Spatially Resolving the Mass Surface Density Distribution in 12 Compact Galaxies with the Hubble Space Telescope

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Spatially Resolving the Mass Surface Density Distribution in 12 Compact Galaxies with the Hubble Space Telescope

A Thesis
Presented to
The Department of Physics & Astronomy
Bates College
in partial fulfillment of the requirements for the
Degree of Bachelor of Science

By
Sophia Carline Warner Gottlieb I
Lewiston, ME
April 4, 2017
Acknowledgements

Microscopically to macroscopically, I would like to thank Aleksandar M. Diamond-Stanic for all of his guidance and support on this project, as well as taking the role of my mentor. I’d also like to thank my teammates in the Bates Astrophysics Galaxy Evolution Lab (the Bagel), specifically Josh H. Rines for his contributions to my analysis and insights to the project. I also appreciate Bates College and its Physics and Astronomy Department for allowing me the opportunity to complete a second thesis. I’d also like to thank the National Aeronautics and Space Administration, without whom this research would not be possible.

Dedication

To J0826, the light of my thesis & the one that started it all…
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Abstract

Why are galaxies so bad at forming stars? Observations and simulations of how efficiently galaxies can collapse cold, dense gas into stars differ by an order of magnitude. Scientists turn to processes that inject energy or momentum into galaxies to prevent gas from cooling and forming stars. Our research investigates whether radiation or ram pressure from stars could produce high-velocity outflows of cold, dense gas and reduce galactic star formation. Understanding why galaxies struggle to form stars out of normal matter will inform our knowledge of the galactic lifecycle, and resolve the inefficiency dilemma between observations and simulations. Typical outflow velocities from star-forming galaxies range from 100 to 500 km/s, but some massive, compact galaxies have been observed to eject gas at speeds exceeding 1000 km/s. Outflows like these are typically attributed to an active galactic nucleus (AGN), but there is no evidence for AGN activity for most galaxies in this sample from optical, infrared, and x-ray observations. We present an investigation of whether or not the radiation pressure from a recent starburst event could be responsible for the outflows in each of a sample of 12 galaxies. In particular, we focus on observations at rest-frame U, V, and J wavelengths with the Wide Field Camera 3 (WFC3) on the Hubble Space Telescope (HST) that were designed to spatially resolve the mass distribution for these massive galaxies.
Introduction

Figure 1: Messier 104, or The Sombrero, displays a nice long, thin disk and a prominent central bulge. It is located in the Virgo constellation at a distance of 50 million light years.

Image credit: ESO/ P. Barthel

A galaxy is a collection of dark matter, stars, dust, and gas held together by gravitational attraction. Like all things in this world, galaxies are not eternal; they have a lifecycle defined by how effectively the galaxy forms stars. The anatomy of a galaxy is composed of two main visible features: a spherical central bulge and a long thin disk (Figure 1). These two components lay within a larger ‘halo’, composed of dark matter and a reservoir gas for star formation. Galaxies are classified as “star-forming” when galactic gas collapses to form many stars at a given time and “passive” when star formation occurs at a much lower rate (Heckman 2011). Sometimes, two galaxies are close enough to gravitationally attract each other so that they merge. The mixing
of the interstellar medium often creates an increase in star formation, called a starburst event. Galaxies can change from star-forming to passive, but the mechanisms behind the changes are not clear. What causes a galaxy to increase or decrease its star formation rate? It very well may have something to do with the supply of cold, dense gas that can collapse and form stars.

To understand the universe in which we live, scientists run simulations and make models. These models make several assumptions that are motivated by observational constraints to run as accurately as possible. When modeling galaxy formation, simulations from a cold dark matter model, ΛCDM, without strong feedback over predict baryon fractions that form stars by a power of ten and make what is called an “overcooling problem” (Kereš 2009). Massive galaxies are then simulated more luminous and blue than actually observed (Croton 2006, Gabor 2011). To solve this problem, theorists have attempted to incorporate the physics of how massive stars and accreting supermassive black holes eject cold gas and prevent hot gas from cooling, thus regulating the gas supply and quench star formation rates (Hopkins et al. 2014, Vogelsberger et al. 2014, Schaye et al. 2015).

