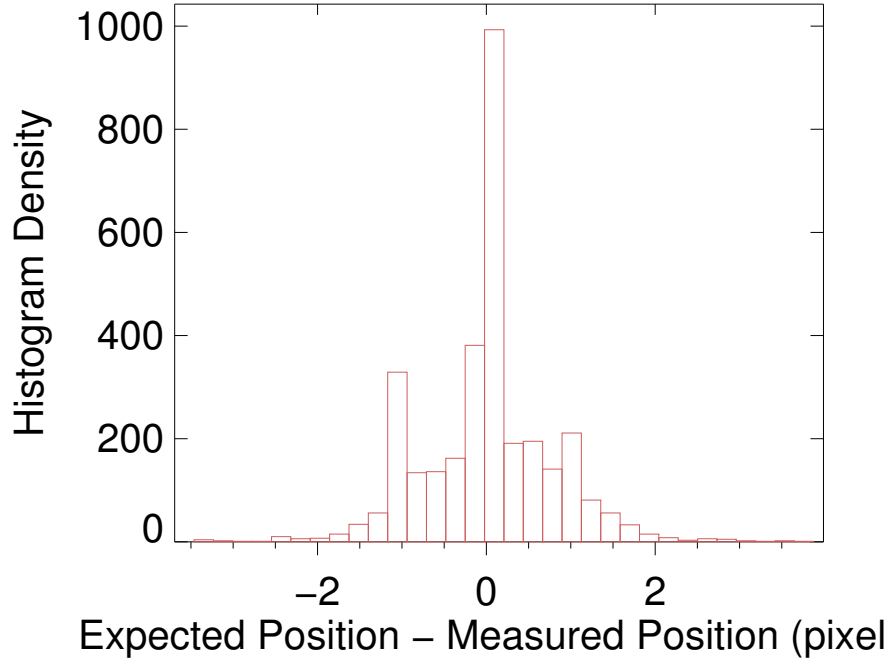


Figure 3.1 Expected position - measured position histogram for full MOSDEF sample. The majority of galaxies were within 2 pixels of the expected position. There are spikes at 0, 1, and -1 because the expected position was rounded in earlier versions of BMEP.

The extraction program uses the expected position of an object to clearly marks the position of the primary object in the 2D spectra. This allows the user to unambiguously find the primary target if there are multiple objects in the slit. Serendipitous objects are also extracted and we attempted to find the corresponding 3D-HST catalog ID.

After extraction, the spectrum is plotted and can be inspected. The user can adjust parameters of the extraction such as the width or weighting. The locations where the user clicked are also drawn in red on the plot. In noisy spectra, this allows the user to easily find emission lines in the 1D spectra. Once an emission line is found, the user can fit the line to a Gaussian, input which line it is, and calculate a redshift. All emission lines and calculated redshifts are saved in a catalog. A separate program consolidates all the lines fit for each object and calculates the most likely redshift. This code takes into consideration the fact that some lines may be mis-identified.

In cases where an object had no obvious emission lines or continuum in the 2D spectrum, a

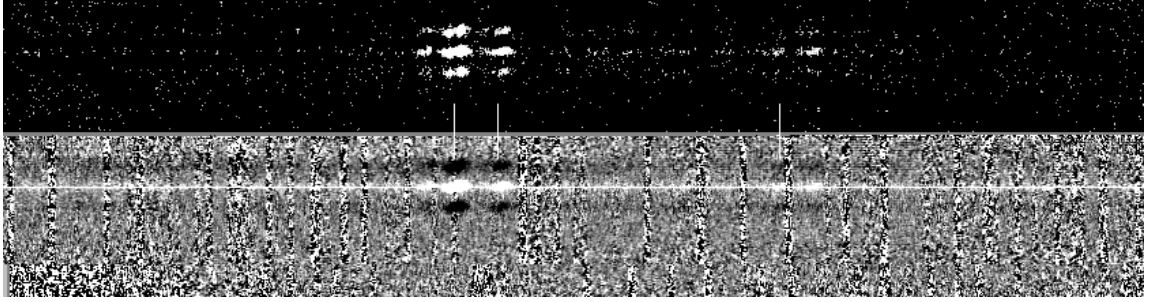


Figure 3.2 Screenshot of a 2D spectrum from BMEP. The top image is a S/N image where pixels below a S/N of 2 are set to black. The bottom image is the science image with a 1 pixel wide white line drawn across the expected position of the object. The location of each object is in the mask file and is used by BMEP to calculate the expected position. Generally, the object is within 2 pixels of the expected location (see Figure 3.1). For the MOSDEF spectra, we drew dashed white lines over other objects that may have fallen into the slit based on the HST v4.1 catalog of objects. The vertical white lines are drawn based on the best redshift guess from either spectroscopic, grism, or photometric redshift measurements. The $H\alpha$, [NII], and [SII] lines are marked.

“blind” extraction was performed. For objects with no signal in any bands, the blind extraction uses the expected position of the object calculated from its RA and DEC and uses the same extraction width as the star’s width in each filter. For objects with signal in one or more bands, the blind extraction used the average extraction widths and centers from filters where there was signal from the object. These blind spectra allow us to put upper limits on emission lines for spectra if we know the redshift. In the final MOSDEF survey, 23% of the spectra were extracted with the blind extraction code.

In general, any spectrum can be extracted using BMEP. The main code is through a call to an image handler (`BMEP_display_image`) and as long as one writes a wrapper that makes an appropriate call to that image handler could use BMEP to reduce data. There are 4 versions of `BMEP` that can serve as examples of reading in spectra. The main difference between these are the folder system for the 2D data. For instance, the DRP groups masks into different folders but the MOSDEF reduction program puts all spectra into one folder. The original program, BMEP reduces MOSFIRE data reduced with the DRP. `BMEP_MOSDEF` reduces MOSFIRE data reduced with the MOSDEF 2D reduction program. `BMEP_LRIS` reduces LRIS data reduced using CarPy². `BMEP_stupid` reduces

²<http://code.obs.carnegiescience.edu/carnegie-python-distribution>

any data in the current directory so long as the names of the science and variance are [name].fits and [name].sig.fits, respectively.

Using **BMEP** is straightforward. The user selects an image to reduce, selects a range of wavelengths to sum and create a weighting profile (using continuum mode if there is continuum to remove skylines), fits a Gaussian to the profile (to calculate the center, width, and weighting for extraction), and then extracts. There are many complications that can arise such as emission lines being near sky lines, two nearby objects, two objects that dithered into each other, serendipitous objects, rotation, broad emission, and dithering out of the slit. After extracting, the user is shown the extracted spectrum along with markings of wavelengths that were included in the profile. These markings help guide the user to emission lines to calculate the redshift. Reducing a mask of 30 objects and measuring redshifts usually took 45-60 minutes (for an experienced user) while using **BMEP**. A large fraction of objects typically took very little time while a small number of objects took longer.

Attempts to build an automated version of **BMEP** have not been successful. For some spectra, an automated extraction worked perfectly, but for others it would completely fail. The end result would be that the spectra would all have to be checked by hand anyway.

3.1.2 Sub-pixel Extraction Equations

While testing the software, we compared extractions of a bright object done by several different users. To our surprise, some extractions were brighter or dimmer at all wavelengths for some users. We traced the cause of this difference to rounding differences between two extraction profiles. Rounding the width of extraction, in general, has little impact on the extracted flux. From the bottom pannel of Figure 3.3, we show that rounding can cause a 2-4% difference in flux measured.

Eq. 8 from Horne is what the optimal extraction is based. However, it is simplified for Mosfire reduction because there is no sky subtraction or cosmic ray rejection needed as these are

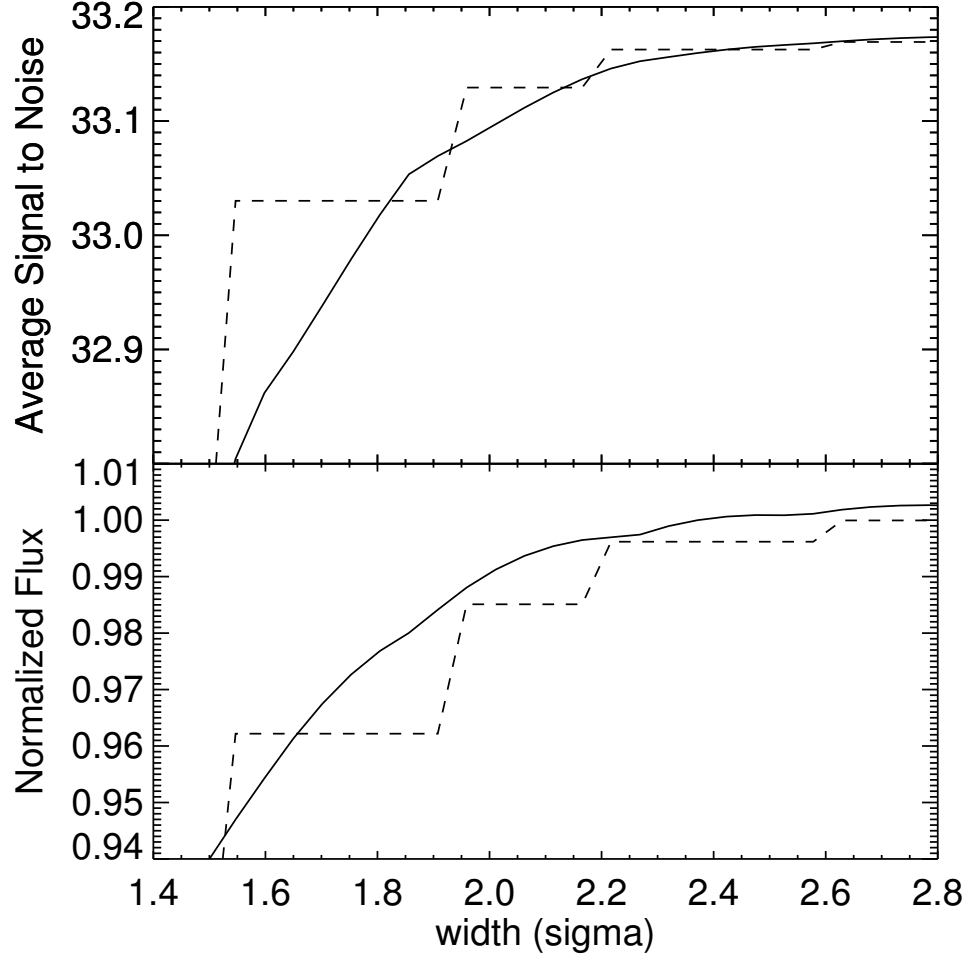


Figure 3.3 A comparison between sub-pixel and the Horne (1989) extractions. The solid line is the sub-pixel extraction and the dashed is the Horne (1989) extraction. This plot is made by first extracting a star normally, then looking for a section of the spectrum where the flux is relatively constant and there are no absorption features, emission lines, or sky lines. Next, the spectrum is extracted using widths between 1.5 and 5.0 pixels with an 0.075 spacing. The points are plotted as the lines in the figure above. Because each star has a slightly different width, we convert the width in pixels to a width in “sigma”. We extract at a width of 2.355 sigma.

done during the 2D reduction. We also remove the wavelength subscript for simplification; each of these equations calculates the flux at one wavelength or column in the 2D spectrum. The equations from Horne 1989 with these simplifications are:

$$x'_b = \mathbf{R}(c - w)$$

$$x'_t = \mathbf{R}(c + w)$$

$$\sum_{x'_b}^{x'_t} D = F'_{box} \quad (3.1)$$

$$\sum_{x'_b}^{x'_t} V = V'_{box} \quad (3.2)$$

$$\frac{\sum_{x'_b}^{x'_t} PD/V}{\sum_{x'_b}^{x'_t} P^2/V} = F'_{opt} \quad (3.3)$$

$$\frac{\sum_{x'_b}^{x'_t} P}{\sum_{x'_b}^{x'_t} P^2/V} = V'_{opt} \quad (3.4)$$

Unnumbered equations are defining relationships or variables. Bold letters indicate functions. $\mathbf{R}$ is the round function, c is the center of the object from the Gaussian fit to the profile, w is 2.35 times the sigma found from the Gaussian fit to the profile, D is the the flux in one pixel, V is the variance in one pixel, P is the weighting profile, x_b is the pixel at the bottom of the profile, and x_t is the pixel at the top of the profile. The weighting profile comes from the Gaussian fit to the binned profile. F'_{box} is the boxcar flux, V'_{box} is the boxcar variance, F'_{opt} is the optimal flux, and V'_{opt} is the optimal variance for the Horne (1989) algorithm that does not include sub-pixel corrections.

