A pipeline to study HST ACS/WFC3 data and examples of its applications

William V. Waldron

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A PIPELINE TO STUDY HST ACS/WFC3 DATA AND
EXAMPLES OF ITS APPLICATIONS

by

WILLIAM V WALDRON

A DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in
The Department of Physics & Astronomy
to
The School of Graduate Studies
of
The University of Alabama in Huntsville

HUNTSVILLE, ALABAMA

2022
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William V Waldron

9 / 26 / 2022

(date)
DISSERTATION APPROVAL FORM

Submitted by William V Waldron in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Astrophysics and accepted on behalf of the Faculty of the School of Graduate Studies by the dissertation committee.

We, the undersigned members of the Graduate Faculty of The University of Alabama in Huntsville, certify that we have advised and/or supervised the candidate of the work described in this dissertation. We further certify that we have reviewed the dissertation manuscript and approve it in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Astrophysics.

Committee Chair

Dr. Ming Sun

09/24/2022

Dr. Jim Miller

Date

Dr. Richard Lieu

Date

Dr. Max Bonamente

9-16-22

Dr. Stephen Walker

9/12/2022

Department Chair

Dr. Jim Miller

Date

Dr. Rainer Steinwandt

Date

College Dean

Dr. Jon Hakkila

Date

Graduate Dean
Even at over 30 years after its launch, HST still provides cutting-edge data in the optical, especially with its imaging cameras WFC3 and ACS. We present a pipeline to reduce and study the WFC3 and ACS data on nearby galaxies. Particularly, the results on an archetypal galaxy undergoing RPS, ESO 137-001, in the nearby cluster Abell 3627, are discussed in detail. ESO 137-001 is known to host a prominent tail caused by RPS that is detected in many bands from X-rays, Hα to CO. The HST data reveal significant features indicative of RPS such as asymmetric surface brightness and dust profiles as well as many blue young star complexes in the tail. We study the correlation between the blue young star complexes from HST, H II regions from Hα (MUSE) and dense molecular clouds from CO (ALMA). The correlation between the HST blue star clusters and the H II regions is very good, while their correlation with the dense CO clumps are typically not good. In comparison to the Starburst99+Cloudy model, many blue regions are found to be young (< 10 Myr) and the total star formation (SF) rate in the tail is 0.3 - 0.6 M⊙/yr for sources measured with ages less than 100 Myr, about 40% of SF rate in the galaxy. We also
demonstrate the importance of including nebular emissions and a nebular to stellar extinction correction factor when comparing the model to the broadband data. Our work demonstrates the importance of the \textit{HST} data to constrain the SF history in the tail, with the quantitative results for ESO 137-001’s tail presented. Future sample works with \textit{HST} can constrain the general SF history in stripped tails. To emphasize the extendable utility of this analysis pipeline, we also present preliminary results for some other galaxies, including NGC 5044, D100, and M87. The pipeline built from this work will be applied on more \textit{HST} data in the future and provides a key starting component for future research projects with the \textit{HST} data at the UAH.

Abstract Approval: Committee Chair

\begin{center}
\textbf{Dr. Ming Sun} 09/24/2022
\end{center}

Department Chair

\begin{center}
\textbf{Dr. Jim Miller}
\end{center}

Graduate Dean

\begin{center}
\textbf{Dr. Jon Hakkila}
\end{center}
I must first begin with thanking Dr. Ming Sun for all the guidance he has given me over the years. He has refined me into a better physicist, researcher, and teacher. I would have not made it to the end without his insight, wisdom, and expertise. I must also thank the numerous other UAH professors who shaped and challenged me: Dr. Richard Lieu for teaching me to find the beauty in physics, Dr. Robert Preece for teaching me to not overthink a problem, Dr. James Miller for helping me remember to always consider the big picture, Dr. Vladimir Florinski for showing me to power of computation, and Dr. Massimillano Bonamente for simplifying the complicated world of statistical data analysis. I would also like to thank my UAH peers Dr. Sarthak Dasadia, Dr. Sunil Laudari, Dr. Parisa Mostafavi, Aniket Bire, and Hosna Sultana who helped me every step of the way. From Harding University, I thank Dr. James Mackey, Dr. Lambert Murray, and Dr. Ed Wilson for helping me fall in love with physics and for tolerating my more social years. Likewise, I thank Dr. Steven Barber, Dr. David Donley, and Dr. Michael Gutierrez for helping me get on my feet as a teacher and encouraging me to finish. In terms of emotional support, I’d like to thank my parents for their endless cheer leading in my academic career. Finally, I would like to thank my wife, Jen, and our children for being with me in the the highest of highs and the lowest of lows. You have been a constant companion and partner in love. I cannot thank you enough for everything you have given me.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF FIGURES</td>
<td>x</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xiii</td>
</tr>
<tr>
<td>LIST OF ACRONYMS</td>
<td>xiv</td>
</tr>
<tr>
<td>LIST OF SYMBOLS</td>
<td>xvii</td>
</tr>
<tr>
<td>1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Galaxy Clusters</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Galaxy Evolution</td>
<td>2</td>
</tr>
<tr>
<td>1.2.1 Ram Pressure Stripping</td>
<td>4</td>
</tr>
<tr>
<td>1.2.2 Ram Pressure Stripping Observations</td>
<td>9</td>
</tr>
<tr>
<td>1.2.3 Ram Pressure Stripping Simulations</td>
<td>12</td>
</tr>
<tr>
<td>1.3 The Nature of Stars</td>
<td>13</td>
</tr>
<tr>
<td>1.3.1 Star Formation</td>
<td>13</td>
</tr>
<tr>
<td>1.3.2 Stellar Evolution</td>
<td>17</td>
</tr>
<tr>
<td>2 Hubble Space Telescope</td>
<td>21</td>
</tr>
<tr>
<td>2.1 The Advanced Camera System</td>
<td>24</td>
</tr>
<tr>
<td>2.2 The Wide Field Camera 3</td>
<td>26</td>
</tr>
<tr>
<td>3 Data Reduction Pipeline</td>
<td>29</td>
</tr>
</tbody>
</table>