From an observational perspective, one very common thing we see in star-forming galaxies are gaseous outflows. Typical outflow velocities range from 100 km/s to 500 km/s, but some galaxies see much larger (v~1000 km/s) outflows (Tremonti et al. 2007, Diamond-Stanic et al. 2012). These galaxies with faster outflows are important because they imply a more powerful energy source that could remove the cold gas supply and shut down subsequent star formation. Although the cause is unknown, data from the Hubble Space Telescope can be used to investigate whether or not feedback from compact starbursts with high star formation rate (SFR) surface density could be responsible for the high velocity outflows (Diamond-Stanic et al. 2012, Sell et al. 2014).
With such high velocities, a common assumption is that feedback from an active galactic nucleus (AGN) must be the responsible mechanism (Sharma & Nath 2013, Hopkins 2013). However, most galaxies in our sample show no evidence for AGN activity on the basis of optical, infrared, and X-ray observations. It is known that the radiation pressure from stars exceeding the Eddington limit drive high-velocity stellar winds. The Eddington limit is the hydrostatic equilibrium for a celestial body which the outward force of its radiation equals its gravitational force inwards. As the SFR surface density approaches the Eddington Limit, near 1000 M_☉/yr/kpc^2, the outward force of radiation pressure exceeds the force of gravity and disrupts subsequent star formation (e.g., Thompson et al. 2005). However, radiation pressure is not the only possible source for ejective feedback. Outflows at these high velocities are usually attributed to active galactic nuclei (AGN) activity, but because observations in the optical and x-ray spectrum do not support AGN activity in all galaxies, it is an unsatisfactory solution.

Massive stars impart momentum through radiation pressure on the surrounding gas and dust, which has the ability to launch outflows on the order of a body’s escape velocity (Murray et al. 2011) or even an order of magnitude larger than the escape velocity (Thompson et al. 2015). Velocities for outflowing gas driven by the radiation pressure of stars and the ram pressure of supernovae are expected to be proportional to the inverse square of the effective radius of the galaxy (Heckman et al. 2011; Diamond-Stanic et al. 2012). The compact morphologies for the galaxies in our sample suggest that their escape velocities could be as large as 1000-2000 km/s (Diamond-Stanic et al. 2012). However, that estimate of the escape velocity assumes that the stellar mass of these galaxies are as compact as their light profiles. Given that the light is dominated by young stars, which have a small mass-to-light ratio, there is reason to expect that the mass would be more extended than the light and that the central escape velocities for these
galaxies would be significantly smaller than 1000 km/s. If the escape velocities are on the order of the observed outflow velocities, it is likely that radiation pressure from the star formation is capable of driving these high velocity outflows (Murray et al. 2011). On the other hand, if we find that the escape velocity is significantly smaller than the outflow velocities, the physical mechanism driving these outflows must be able to accelerate gas to speeds that exceed the escape velocity by a significant factor (e.g., Thompson et al. 2015).

To test this hypothesis, we spatially resolve the mass for a better calculation of the escape velocity. We used the rest-frame $U-V$ color, which is sensitive to the relative contributions of recently formed stars, for which the light is dominated by hot stars that are blue in color, versus older stars, for which the light is dominated by cooler stars that are red in color. Although there are relative few massive hot stars, they account for most of the luminosity for a star-forming galaxy (Figure 2).

This research builds on the work done by Tremonti et al. 2007, and the discovery of the high velocity outflows in these rare galaxies. Diamond-Stanic et al. 2012 used data from HST at 814 nm to suggest that because of how compact these luminous starbursts are, the high-velocity outflows could be explained without invoking feedback from AGN. By studying the relationship between outflow velocity and AGN activity, AGN was ruled out as the source for the fast outflows (Sell et al. 2014). Geach et al. 2014 demonstrated that the compact starbursts have the ability to produce these high-velocity outflows and that could be responsible for the decrease in star formation rate, therefore strongly affecting galactic evolution. Rines 2016 calculated magnitudes for the $U-V$ color, mass-to-light ratios, and annular mass surface density as a function of radius for three compact galaxies. This study takes the work of Rines 2016 and
expands it to 12 galaxies. It also performs a new analysis on the same galaxies where luminosity, mass to light ratio, and mass are computed for each pixel for each galaxy.

Figure 2: Stars come in a variety of masses, temperatures, and life expectancies. The most massive, hottest, and shortest lived are not only the bluest but also most least common. For every fifty sun-sized stars, there is only one star with 10 to 150 solar masses. Supermassive stars are short lived - they only exist for around one million years before exploding as a supernova.