We extend this equation to extract a fraction of each pixel. The central region of extraction is extracted like normal, then a fraction of the outer pixels are added to this flux. First we calculate the range which the flux is extracted in the same manner as equations A1-A4. This is between xb' and xt' which are calculated as follows:

$$x_b = \mathbf{L}(c - w + 1)$$

$$x_t = \mathbf{L}(c + w)$$

The $\mathbf{L}$ indicates the “Floor” function (which removes any decimals). Next, calculate the “remainder” from the bottom (R_b) and the top (R_t). This is how much the extraction “hangs out”

of the central pixels:

$$R_b = 1 - (x_b - x'_b)$$

$$R_t = x_t - x'_t$$

Now we calculate the weighting for sub-pixel extraction on the edges:

$$P_t = P(x_t + 1)R_t$$

$$P_b = P(x_b - 1)R_b$$

The boxcar extraction for the sub-pixel algorithm is:

$$B = D(x_b - 1)R_b$$

$$T = D(x_t + 1)R_t$$

$$\sum_{x_b}^{x_t} D + B + T = F_{box} \quad (3.5)$$

$$\sum_{x_b}^{x_t} V + V_b R_b + V_t R_t = V_{box} \quad (3.6)$$

Where B and T are the flux from the bottom and top pixels to be added to the central region. For the optimal extraction this extra flux is:

$$B = \frac{P_b D(x_b - 1)R_b}{V(x_b - 1)}$$

$$T = \frac{P_t D(x_t + 1)R_t}{V(x_t + 1)}$$

Calculate sub-pixel flux and variance:

$$\frac{(\sum_{x_b}^{x_t} PD/V) + B + T}{\sum_{x_b}^{x_t} P^2/V + P_b^2/V_b + P_t^2/V_t} = F_{opt} \quad (3.7)$$

$$\frac{(\sum_{x_b}^{x_t} P) + P_b + P_t}{\sum_{x_b}^{x_t} P^2/V + P_b^2/V_b + P_t^2/V_t} = V_{opt} \quad (3.8)$$

If the pixels did not need to be rounded and happened to end up on whole numbers, then $R_b = 1$, $R_t = 0$, $x'_b = x_b + 1$, and $x'_t = x_t$. One can show the final equations in the sub-pixel extraction would result in the same flux and error as the original equations in this case.

Figure 3.3 shows a comparison of the sub-pixel optimal vs normal optimal. This figure was produced by selecting a flat, featureless section of a star that has no sky lines. Within this region, we calculated the average flux and S/N, then we varied the extracted width. As one might expect, the Horne extraction has steps where the width rounds to the next pixel and the sub-pixel curve is smooth. Though the jumps in flux are severe when the width is small, the steps flatten out as width increases. At the width where we extract (2x FWHM), the jumps between steps is quite small, at worst around 4%. However, since we use a standard star to calculate the absolute flux this can cause every flux for a mask to be 4% different when two different people extract a mask only due to rounding.

3.2 MPMCMCFUN: A Generalized Markov Chain Monte Carlo Code in IDL

There are many different methods to estimate a parameter of a model and the error of that parameter. In this work, we used a markov chain monte carlo method of estimating parameters and errors for our models. This method is the best for our models because there may be degeneracies between parameters which make error estimation difficult when fitting with other methods. The MCMC method does not make any assumptions about the shape or correlations between parameters.

One of the most widely used fitting codes is called **MPFIT** which uses the Levenberg-

Marquardt technique to calculate the best parameters for a model given some data and errors using the least-squares technique. The wrapper, `MPFITFUN`, allows the user to generally fit any function to data. We model the functionality of `MPMCMCFUN` to mimic the usage of `MPFITFUN`. This similarity allows anyone familiar with `MPFITFUN` to easily use `MPMCMCFUN`.

The MCMC Metropolis-Hastings algorithm is an extremely simple method. First, a likelihood is calculated based on an initial guess. Next, one of the parameters is perturbed by some amount determined by the stepsize and the likelihood is calculated for this new model. If the likelihood is larger, the new model is accepted and if the likelihood is smaller, the new model is accepted if a random number between 1 and 0 is higher than the ratio of the new likelihood to the old likelihood. The best fit value and errors are calculated from the distribution of accepted models.

When fitting any model using MCMC Metropolis-Hastings algorithm the user needs to supply an initial guess and a “stepsize” for each parameter. The stepsize is the amount by which each parameter is perturbed when fitting the data. The stepsize is crucial because the MCMC algorithm works best when about half of the models are accepted. As explained in Chapter 2, we use an initial fit from `MPFIT` to determine our initial guess (which avoids burn in) and the stepsizes for each parameter.

Chapter 4

Summary

4.1 Broadened Emission in High Redshift Galaxies

This work presents results from the MOSFIRE Deep Evolution Field (MOSDEF) survey on broad emission from the nebular emission lines $H\alpha$, $[NII]$, $[OIII]$, $H\beta$, and $[SII]$. After removing known AGN, the sample consists of 127 galaxies with $1.37 < z < 2.61$ and 84 galaxies with $2.95 < z < 3.80$. We study broad flux by decomposing the emission lines using narrow ($FWHM < 275 \text{ km s}^{-1}$) and broad ($FWHM > 300 \text{ km s}^{-1}$) components for individual galaxies and stacks. For the $z \sim 2$ sample, the broad flux accounts for 10-50% of the flux in nebular emission lines when detected and in the $z \sim 3.3$ sample the broad component comprises 10-60% of the flux when detected. For individual galaxies, there are no correlations between the broad to narrow flux fraction as a function of mass, SFR, sSFR, or star formation surface density, but there is a strong correlation with higher signal-to-noise galaxies and a broad component detection.

We calculate $[NII]/H\alpha$, and $[OIII]/H\beta$ line ratios for the narrow components and broad components and compare these to a single Gaussian fit. When placed on the N2-BPT diagram ($[OIII]/H\beta$ vs. $[NII]/H\alpha$) the broad components are shifted towards the higher $[OIII]/H\beta$ and $[NII]/H\alpha$ ratios. We compare the location of the broad components to shock models and find that

the broad component could be explained as a shocked outflow.

The narrow line ratios are at lower $[\text{OIII}]/\text{H}\beta$ and $[\text{NII}]/\text{H}\alpha$ ratios than the single Gaussian measurements and are closer to where local star-forming galaxies lie on the BPT diagram.

Assuming the broad component is an outflow we estimated the mass loading factor ($\eta = \text{mass outflow rate}/\text{star formation rate}$) as a function of mass and find generally good agreement with previous studies. We find our galaxies are compatible with simulations only if a large fraction of the outflows are below 300 km s^{-1} for galaxies below $10^{10} M_{\odot}$ stellar mass.

We show that adding shocks to $z \sim 0$ spectra from SDSS shifts galaxies towards the location of $z \sim 2$ galaxies on several emission line diagnostic diagrams and is therefore a plausible candidate for the cause of the offset to the N2-BPT diagram. The lack of an offset in the $[\text{SII}]/\text{H}\alpha$ vs. $[\text{NII}]/\text{H}\alpha$ diagram may be explained by the decrease of the shocked $[\text{SII}]/\text{H}\alpha$ ratio as electron density increases.

Shocked emission may impact measurements made from emission lines affected such as calculating star formation rate from $\text{H}\alpha$ which would be overpredicted by 10-50%.

4.2 BMEP and Other Software

The MOSDEF survey has taken spectra for ~ 1500 galaxies at redshifts of $z \sim 1 - 3$. Extracting 1D spectra from 2D images in the Y, J, H, and K bands is challenging because of the large number of sky lines, high background noise, and nearly no continuum for most galaxies. The usual method to extract spectra would be to bin the data in the wavelength axis to create a profile. Doing this for MOSFIRE data would add in a large amount of noise to the profile because there is almost no stellar continuum for most of the galaxies and high background noise. Most galaxies have only significant flux from emission lines. This produced a unique challenge in that only select wavelength regions should be used to create the weighting profile for extracting spectra.

To solve this problem, I have written the 2D to 1D extraction code called **BMEP**. This code reads in data from the 2D MOSDEF reduction program and allows the user to interactively select

the wavelengths to sum together to create the weighting profile. BMEP also has a “continuum mode” that automatically removes skylines from the wavelength range selected for galaxies with continuum. Seven members of the MOSDEF team used BMEP and reduced 4900+ spectra with it.

BMEP is hosted on the website GitHub and has an extensive wiki that explains how to install, common mistakes, outputs, commands, and much more. The code is listed on the Keck MOSFIRE Data Reduction Tools Wiki¹.

4.3 Possible Future Work

There are several ways in which this work can be expanded upon. These include searching for broad flux in local galaxies, improving measurements on parameters to estimate the mass loading factor, and including more galaxies from the MOSDEF sample.

This work shows that broad emission from shocks may be affecting measurements of physical properties from galaxies at high redshift but does not show that shocks are not present in local galaxies as well. It would be beneficial to search through local galaxies and fit them using the same method described in Section 2.3 and determine the prevalence of broad emission in local galaxies. The contribution from shocks is likely small because the average SFR is a factor of ~ 10 smaller than at $z \sim 2$. Additionally, the spectra would show obvious signs of broadened, shocked emission and no studies have shown that this is the case. Appendix D has an SQL query that would return galaxies that could be analyzed for broad emission.

The mass loading factor estimation in Section 2.5.3 relied on many assumptions and measurements from other studies. The largest source of uncertainty is the electron density. The electron density of the broad emission could be measured with deeper [SII] observations. The geometry and radial extent of the broad emission is difficult to constrain with slit-based spectroscopy. Using an integral field unit would greatly improve the constraints on the geometrical factors of the outflow.

This dissertation is based on only the first two years of data from the MOSDEF survey.

¹https://www2.keck.hawaii.edu/inst/mosfire/post_observing.html

Including the rest of the sample would double the sample size. With the larger sample, there would be more individual detections, and it might be possible to place the broad components from stacks on the S2-BPT diagram. If the broad emission from the S2-BPT diagram lies on or near the narrow components, that might show that shocks are the reason that $z \sim 2$ galaxies are not offset from local galaxies in the S2-BPT diagram.

This work is a critical step to understanding the properties of galaxies at $z \sim 1 - 3$. The possibility that shocked emission in the form of a broad component in emission lines is intriguing and might explain the differences between $z \sim 0$ and $z \sim 1 - 3$ galaxies.