vii
3.1 HST Image Data Reduction ............................................ 29
3.2 Photometry ................................................................. 32

4 ESO 137-001 Results ..................................................... 40
4.1 ESO 137-001 Introduction ........................................... 40
4.2 ESO 137-001 Observations .......................................... 44
4.3 ESO 137-001 Properties ............................................... 47
  4.3.1 Morphology & Light Profiles ................................. 47
  4.3.2 Dust Features ...................................................... 51
4.4 Young Star Clusters in the Tail ................................. 54
  4.4.1 Regions of Interest and Source Sample .................... 54
  4.4.2 Color - Color diagram ....................................... 61
  4.4.3 Comparison with SSP tracks ................................ 63
  4.4.4 Properties of the HII regions ............................... 68
  4.4.5 Relationship with the Chandra X-ray sources .......... 72
4.5 Clump Colors ............................................................ 73
4.6 Quantitatively Selected Source Analysis ..................... 75
4.7 Discussion .............................................................. 77
  4.7.1 Star formation in the tail .................................. 77
  4.7.2 Stripping history of ESO 137-001 ......................... 89

5 Other Results ............................................................ 92
5.1 NGC 5044 ................................................................. 92
5.2 D100 ................................................................. 94
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 The phase diagram for the gas in RPS tails presented by Boselli <em>et al.</em> (2022, Figure 6).</td>
<td>10</td>
</tr>
<tr>
<td>1.2 The HR diagram which maps where stars tend to measure in terms of the luminosity-temperature relationship.</td>
<td>18</td>
</tr>
<tr>
<td>2.1 <em>HST</em> instruments and control/support systems.</td>
<td>22</td>
</tr>
<tr>
<td>2.2 The FOVs of various <em>HST</em> instruments.</td>
<td>23</td>
</tr>
<tr>
<td>2.3 <em>HST</em> filter throughputs with reference spectra.</td>
<td>24</td>
</tr>
<tr>
<td>3.1 The comparison of images between the <em>HST</em> image pipeline and the one detailed in this thesis.</td>
<td>33</td>
</tr>
<tr>
<td>3.2 A comparison of the measured flux on 10 ESO 137-001 sources in the F814W filter.</td>
<td>36</td>
</tr>
<tr>
<td>3.3 ESO 137-001 flux and color comparisons for methodological validation.</td>
<td>38</td>
</tr>
<tr>
<td>4.1 The RGB image (blue: F275W; green: F475W; red: F814W) of ESO 137-001 with zoom-ins on 40 regions (Large Image Credit: STScI; zoom-ins are from this work).</td>
<td>42</td>
</tr>
<tr>
<td>4.2 Continued from Figure 4.1</td>
<td>43</td>
</tr>
<tr>
<td>4.3 The central regions of the galaxy in the four <em>HST</em> bands.</td>
<td>48</td>
</tr>
<tr>
<td>4.4 ESO 137-001 surface brightness profiles.</td>
<td>49</td>
</tr>
<tr>
<td>4.5 ESO 137-001 extinction images.</td>
<td>53</td>
</tr>
</tbody>
</table>
4.6 Regions of interest to be studied in this paper are shown here using the F475W image as a reference. .................................................. 57

4.7 The H\textsc{ii} (red) and blue tail sources (blue) plotted in Figure 4.6 are shown on the MUSE H\textsc{\textalpha} image from Sun \textit{et al.} (2021). ............... 59