Credit: Pearson Education, Inc.
Data

The sample began with a large parent sample of around one thousand galaxies from the Sloan Digital Sky Survey (SDSS, York et al. 2000) that exhibited post-starburst features and had redshift between 0.3 and 1 (Tremonti et al. 2007, Diamond-Stanic et al. 2012). From that sample, a set of 29 were observed at 814 nanometers by HST in two proposals (12019 and 12272, PI: Christy Tremonti). From the 29, our twelve galaxies were selected for having the largest SFR surface densities. We have obtained new observations at F475W and F160W from HST proposal 13689 (PI: Diamond-Stanic) to spatially resolve the mass of these compact starbursts.

Our sample has four main qualities that make them ideal for this study. These galaxies are massive, with total stellar masses around $10^{11} M_\odot$. At the same time, they have compact morphologies (most of the light comes from a small portion of the galaxy), with effective radii $\sim 100$ pc. The small radius and large mass means these are very compact galaxies. The sample has redshifts between 0.4 and 0.8. As the HST imaging shows (Sell et al. 2014), these galaxies are the remnants of recent gas-rich mergers. As a result, these galaxies have experienced a starburst event in the past 100 million years, which may be why we see high velocity outflows. In addition, they have a recent star formation rate greater than 50 $M_\odot$ year$^{-1}$ (Diamond-Stanic 2012), and a star formation rate surface density between 30 and 3,000 $M_\odot$ yr$^{-1}$ kpc$^{-2}$.

Why do we need data from the Hubble Space Telescope? The massive original sample was selected through data from the Sloan Digital Sky Survey (SDSS) from a ground-based telescope at Apache Point Observatory in New Mexico, USA. The data from the SDSS were not sufficient to measure either outflow velocities or morphologies for these galaxies because the SDSS spectroscopy had low signal-to-noise and the SDSS imaging had limited spatial resolution (Figure 3). After the discovery of high-velocity outflows in spectroscopy with larger telescopes
(Tremonti et al. 2007), our team pursued high-resolution imaging with the Hubble Space Telescope.

![Image of galaxy comparison]

Figure 3: A comparison of the resolution of SDSS and the Hubble Space Telescope, for J0826.

Left: (skyscanner.sdss.org) Right: created in DS9.

The Hubble Space Telescope was launched in 1990 and has made over 1.3 million observations (Figure 4). The observations for this research were taken by the Wide Field Camera 3 (WFC3). It collects high resolution data in near infrared, visible, and near ultraviolet over a larger field of view than its predecessor, WFC2 (NASA). As part of HST programs 12019 and 12272, our team obtained imaging in the F814W filter for a sample of 29 galaxies (Diamond-Stanic et al. 2012, Sell et al. 2014). This data allowed us to spatially resolve the luminosity of the galaxies. To spatially resolve the mass, our team submitted a subsequent proposal (13689, PI: Aleksandar Diamond-Stanic), to obtain WFC3/UVIS observations with the F475W filter and WFC3/IR observation with the F160W filter (Figure 5). These filter bandpasses correspond to rest-frame $U$ and $V$ at the redshifts of the galaxies in our sample. In addition, observations in $U-V$...
and $V-J$ colors distinguish dusty, active galaxies from older, passive galaxies, which can appear similar in a single wavelength (Williams et al. 2009).

Figure 4: The Hubble Space Telescope. Credits: NASA

The background subtraction was part of the image processing that was performed by Paul Sell. By default, the counts in a pixel would be a combination of counts from the source and counts from the background. An effort was made to estimate the average background flux per pixel and then subtract that background flux from all pixels. This has the advantage that we don't have to subtract off the background level when computing a total flux. But because there are fluctuations in the background flux level across different pixels (due to noise), this means that subtracting off the mean background value will result in some negative pixel values.
Figure 5: J0826 in HST's three filters, and an RGB composite image. The spatial resolution of the F475W and F814W images (FWHM approximately 0.07") is better than the spatial resolution of the F160W image (FWHM approximately 0.13"), so we focus our analysis in this thesis on the two bands with comparable spatial resolution (F475W and F814W).

Top left: F475W. Top right: F814W bottom left: F160W bottom right: A composite image of J0826, a beautiful galaxy with a prominent tidal tail where 1600 nm, 814 nm, and 475 nm are used as red, green, and blue weights, respectively. (DS9).
Methods

Set Up

We receive the data from the WFC3 on HST as a 7500 x 7500 array of values, which arrives in a Flexible Image Transport System (FITS) file. Along with the data, these processed FITS images contain several important parameters stored in the image header. The units in the image need to be converted to $f_\nu$ flux in $\frac{erg}{s*cm^2*Hz}$, which requires relevant header keywords, and then $\nu * L_\nu$ or luminosity, which requires information about frequency and luminosity distance. Specifically, we needed access the exposure time and the frequency to calculate the flux in Janskys. The analysis was written and carried out in Python, using Aquamac, DS9, and a terminal window. Written codes can be found in the Bates Galaxy Lab GitHub Repository (https://github.com/aleksds/bates_galaxies_lab).