Appendix A

BFR vs SFR, sSFR, and Σ

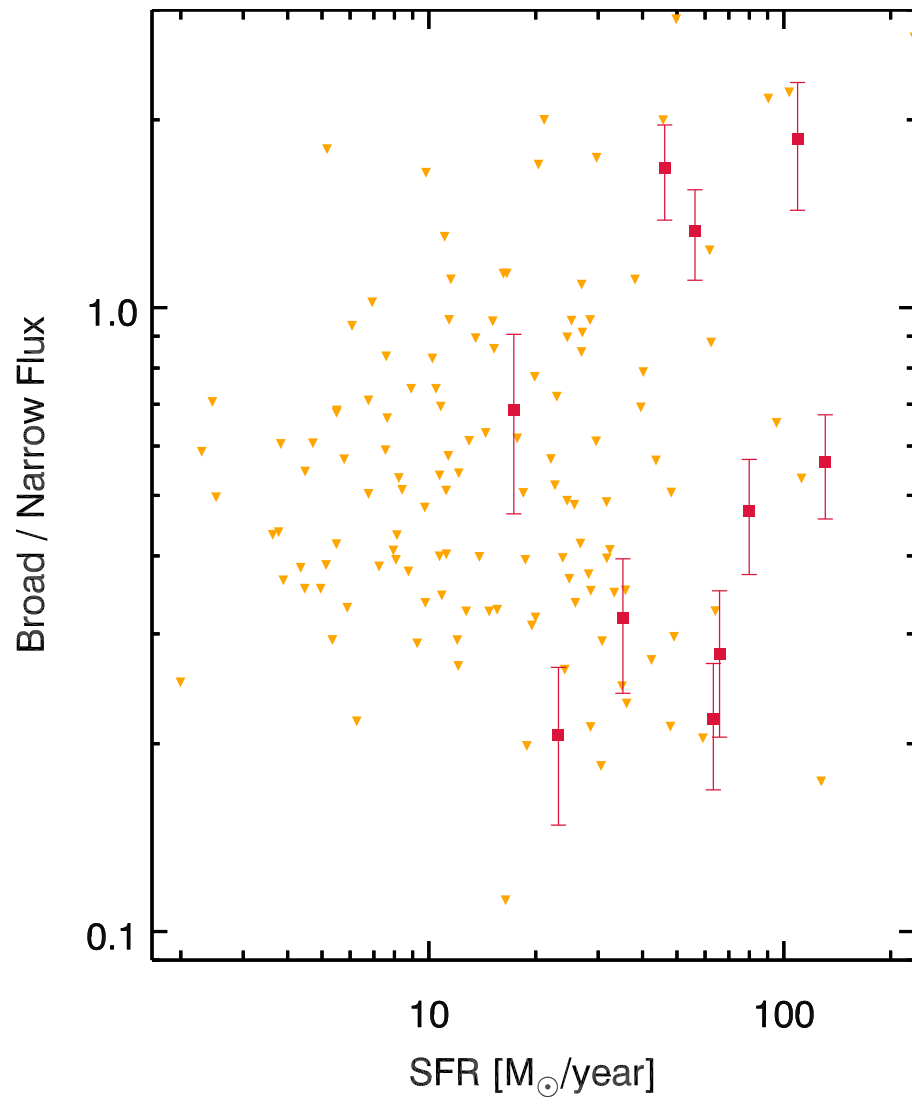


Figure A.1 BFR as a function of SFR for H α . Symbols are the same as Figure 2.6

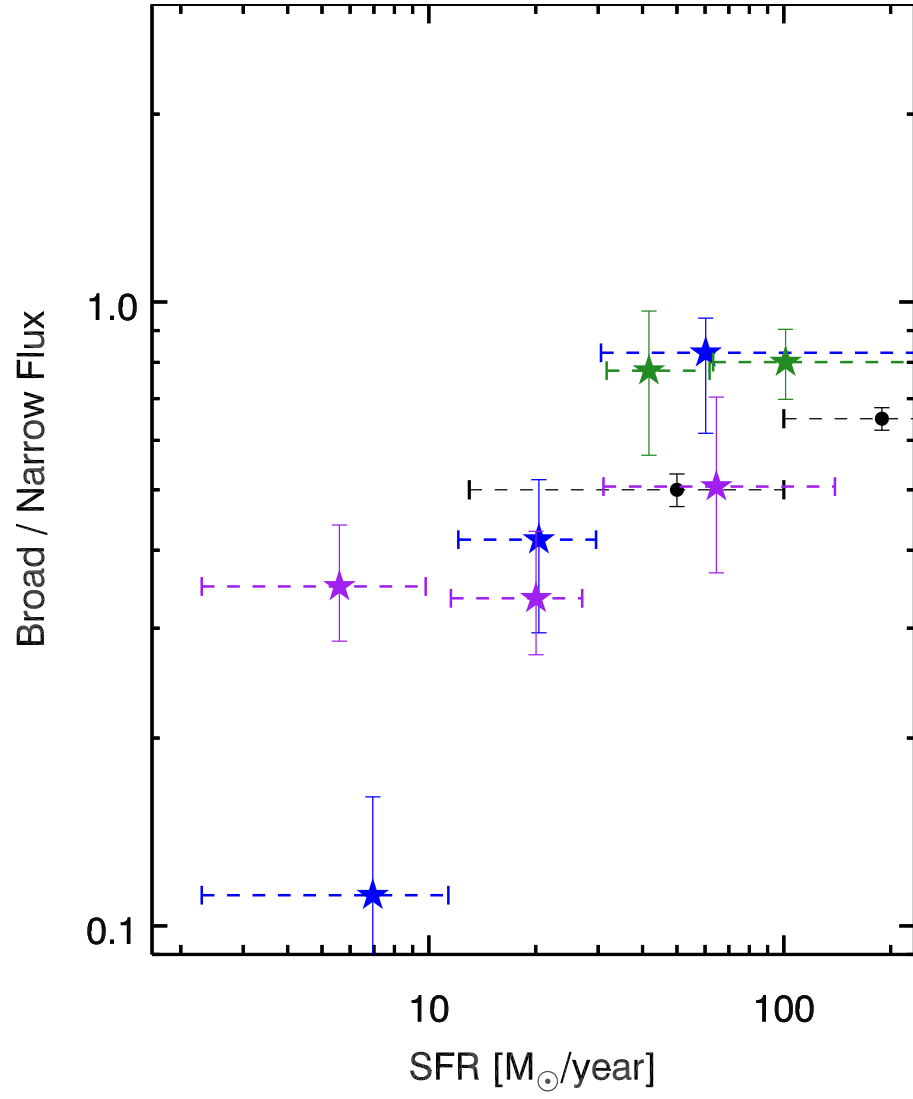


Figure A.2 BFR vs SFR measured from $H\alpha$ for stacks. Symbols are the same as Figure 2.7.

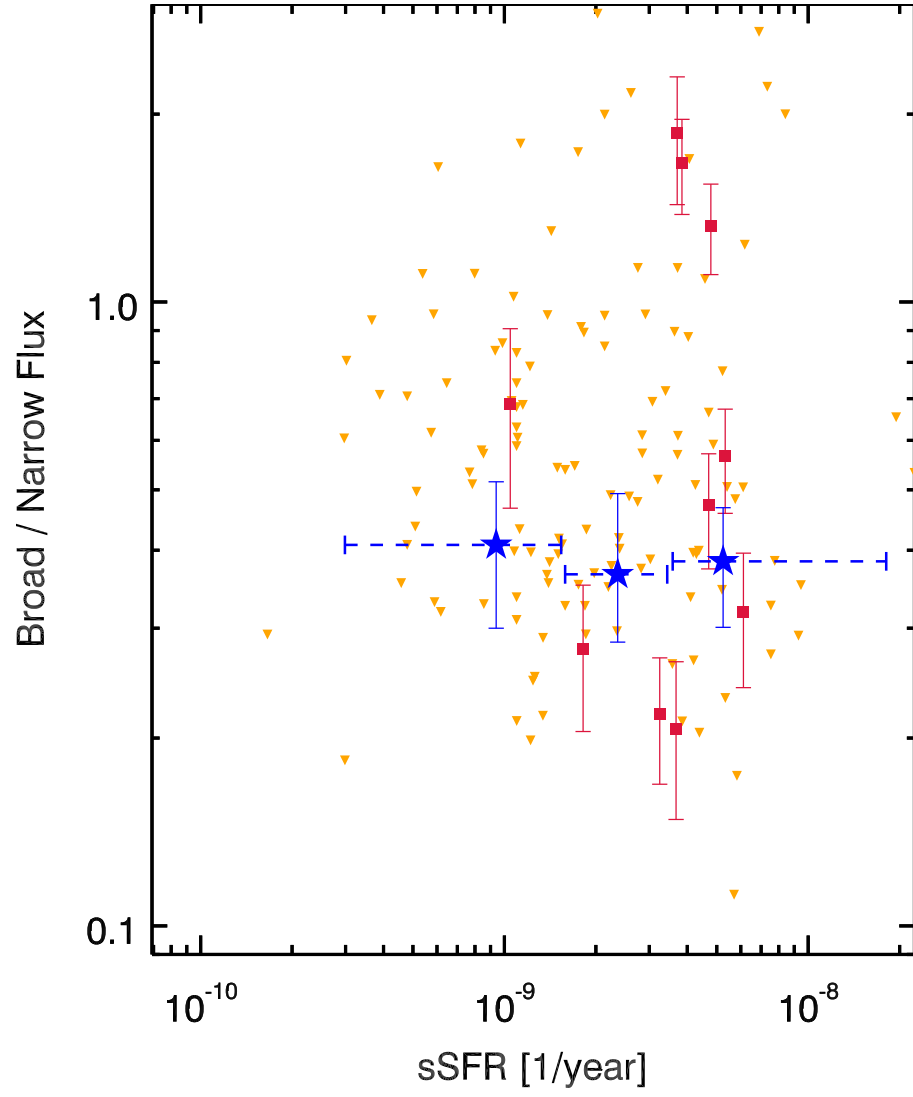


Figure A.3 BFR vs sSFR measured from $H\alpha$ for stacks and individual galaxies. Symbols are the same as Figures 2.6 and 2.7.