After acquiring the data, we use SDSS to identify the galaxy on DS9. In DS9, we manipulate z-scale and zoom to find the pixel with the highest flux in the 814 filter. This is our estimate for the center of the galaxy. We feed these coordinates, along with a galaxy’s z parameter to “sg_compoverlay_loop.py”, which takes the data from each galaxy in our study and produces three plots: mass as a function of radius using an annular mass-to-light ratio (MLR) method, mass as a function of radius using a broad MLR method, and the mass surface density as a function of radius for the spatially resolved color (SRC) and spatially integrated color (SIC) methods.
**Basis of the Code**

The general methods used in this thesis follow the sample calculation process; for any given flux value, in any given filter, we can calculate mass with the product of a mass-to-light ratio. For each filter, we extracted the flux and exposure time from our FITS file, and we calculate the observed-frame and rest-frame frequency based on the central wavelength of the filter and the redshift of the galaxy. We created flux in Jansky by multiplying the flux values (data) by flux conversion factor ($f_{cf}$) and dividing by exposure time (exp) (Equation 1). Then, we calculated the monochromatic AB magnitude (Equation 2). At this point, we have a magnitude for each filter or wavelength: 475 nm is our $U$ filter, 814 nm is our $V$ filter, and 1600 nm is our $J$ filter. An important point is that observed 475 nm corresponds (only approximately) to rest-frame $U$ at the redshifts of these galaxies. The $U$ band is actually centered around 360 nm, but the approximation suffices for this analysis at present.

\[
\text{flux [Jy]} = \text{data} \times \frac{f_{cf}}{\text{exp}} \quad \text{Equation 1}
\]

\[
\text{mag}_{AB} = - \frac{5}{2} \log_{10} \left( \frac{f_v}{3631} \right) \quad \text{Equation 2}
\]

At this point, we have calculated magnitudes in 3 filters / rest frames for the geometric array of fluxes appropriate for the analysis method. Now, for the first time for these galaxies, we can create rest-frame $U-V$ and $V-J$ colors, which are crucial to the mass-to-light ratio (MLR). The $U-V$ color comes from subtracting the $V$ absolute magnitude from the $U$ absolute magnitude, and a similar line of thought occurs for the $V-J$ color. Although we calculated a $V-J$ color, we did not make use of it in this project at the time of this thesis.
What Color Reveals About Stellar Population

As mentioned before, virtually all of the light comes from only a few super-hot, massive stars (Figure 6). Compared to their less massive counterparts, these stars live a short life before exploding as supernovae. From Wein’s law, we know that temperature and wavelength are inversely proportional; the hotter the blackbody, the shorter wavelength its peak wavelength. These massive stars are therefore “bluer”, meaning they radiate more at shorter wavelengths than at higher wavelengths. The differences of absolute magnitude of absolute magnitude in two wavelengths can tell us about the color of a galaxy: when subtracting magnitudes between filters, positive values are more “red” (areas have more flux at longer wavelengths), where the negative values are “bluer” (areas have more flux at shorter wavelengths).
Figure 6: the relationship between the luminosity and surface temperatures of stars on the main sequence. Hotter stars (on the left of the graph) are more luminous, while colder stars are less luminous. The frequency and life expectancy of such stars increases on this graph from left to right. Credit: Pearson Education, Inc.

The blue regions of the galaxy are dominated by a few young, bright, supermassive stars that radiate more at lower wavelengths. Because these stars are extremely luminous and there are few of them, these regions have very low MLRs. In our analysis, these have negative values for color. The red regions are comprised mainly of a higher number of older, smaller stars for a larger MLR. These regions have a positive value of color.
These relationships were investigated by Bell & de Jong in 2001. They presented a mathematical basis for the relationship between color and MLR (see equation 3). They produce a and b coefficients for six models of galaxies: closed-box, gas infall, outflow, dynamical time, formation epoch, and a formation epoch with bursts. In their coefficient table, Bell and de Jong included coefficients from Cole et al. 2000, which incorporates the evolution of bulges unlike Bell and de Jong (Appendix A)

\[ MLR = 10^{a+b\text{color}_{UV}} \]  

*Equation 3*

For our sample, observed-frame 814 nm corresponds roughly to rest-frame 550 nm (V band), and observed-frame 475 nm corresponds roughly to rest-frame 320 nm (U band). In detail, we should (but are not yet) be applying "K-corrections" to do this more accurately. In addition, we are adopting the B-V coefficients from Bell & de Jong as an approximation because Bell & de Jong do not provide coefficients for U-V. Going forward, the plan is to abandon the Bell & de Jong values entirely and to instead use customized K-corrections and stellar populations models from iSEDfit (Moustakas et al. 2013). For now, the B-V coefficients from Bell & de Jong are useful in the sense that the provide useful information about the mapping between color and mass-to-light ratio, but the specific MLR values need to be updated.