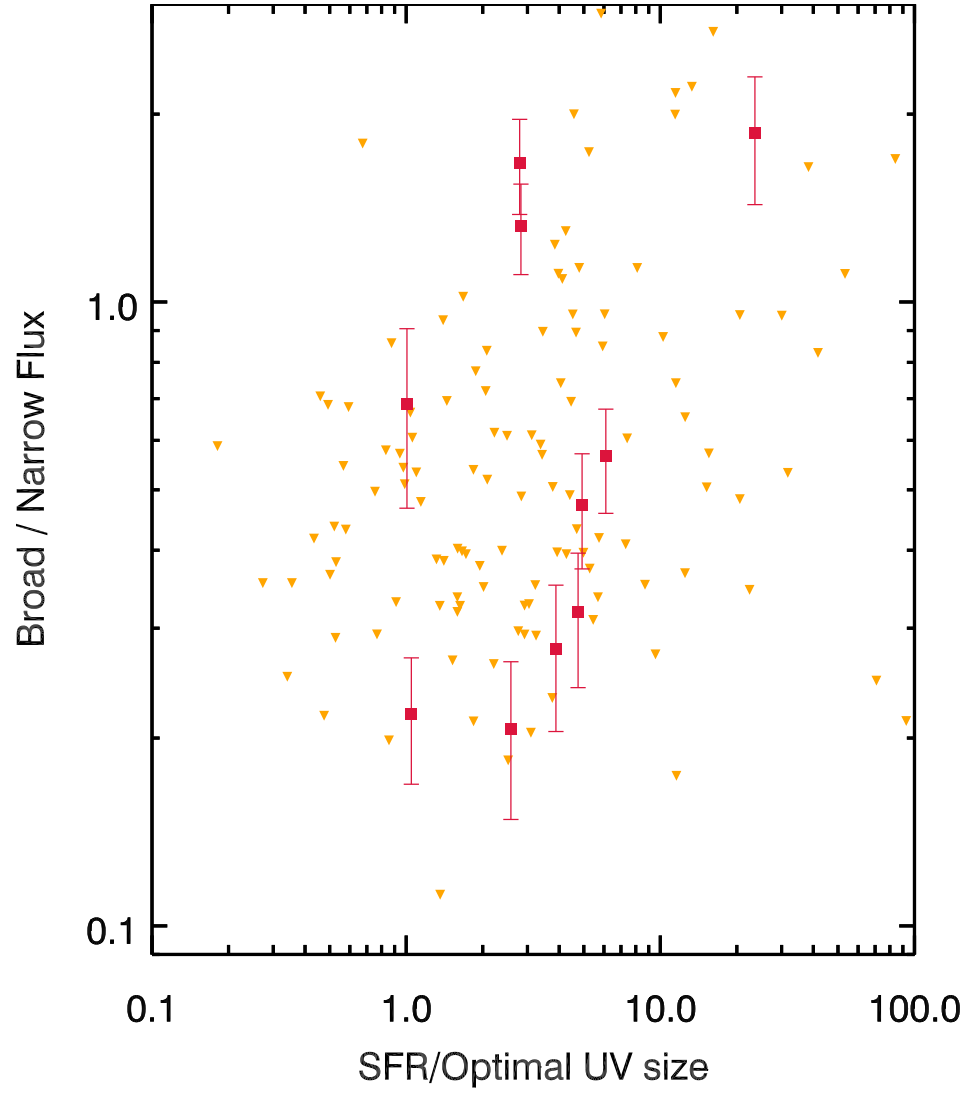


Figure A.4 BFR as a function of Σ_{SFR} measured from $\text{H}\alpha$. Symbols are the same as Figure 2.6.

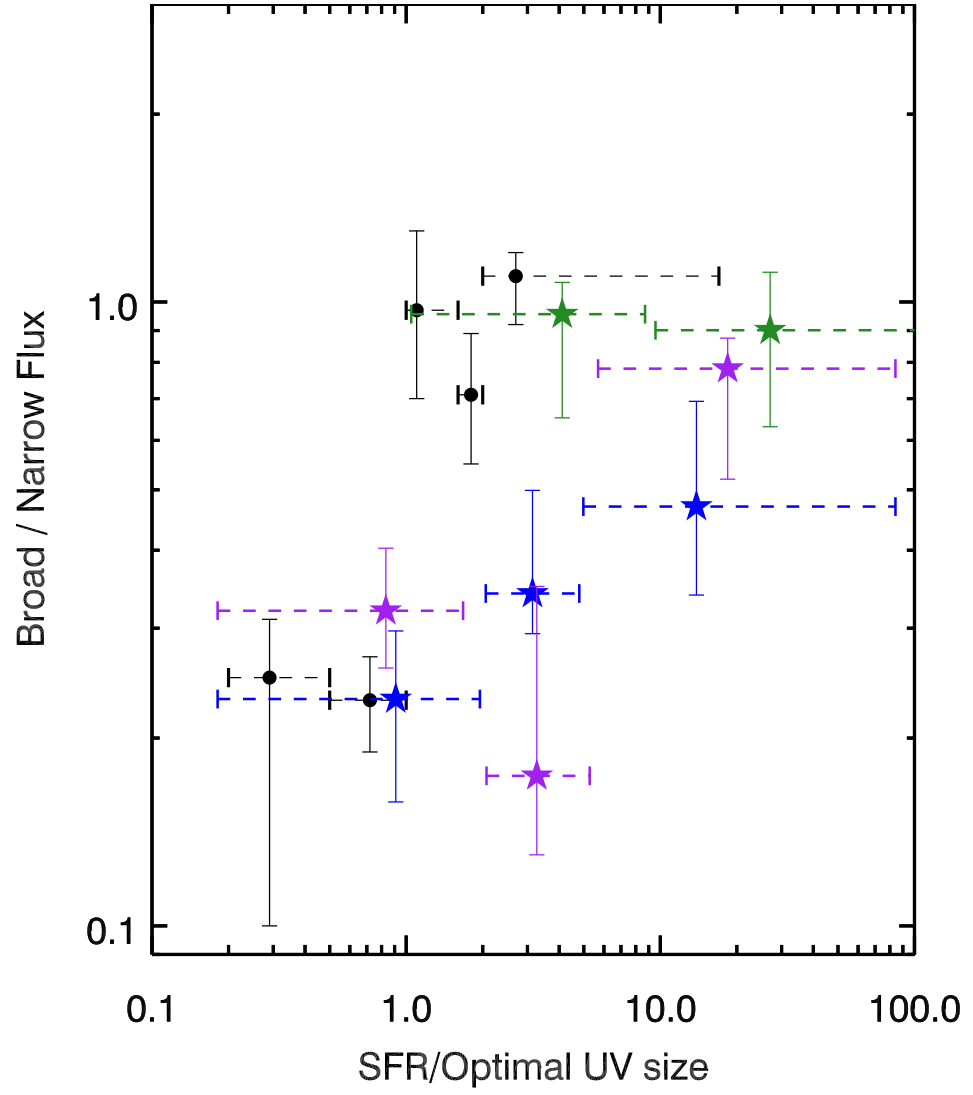


Figure A.5 BFR as a function of Σ_{SFR} measured from $\text{H}\alpha$ for stacks. Symbols are the same as Figure 2.6.

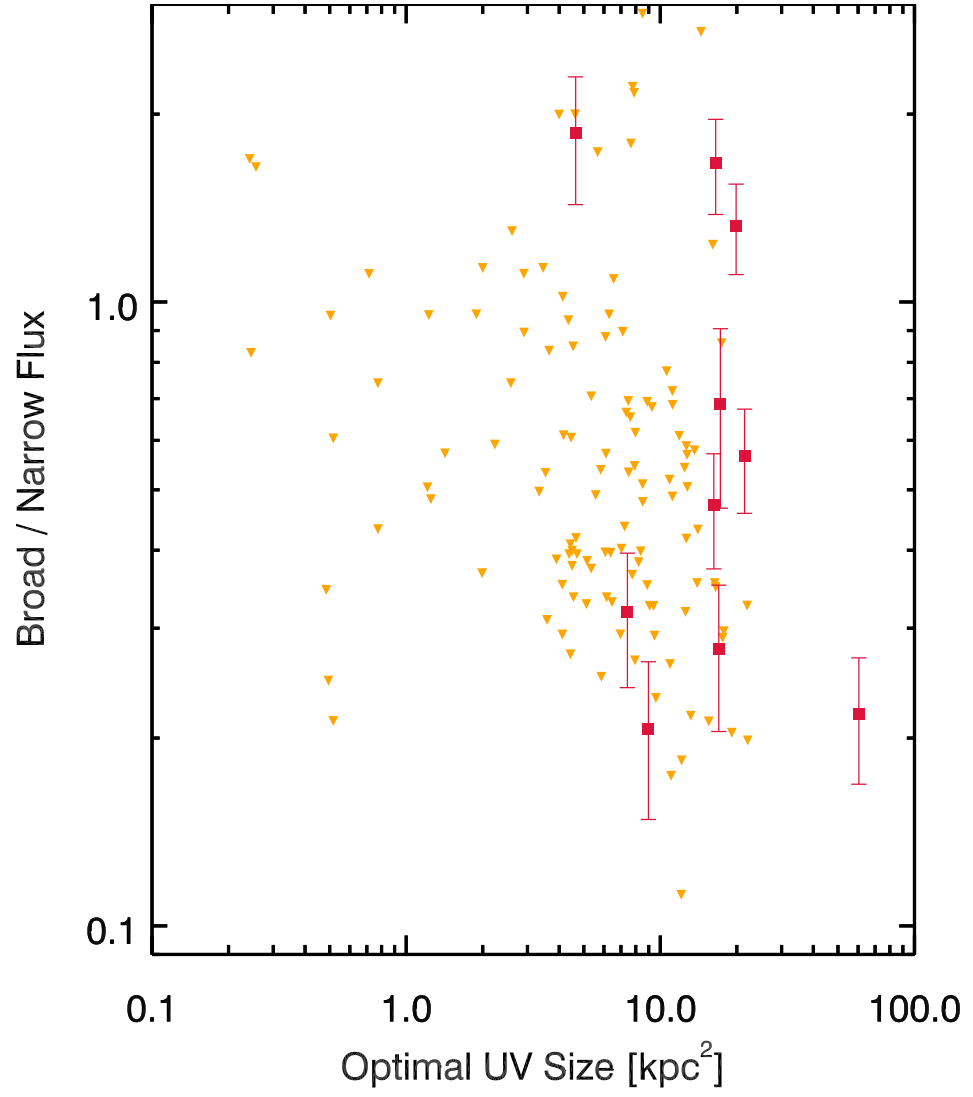


Figure A.6 BFR as a function of area measured from H α . Symbols are the same as Figure 2.6.

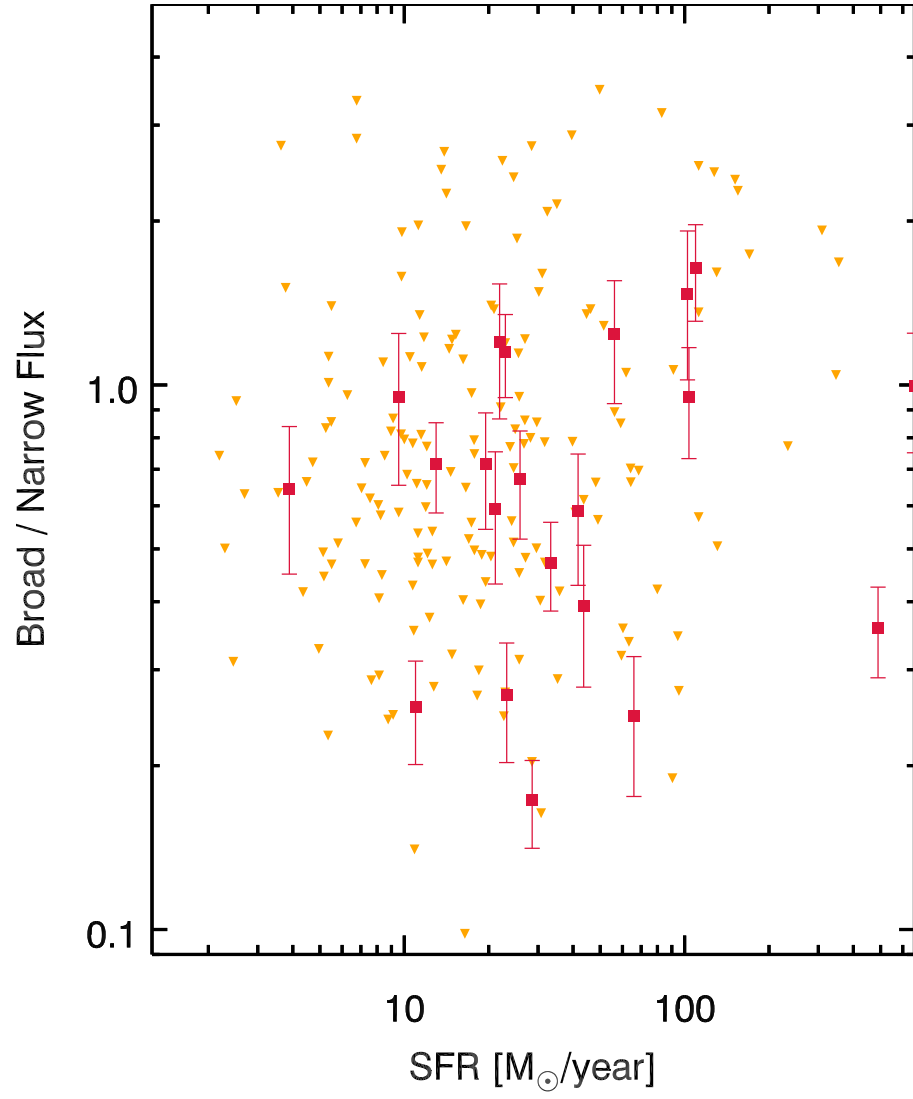


Figure A.7 BFR as a function of SFR for [OIII]. Symbols are the same as Figure 2.6