**Luminosity**

Now that we have found a mass-to-light ratio, we must find the light, or luminosity of our geometric region. As we have the flux in Jansky from earlier, this follows equation 24 from Hogg (1999). With each specific luminosity and mass-to-light ratio, we can calculate a mass for each area of interest by mapping our observed frame measurements to the galaxy’s rest frame.
\[ L_{\nu_e} \nu_e = 4\pi \nu f_\nu d_L^2 \quad \text{Equation 4} \]

We applied the same method on two different geometric distributions of the galaxies. We divided each galaxy into 40 annuli and sum up the total flux for each using photutils in Python. The annuli were calculated with radii increasing linearly; as the annuli get farther from the center, the area of the annuli increases quadratically. Each annulus has a value of flux in multiple filters to calculate MLRs, rest-frame luminosity, and stellar mass. We refer to this as stellar mass by spatially resolved color (Msrc, or mass profile). We also summed the flux for the entire galaxy. This gave us a single MLR that we used to scale our light values to mass to produce a mass by spatially integrated color (Msic or light profile). From these two calculations, we compare the light and mass profile of the galaxies.

The second method was a pixel-by-pixel analysis. We rewrote the code so that it could be set to analyze a specific grid of pixels. In this method, each pixel has its own luminosity, MLR, and stellar mass. We use the mass of each pixel to create a heat map of where the mass is in the galaxy. We also plot the mass as a function of its radius from the center of the galaxy. Again, we used the total flux from this to make a single MLR and therefore another light profile to compare with the mass profile.

**Understanding the Terminology**

We used the method above in two distinct ways. When the total flux of a galaxy is used to create a single MLR, which is used to transform a collection of luminosity values to a collection of mass values, the resulting mass is called the “Spatially Integrated Mass”. By multiplying all values of luminosity by the same MLR, the result tells us more about the light distribution than the mass distribution. Therefore, it is called the “light mass”:

...
had a strictly proportional relationship, this measurement would be ideal. However, what we
know of the stellar population informs us this is incorrect.
Results

Annular Method

Our annular analysis plotted the mass contained in an annulus as a function of radius. They show that most of the stellar mass is not contained within the central kpc. That said, we know that the center of the galaxy has the highest mass density, so we also plotted mass surface density. Our mass surface density plots show more clearly what the mass profile looks like as a function of radius (Figure 7). We will describe some implications of these results here and then discuss them further in the Discussion section.

![Image](image.png)

Figure 7: Sample results from J0826. Left: Mass by spatially resolved color in each annulus, showing that the center of the galaxy does not contain the majority of the mass. Right: mass and light (Msrc, Msic) surface density profiles, both of which are highest in the center of the galaxy. While the light is very compact, the mass density is much more extended.)
From this method, we compared the mass from the central 2 kiloparsecs of the galaxy to the total mass calculated from this method (Table 1). We see over all, a small percentage of the total mass within the center of the galaxy, ranging from 3% - 30% with an average of 11% throughout these twelve galaxies.

The light mass gives an estimate for mass if light and mass differed only by a single constant MLR. Using the total flux of the galaxy, we create a single mass-to-light ratio and use that to scale the fluxes of each annulus to calculate a mass. In this way, we are simply scaling the light profiles into units of mass so it is comparable to our mass from the spatially resolved color method. From the spatially resolved color method, we can also compare the light at the center of the galaxy to the total light of the galaxy. We found each galaxy had a large percent of the total light within the center, ranging from 20 to 70 percent with an average of 55%.