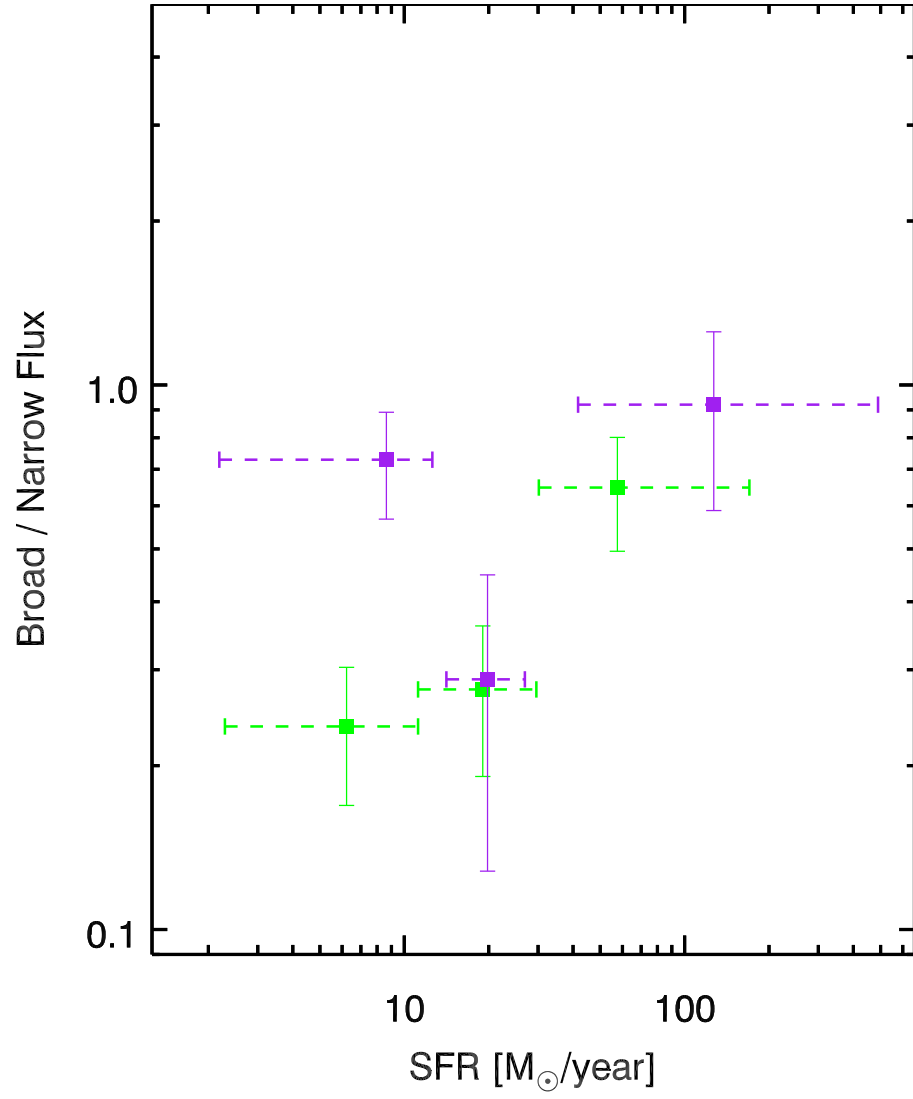


Figure A.8 BFR as a function of stellar mass for stacks of [OIII]. Symbols are the same as Figure 2.7

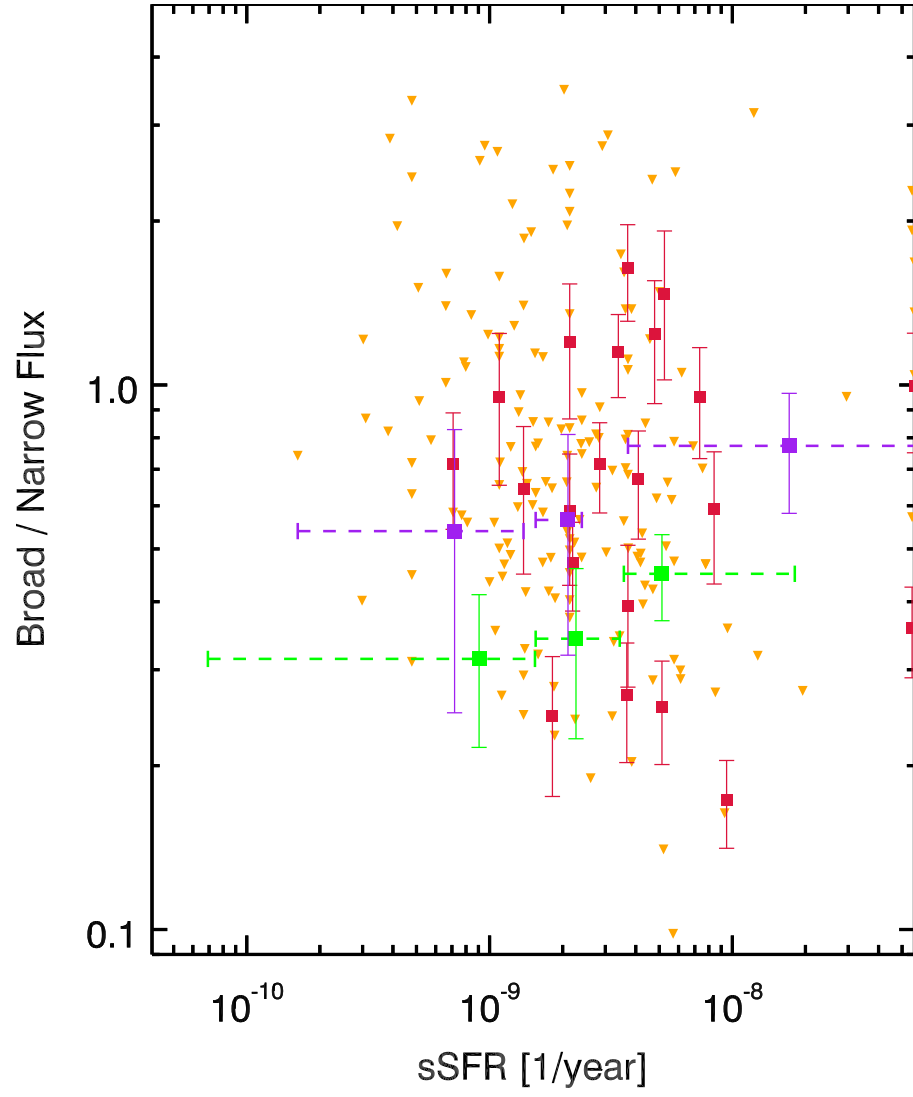


Figure A.9 BFR as a function of sSFR for [OIII]. Symbols are the same as Figure 2.6 and Figure 2.7

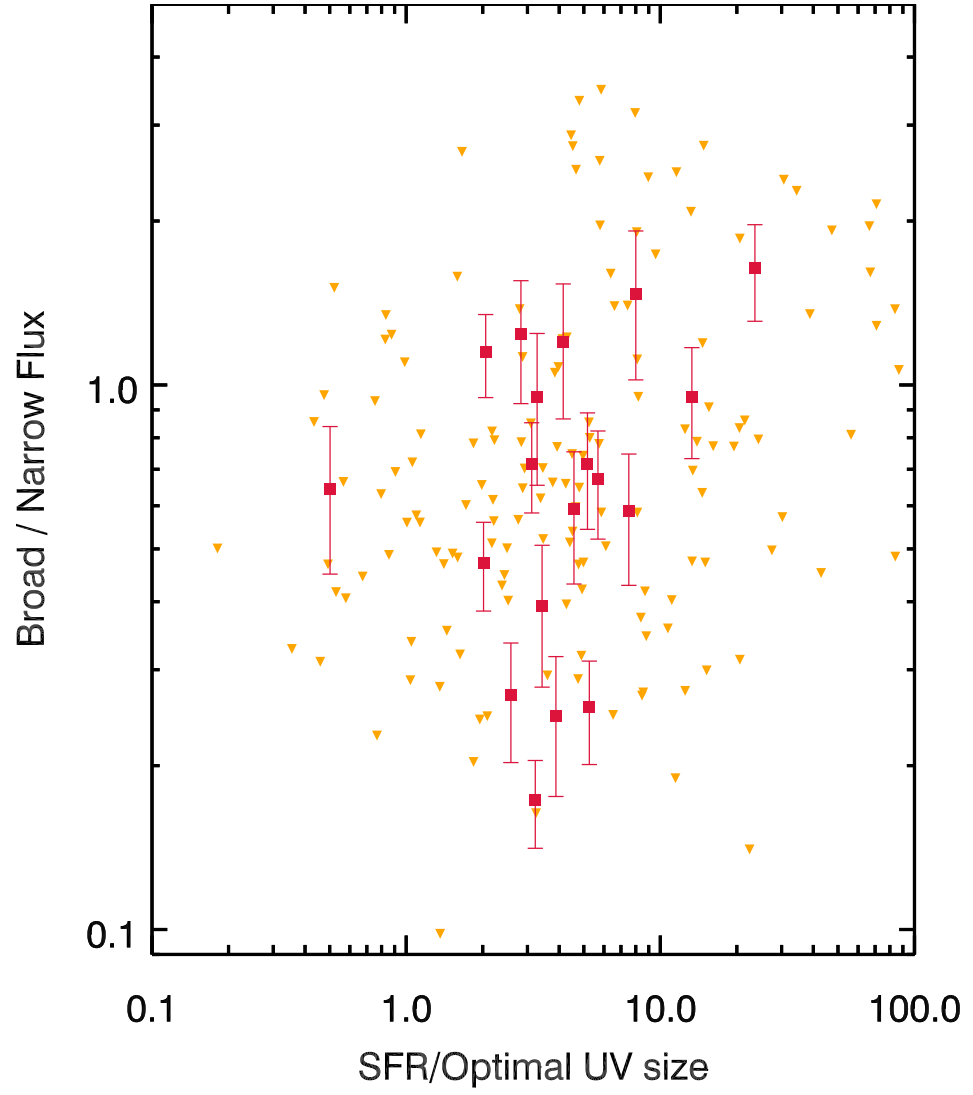


Figure A.10 BFR as a function of Σ_{SFR} for [OIII]. Symbols are the same as Figure 2.6

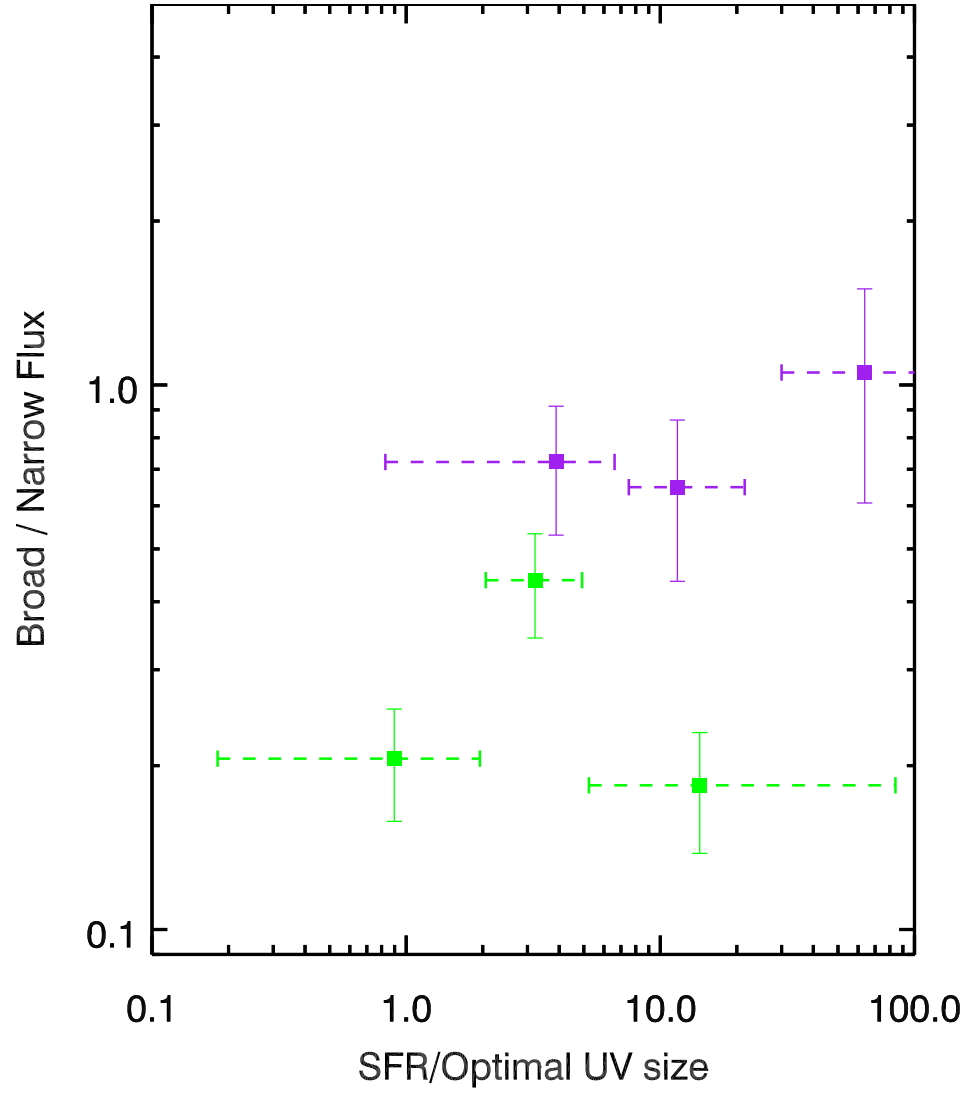


Figure A.11 BFR as a function of Σ_{SFR} for stacks of [OIII]. Symbols are the same as Figure 2.7

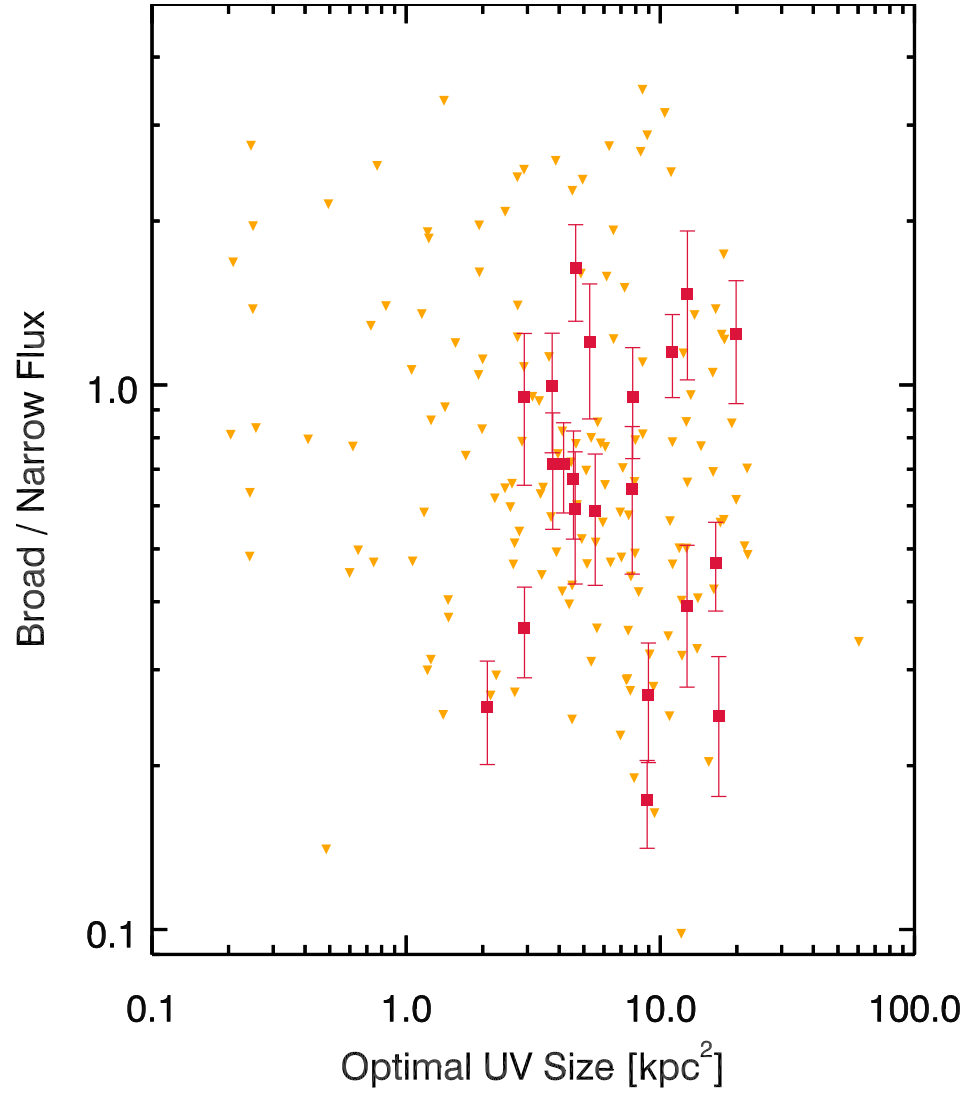


Figure A.12 BFR as a function of area for [OIII]. Symbols are the same as Figure 2.6

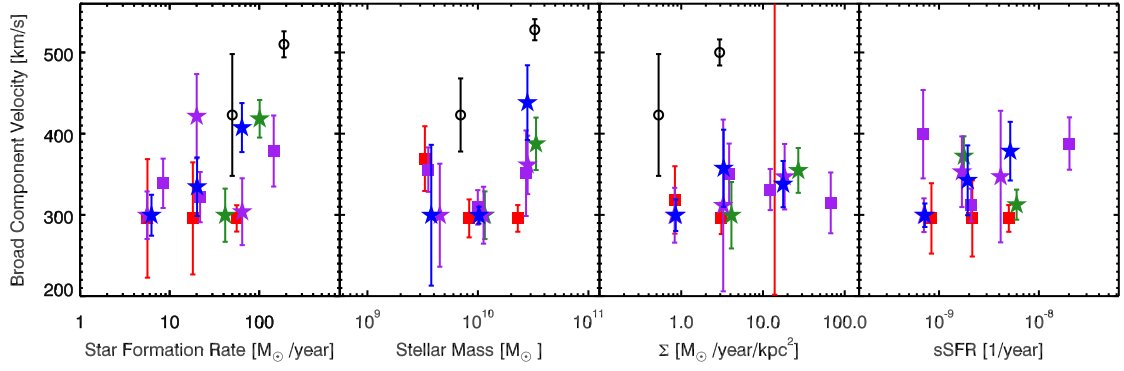


Figure A.13 FWHM vs. SFR, Σ_{SFR} , and sSFR for stacks ($\text{H}\alpha$)

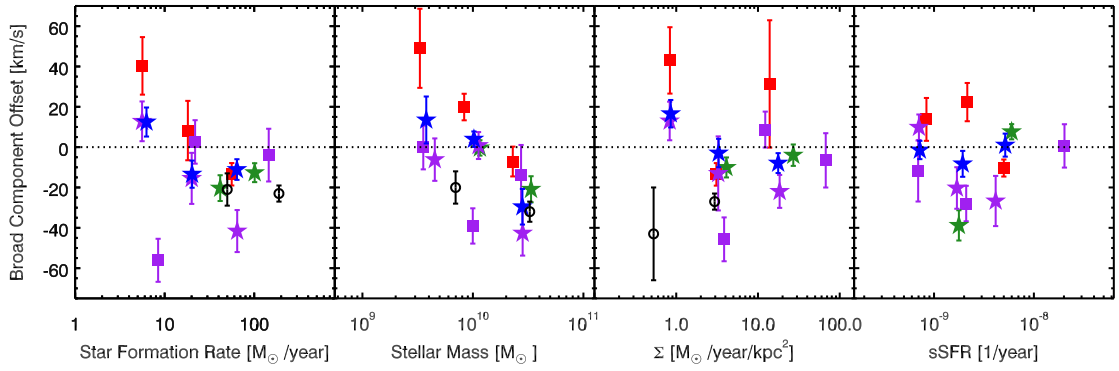


Figure A.14 ΔV vs. SFR, Σ_{SFR} , and sSFR for stacks ($\text{H}\alpha$)