Also note that the spatially resolved method produced larger masses than the spatially integrated masses. This is due to the fact that applying the MLR for the total galaxy, which is dominated by blue light from the center of the galaxy, tends to underestimate the mass from fainter regions of the galaxy that are red in color. We will show in later plots that the single MLR method tends to overestimate some central pixels, but will severely underestimate most pixels located not directly at the center. This explains why, overall, the spatially integrated color method will underestimate the mass of these galaxies.
Table 1: Results from the annular method of analysis

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Msrc total ((\text{M}_{\odot} \times 10^{11}))</th>
<th>Msrc inner 5 (percent)</th>
<th>Msic total ((\text{M}_{\odot} \times 10^{11}))</th>
<th>Msic inner 5 (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0826</td>
<td>9.1 +/- 1.3</td>
<td>8%</td>
<td>2.4 +/- 0.1</td>
<td>60%</td>
</tr>
<tr>
<td>J0901</td>
<td>11.2 +/- 2.0</td>
<td>4%</td>
<td>2.3 +/- 0.1</td>
<td>54%</td>
</tr>
<tr>
<td>J0905</td>
<td>4.4 +/- 0.3</td>
<td>32%</td>
<td>2.5 +/- 0.2</td>
<td>72%</td>
</tr>
<tr>
<td>J0944</td>
<td>8.1 +/- 1.2</td>
<td>16%</td>
<td>3.4 +/- 0.2</td>
<td>66%</td>
</tr>
<tr>
<td>J1107</td>
<td>8.5 +/- 1.4</td>
<td>5%</td>
<td>2.0 +/- 0.1</td>
<td>53%</td>
</tr>
<tr>
<td>J1219</td>
<td>27 +/- 6</td>
<td>6%</td>
<td>10.5 +/- 1.3</td>
<td>47%</td>
</tr>
<tr>
<td>J1341</td>
<td>2.1 +/- 0.1</td>
<td>22%</td>
<td>1.2 +/- 0.1</td>
<td>56%</td>
</tr>
<tr>
<td>J1506</td>
<td>9.5 +/- 1.3</td>
<td>6%</td>
<td>2.3 +/- 0.2</td>
<td>55%</td>
</tr>
<tr>
<td>J1558</td>
<td>3.6 +/- 0.3</td>
<td>7%</td>
<td>1.8 +/- 0.1</td>
<td>33%</td>
</tr>
<tr>
<td>J1613</td>
<td>20 +/- 4</td>
<td>11%</td>
<td>10 +/- 1</td>
<td>46%</td>
</tr>
<tr>
<td>J2116</td>
<td>130 +/- 4-</td>
<td>2%</td>
<td>9.9 +/- 0.8</td>
<td>56%</td>
</tr>
<tr>
<td>J2140</td>
<td>50 +/- 10</td>
<td>18%</td>
<td>18 +/- 2</td>
<td>64%</td>
</tr>
</tbody>
</table>
Pixel Analysis

The pixel method creates MLRs and mass for each pixel across the entire face of each galaxy. This is useful because it doesn’t assume radial uniformity of our galaxies. We prefer this to annular binning because we don’t lose information to the averaging done in the aperture photometry. This method currently runs for a 15x15 pixel array in the center of the galaxy, which is a much smaller area than the annular method. The center of the galaxy is less likely to include background pixels with low SNR. Due to the subtractive nature of the flux, background pixels often have negative flux which breaks the code for the MLR (Equation 2). The negative pixel values break the analysis due to the logarithm. That means at these larger scales, the analysis does not produce coherent mass or mass distributions. The analysis runs successfully for a 15x15 pixel array currently, which is a small area when compared with the area for the annular method, which has a radius of 40 pixels. Because it focuses on a smaller region, the pixel analysis produces smaller estimates for total mass of the galaxies.
Figure 8: A comparison of light and mass profiles of J0826 for 255 and 15 pixels. Light profiles consistently show sharper profiles of the galaxies than the mass distribution.

The pixel method also calculates a mass and a light profile (Figure 8). All galaxies have similar graphs: there is a lot of light in the center and it quickly tapers off (Appendix C). Also, the light in pixels at the same distance from the center have similar values. The mass is much lower at the center of the galaxy, but does not taper with the same intensity. We also see much more variation of mass at the same distance away from the center. The total mass produced by
the pixel mass profile is between 2 and 6 times than the light profile (Table 2). This tells us that there are many more super bright, massive stars at the center of the galaxy. They account for most of the light and very little of the mass and exist because of the recent gas-rich merger their galaxy went through. We don’t see the same concentration of these massive stars in the outskirts of the galaxy, which have older, redder stars and a higher MLR.

The mass and light profile comparisons are the major improvement over the annular method (Figure 9). The color maps highlight the complicated, non-circular geometry of the galaxies that are lost in the annular analysis. This is specifically true for J1558, J0944, J1613, and J2140 (Appendix C).
Figure 9: Sample mass and light profiles from J0826. The light dominates in the central hundred parsecs or so of the galaxy, but the mass is more extended.
Table 2: Pixel Method Results for total mass by spatially resolved color and spatially integrated color, their standard deviations, and the ratio of the total resolved mass over total integrated mass.

<table>
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<th>Galaxy</th>
<th>Msrc (M_{sun} \times 10^{11})</th>
<th>STD (M_{sun} \times 10^{11})</th>
<th>Msic (M_{sun} \times 10^{11})</th>
<th>STD (M_{sun} \times 10^{11})</th>
<th>Msrc/Msic</th>
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<td>0.3</td>
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<td>66</td>
<td>19</td>
<td>11</td>
<td>1</td>
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The last plot we made using the pixel analysis demonstrates the shortfalls of assuming light and mass trend together. At $10^9$, light and mass profiles are equal. Under this threshold, the light overestimates the mass and over this threshold, the light underestimates the mass (Figure 10). We reiterate here, applying a MLR for a bluer stellar population to a red stellar population, like the outskirts of a galaxy, will underestimate the mass for those red areas.

Figure 10: Log plot for the Mrsc / Msic for each pixel in the galaxy. Pixels under $10^9$ demonstrate where the light profile overestimates the mass of the galaxy, while pixels over $10^9$ show where the light profile underestimates the mass.
Discussion

What have we learned about these galaxies? When comparing light profiles from both the annular and pixel methods, we find all twelve galaxies have more compact light profiles than mass profiles. The more extended mass will lead to a lower escape velocity, which has the potential to rule out some physical models for these high-velocity galactic winds.

When discussing these results, we need to understand what the light profile is and how it is useful. As seen in comparisons between the integrated and resolved color methods, light is not completely analogous to mass. These galaxies were thought to have extremely compact mass because of their compact morphologies. This analysis suggest the mass is much more extended than the light.

Annular fluxes, luminosities, MLRs, and masses were averaged over the area of the annulus. As expected, taking the average over any area loses specific and significant data. One example of this comes from J1558. The original analysis for J1558 was performed around the geographic center of the galaxy, rather than around the brightest pixel (chosen off of the 1600 nm filter). The annular method returned surprising results; nothing similar to either the dip in the spatially resolved mass profile nor the peak in the spatially integrated mass profile appeared in other galaxies (Figure 11).

We were surprised to see more clearly in a composite image that J1558 appears to be two galaxies, around 100 Myr away from their final merged state (Figure 12). We readjusted the center of the analysis to the brighter galaxy, but the results were still unsatisfactory. Averaging the mass distribution for J1558 into annular bins was not a productive method of analysis. This is one of the many trials that suggested we move from annular bins, to pixel bins.
Figure 11: left: initial reports from J1558, where the center of the galaxy wasn’t chosen from 475 or 814 nm, but rather 1600 nm where light bleeds out more. The large dip in the top graph and the peak in the center of the middle graph suggest our center of the analysis was not the center of the galaxy. Upon close inspection, it appears J1558 is two galaxies, mid-merge. We shifted the center of the analysis to the center of the larger galaxy, but the graphs are still unsatisfactory, which motivated the change from the annular to the pixel based analysis.
We used the annular and pixel methods to create mass density profiles for the twelve galaxies in our sample. From both methods, we are able to conclude that the light is much more compact than the mass. We see that for each of our galaxies, a large percent of the light is contained in the center of the galaxy, while we see a much smaller percentage for mass in the same area.

Our results indicate that the mass is more extended than the light, implying that the escape velocities are closer to 300 km/s and that the observed outflow velocities much exceed the escape velocity by factors of a few. This rules out some models of radiation-driven winds, but is consistent with other models for outflows driven by a combination of supernova explosions (e.g., Bustard et al. 2016) and radiation pressure (Thompson et al. 2015).
This research is an improvement from previous studies because it tests the assumption that light is a good analogue for mass. In particular, we find that the compactness of these galaxies is not as extreme as indicated by their light profiles, which had suggested extremely high escape velocities. A second assumption made, specifically by Rines 2016, was that these galaxies have uniformly consistent mass surface density as a function of radius. Although the pixel method improves upon both of these, there are several ways in which this method could be improved. Because this method runs on a series of approximations, the most significant one is to abandon the ‘a’ and ‘b’ coefficients from Bell & de Jong 2001 in favor of custom stellar population models from Moustakas et al. (2013), which will also include accurate K-corrections. The second is to expand the area over which the analysis is run. For this to happen, a binning algorithm must be put in place to collect pixels with low SNR.
Summary