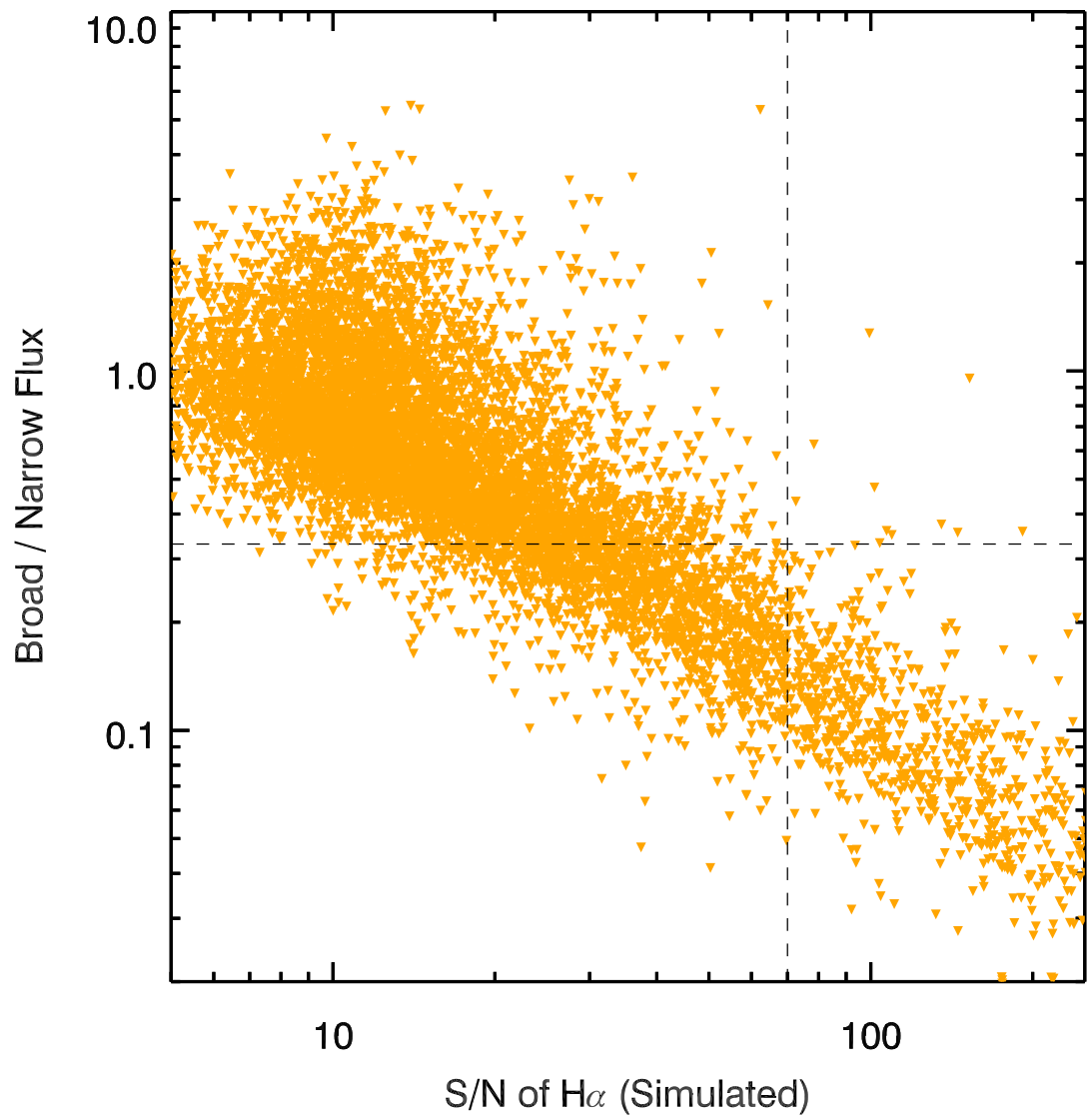


Figure A.15 BFR vs S/N for simulated H α emission with no broad component. Dashed lines mark a S/N of 70 and a BFR of 0.33 (corresponding to 25% of the total flux is broad).

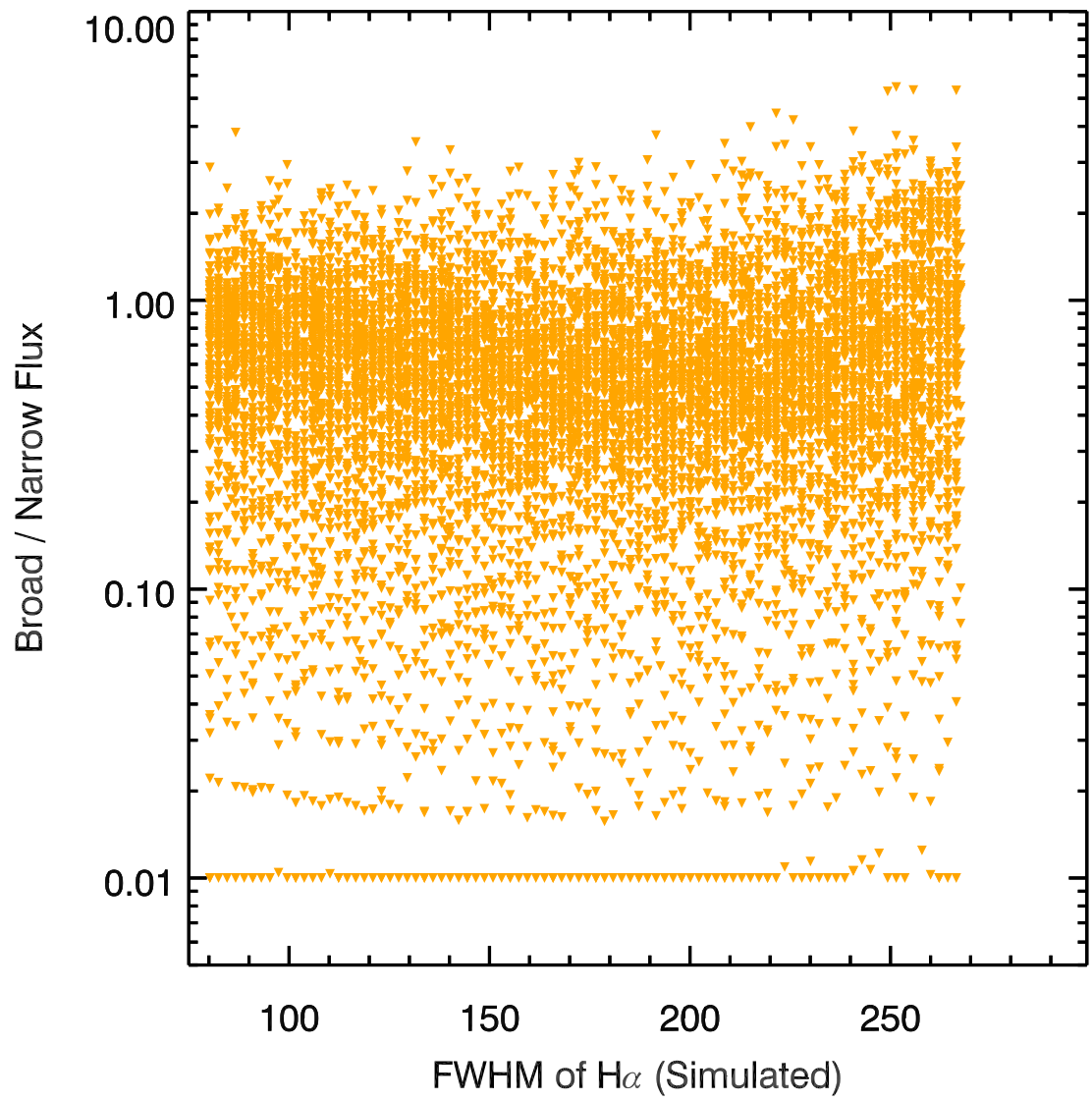


Figure A.16 BFR vs FWHM for simulated H α emission with no broad component. There is no noticeable trend with limit and FWHM.

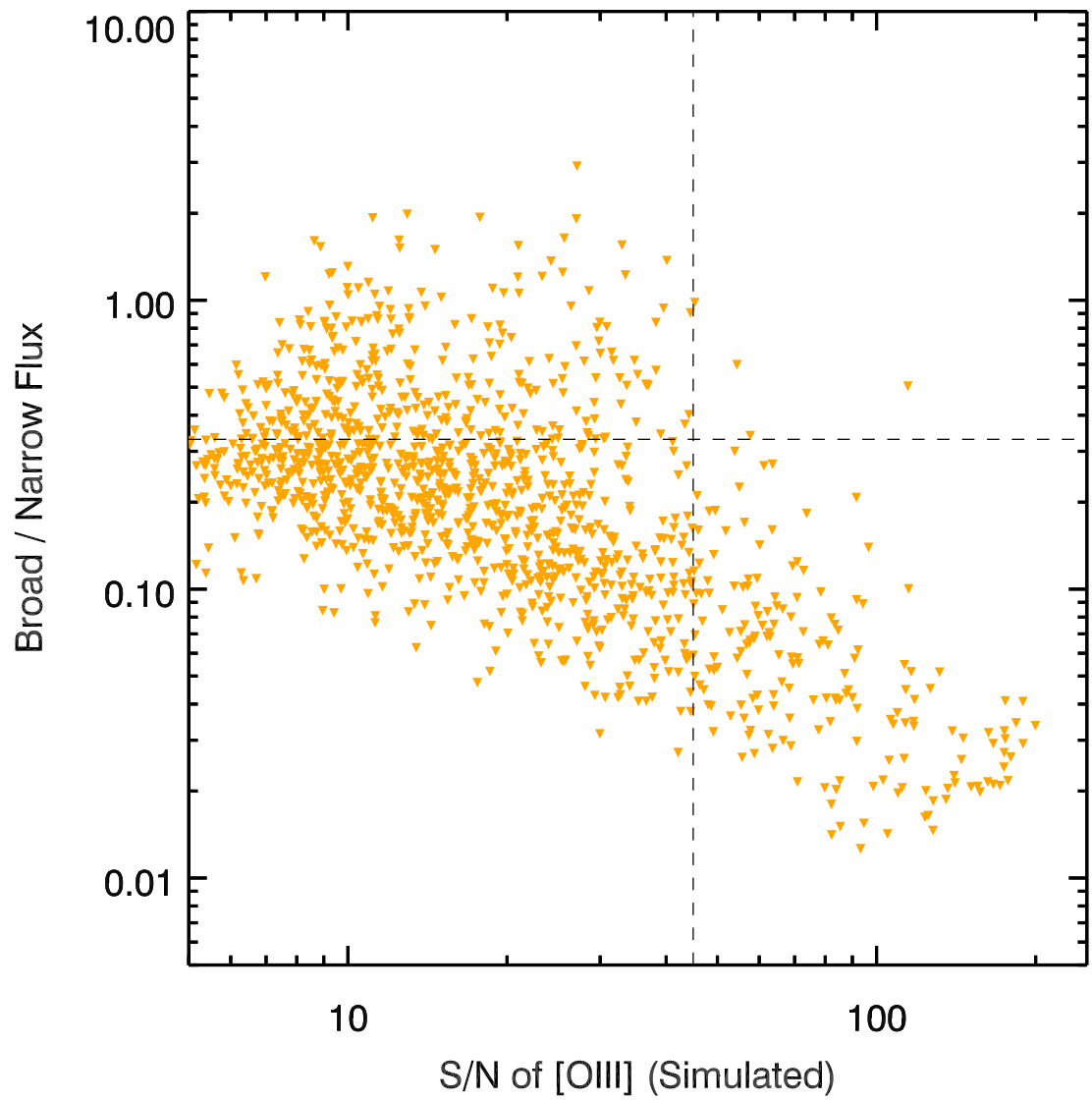


Figure A.17 BFR vs S/N for simulated [OIII] emission with no broad component. Dashed lines mark a S/N of 45 and a BFR of 0.33 (corresponding to 25% of the total flux is broad).