Using images taken at 475 nm, 814 nm, and 1600 nm by the Hubble Space Telescope, we measured fluxes and spatially resolved colors to determine both luminosity and stellar mass for a sample of 12 compact galaxies at $z \sim 0.6$ that are driving fast outflows. We produced and compared mass and light profiles, highlighting the risks of using light as an analogue to mass. With reference to specific galaxies such as J1558, we described the importance of a pixel based method so as not to constrict the true shape of the galaxy into the expected shape of a galaxy. These spatially resolved mass calculations can be used to find escape velocities using customized stellar population modeling with iSEDfit (Moustakas et al. 2013) and careful analysis of the point-spread function, which is beyond the scope of this thesis. With the escape velocities of these galaxies, we can say whether these galaxies fit models where radiation pressure from massive stars can drive the high-velocity winds.

The results of this thesis suggest escape velocities around 300 km/s. This is inconsistent with some models of radiation-driven winds that predict outflow velocities approximately equal to the central escape velocity (e.g. Murray et al. 2011). However, there are still several models of radiation-driven winds that are consistent with this work.

The pixel by pixel analysis is far from robust and comprehensive. As mentioned previously, the flux from HST is background subtracted, which means some pixels with a high signal to noise ratio have some negative values. This causes a problem in when we take the log of the flux to find the luminosity. Instead of crashing, interactive Python continues running with log(n) when $n < 0 = \text{nan}$, which is read in our equations and code as an extremely high value which throws off all of our calculation. Our current work around to this problem has been only running the calculation on small (width $\sim 15$ pixels) areas with high SNR (ea., near the center of
the galaxy). The long term solution is a binning algorithm that groups pixels of low SNR with other nearby pixels to create a bin with a large enough SNR that the data is more than simple noise.

Another improvement that could be made to the pixel analysis is that it runs using the center of the galaxy as a coordinate pair of integer pixels. In reality, we can find the center of the galaxy on a subpixel level. This is crucial, as the center of the galaxy is one of the most important to the calculation of escape velocity. We began a calculation for the sub-pixel level of the galaxy for this thesis, but it was not incorporated at the time this thesis was written.

This thesis calculates the mass by spatially resolved $U-V$ color for the 814 filter, but the future of the project should include the same analysis for 475 and 1600 nm, as well as all three filters with the $V-J$ color. We chose to focus on 814 nm because it has a similar resolution and point spread function to 475. To resolve at the smallest possible spatial scales, we focused on smaller filters. We worked with $U-V$ color because it has been reliable for MLRs given a smooth star formation history (Bell & de Jong 2001). We attempted analysis with $V-J$ color, but due to the variation in its PSF relative to the other filters, it was unsuccessful. As a longer wavelength, the 1600 nm filter looks deeper into the galaxy. When run, $V-J$ (optical, near infrared) will be more sensitive to the differences between young stellar populations and older stellar regions with recent starbursts.

One final future project is that we rely on the 6 models of Bell & de Jong and one of Cole et al. 2001. Ideally, the future of this project includes customized stellar population modeling and improved K-corrections. After these updates, the results for spatially resolved mass will be used in collaboration with John Moustakas and the iSEDfit models (Moustakas et al. 2013) to accurately quantify escape velocities for each galaxy.
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Schaye, J., Crain, Robert A., Bower, R. G., Furlong, M., Schaller, M., Theuns, T., Dalla Vecchia,
C., Frenk, Carlos S., McCarthy, I. G., Helly, J. C., Jenkins, A., Rosas-Guevara, Y. M.,
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Sell, P. H., Tremonti, C. A., Hickox, R. C., Diamond-Stanic, A. M., Moustakas, J., Coil, A.,
Williams, A., Rudnick, G., Robaina, A., Geach, J. E., Heinz, S., & Wilcots, E. M. 2014,
MNRAS, 441, 3417
Vogelsberger, Mark; Genel, Shy; Springel, Volker; Torrey, Paul; Sijacki, Debora; Xu, Dandan;
Appendices

A. Bell & de Jong: Stellar Mass Ratio Coefficients for B-V

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<th>$b_V$</th>
<th>$a_J$</th>
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### B. About the sample:

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C. Results by Galaxy

J0826

![Graphs showing mass vs. radius and mass density vs. radius for J0826 with different wavelengths (475 nm, 814 nm, 1600 nm).]
J1341

J1341 Mass vs. Radius, (Mass Profile)

J1341 Mass vs. Radius, (Light Profile)

J1341 Mass Density vs. Radius, Mass and Light Profiles