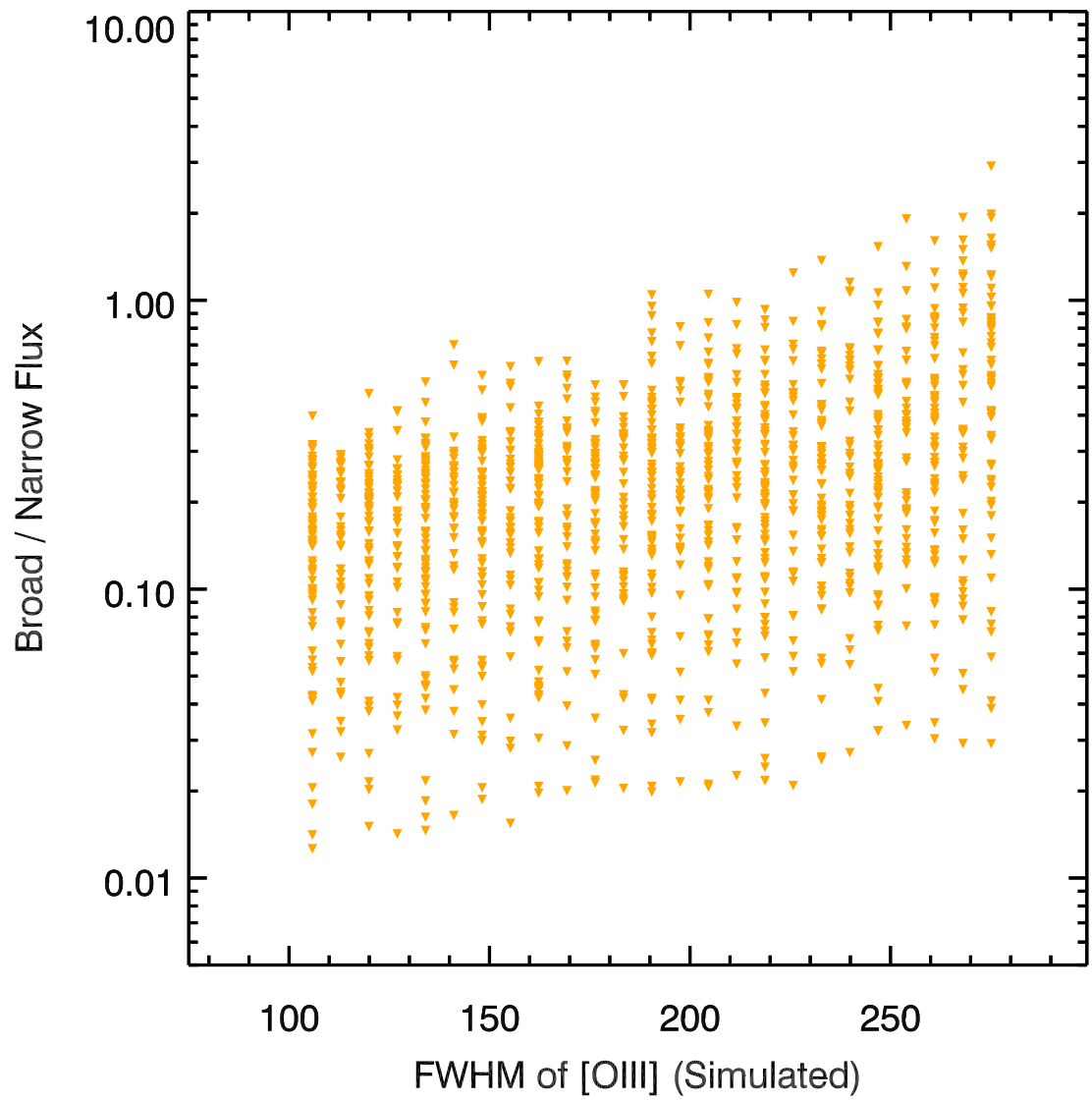


Figure A.18 BFR vs FWHM for simulated [OIII] emission with no broad component. There is no noticeable trend with limit and FWHM.

Appendix B

Unrestricted Fits

For the broad+narrow fits, we assumed that the FWHM_B , FWHM_N , and ΔV are the same for each line that is fit (see Section 3.4). However, the dynamics may be more complicated than we have assumed. Therefore, we fit each stack using an “unrestricted” fit where the widths of each line are not locked to each other and are free parameters. After doing these fits, the reduced χ^2 for many of the fits were significantly less than one and, in general, the broad component for weaker lines ([NII], [SII], $\text{H}\beta$) could only be limited because there were no strong ($> 3\sigma$) detections. Therefore, we remove the broad component for the weaker lines in the unrestricted fits. This results with much more reasonable reduced χ^2 values. The line ratios calculated using the narrow components of the unrestricted fits are shown as solid circles in Figures 2.14 and bptsiidiagram

The unrestricted fit can be thought of as an extreme lower limit on the broad flux measured in the [NII], [SII], or $\text{H}\beta$ lines with regards to calculating line ratios.

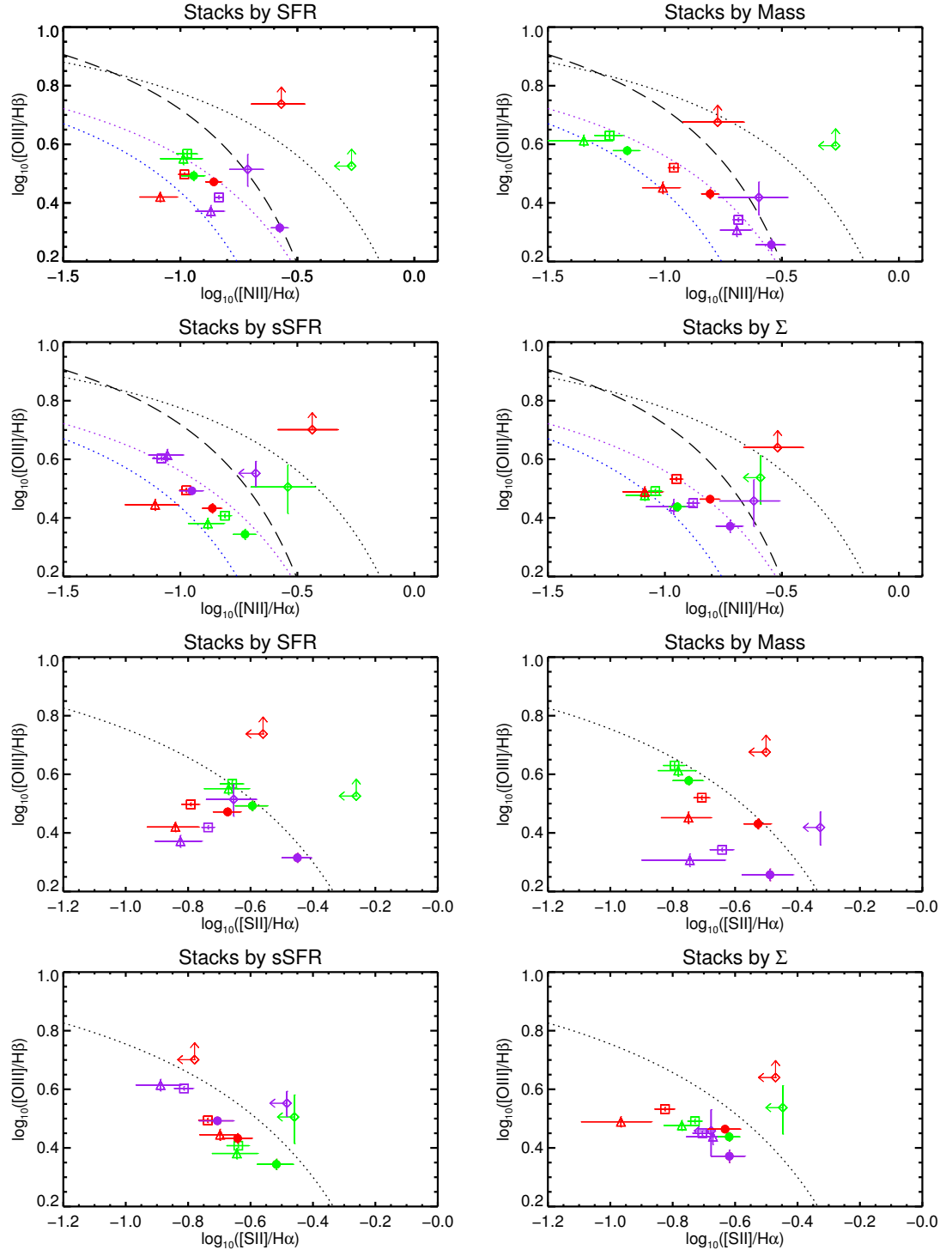


Figure B.1 BPT and S2-BPT diagram with unrestricted fits.

Appendix C

Glossary

η - Mass loading factor (mass outflow rate / star formation rate)

AEGIS - All-wavelength Extended Groth Strip International Survey

AGN - Active Galactic Nucleus

BFR - Broad Flux Ratio

CANDELS - Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

COSMOS - Cosmic Evolution Survey

DRP - Data Reduction Pipeline

FAST - Fitting and Assessment of Synthetic Templates

FIRE - Feedback In Realistic Environments

FMR - Fundamental Metallicity Relation

FWHM - Full Width at Half Maximum

GOODS-N - The Great Observatories Origins Deep Survey North

GOODS-S - The Great Observatories Origins Deep Survey South

HST - Hubble Space Telescope

IDL - Interactive Data Language

IMF - Initial Mass Function

LRIS - Low Resolution Imaging Spectrometer

MOSDEF survey - MOSfire Deep Evolution Field survey

MOSFIRE - Multi-Object Spectrometer for Infra-Red Exploration

N12 - reference to Newman et al. 2012

SED - Spectral Energy Distribution

SETI - Search for Extra-Terrestrial Intelligence

SFG - Star Forming Galaxy

SFR - Star Formation Rate

S/N - Signal to Noise

sSFR - Specific Star Formation Rate (SFR/Mass)

UCR - University of California, Riverside

UDS - CANDELS Ultra Deep Survey

UV - Ultra Violet

z - redshift

Appendix D

SDSS SQL Query for a $z \sim 0$

Comparison

Below is the SQL query used to select the SDSS galaxies that can be compared to the MOSDEF sample. The redshifts should be restricted to be between 0.04 and 0.1 to reduce aperture effects.

```
SELECT
  s.plate, s.fiberid, s.mjd, s.z, s.zwarning,

  g.h_alpha_flux, g.h_alpha_flux_err,
  g.nii_6584_flux, g.nii_6584_flux_err,
  g.oiii_5007_flux, g.oiii_5007_flux_err,
  g.h_beta_flux, g.h_beta_flux_err,
  g.sii_6717_flux, g.sii_6717_flux_err,
  g.sii_6731_flux, g.sii_6731_flux_err,

  m.logMass, m.minLogMass, m.maxLogMass,
  m.SFR, m.minSFR, m.maxSFR,
  m.reducedChi2 ,
  p.expRad_u ,
  p.expRad_g ,
  p.expRad_r ,
  p.expRadErr_u ,
  p.expRadErr_g ,
  p.expRadErr_r
  into mydb.MyTable_10
```

```

from GalSpecLine AS g
JOIN SpecObj AS s ON s.specobjid = g.specobjid
JOIN stellarMassStarformingPort as m ON S.SpecObjID = m.SpecObjID
JOIN PhotoObjAll as p ON S.SpecObjID = p.SpecObjID
WHERE
    h_alpha_flux > h_alpha_flux_err*25
AND oiii_5007_flux > oiii_5007_flux_err*25
AND h_beta_flux > h_beta_flux_err*5
AND nii_6584_flux > nii_6584_flux_err*5
AND sii_6717_flux > sii_6717_flux_err*5
AND sii_6731_flux > sii_6731_flux_err*5
AND oiii_4959_flux > oiii_4959_flux_err*10
AND h_alpha_flux > 0.1
AND h_beta_flux > 0.1
AND oiii_4959_flux > 0.1
AND oiii_5007_flux > 0.1
AND sii_6717_flux > 0.1
AND sii_6731_flux > 0.1
AND s.class = 'GALAXY'
AND s.zwarning = 0

```

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