4.8 ESO 137-001 source position KDEs. .......................................................... 60

4.9 The colors of the \textit{HST} sources detected in the regions defined in Figure 4.6. ................................................................. 62

4.10 The \textit{MUSE} H\textsc{\textalpha} EW and intrinsic extinction measurements for 40 H\textsc{ii} regions. .............................................................. 64

4.11 Colors of \textit{MUSE} H\textsc{ii} regions on the Starburst99 track (dashed line) and the Starburst99 + Cloudy track (solid line) with different intrinsic extinction values. .................................................. 65

4.12 ESO 137-001 H\textsc{\textalpha} EW / broadband age comparison. ................. 69

4.13 ESO 137-001 color-distance relationship. ................................................. 70

4.14 The color-magnitude diagram for the sources in the H\textsc{ii} and tail regions, with the absolute magnitude also shown on the right side. .... 71

4.15 The luminosity distribution for sources detected in the H\textsc{ii} and tail regions defined in Section 4.4.1 with the exception that a F275W - F475W color cutoff of 2.5 is chosen. .................................................. 73

4.16 The colors of individual sources in the clumps defined in Figure 4.1. .. 74

4.17 The H\textsc{ii} (red; see Figure 4.6) and blue non-H\textsc{ii} sources (cyan) are shown on the \textit{MUSE} H\textsc{\textalpha} image from Sun \textit{et al.} (2021). ............... 76

4.18 The colors of the quantitatively selected \textit{HST} sources shown in Figure 4.17. ................................................................. 78

4.19 The color-magnitude diagrams for the quantitatively selected \textit{HST} sources shown in Figure 4.17, with the absolute magnitude also shown on the right side. .................................................. 79

4.20 The mass, age, and SFR for sources younger than 100 Myr as estimated with the Starburst99 + Cloudy model. ................................. 82
4.21 The mass and SFR with the source age for ESO 137-001 sources younger than 100 Myr as estimated with the Starburst99 + Cloudy model.

4.22 The SFR distribution in the tail of ESO 137-001 plotted on the MUSE Hα image.

4.23 The mass, age, and SFR for sources younger than 100 Myr as estimated with the Starburst99 + Cloudy model and divided by the tail zones shown in Figure 4.22.

4.24 Four ideal examples of a symmetrical disk galaxy undergoing RPS and the observed signature of dust distribution.

5.1 Images of NGC 5044.

5.2 The composite image of D100 presented by Cramer et al. (2019).

5.3 The color-color diagram of the initial results for D100.

5.4 M87 false color image with F606W image as R and G channels and F275W as B channel.

5.5 The color-magnitude diagram of the sources measured in M87 using the F275W and F606W images.

B.1 Comparison of tracks between Starburst99, GALEV, and BPASS.
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td><em>HST</em> Optical Telescope Assembly properties. Table credit: STScI.</td>
</tr>
<tr>
<td>3.1</td>
<td>Non-default TweakReg parameters.</td>
</tr>
<tr>
<td>3.2</td>
<td>Non-default AstroDrizzle parameters.</td>
</tr>
<tr>
<td>3.3</td>
<td>Non-default SExtractor parameters.</td>
</tr>
<tr>
<td>4.1</td>
<td>Properties of ESO 137-001</td>
</tr>
<tr>
<td>4.2</td>
<td><em>HST</em> ESO 137-001 Observations (PI: Sun)</td>
</tr>
<tr>
<td>4.3</td>
<td>ESO 137-001 Photometric Parameters</td>
</tr>
<tr>
<td>4.4</td>
<td>GALFIT fits on the F160W image of ESO 137-001</td>
</tr>
<tr>
<td>4.5</td>
<td>Baseline <em>HST</em> sources and their properties.</td>
</tr>
<tr>
<td>5.1</td>
<td><em>HST</em> D100 Observations (PI: Puzia &amp; Sun)</td>
</tr>
<tr>
<td>5.2</td>
<td><em>HST</em> M87 Observations (PI: Renzini &amp; Shara)</td>
</tr>
</tbody>
</table>
# LIST OF ACRONYMS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACS</td>
<td>Advanced Camera System.</td>
</tr>
<tr>
<td>AGN</td>
<td>active galactic nucleus.</td>
</tr>
<tr>
<td>ALMA</td>
<td>Atacama Large Millimeter Array.</td>
</tr>
<tr>
<td>CCD</td>
<td>charge-coupled device.</td>
</tr>
<tr>
<td>COS</td>
<td>Cosmic Origins Spectrograph.</td>
</tr>
<tr>
<td>CR</td>
<td>cosmic ray.</td>
</tr>
<tr>
<td>CTE</td>
<td>charge transfer efficiency.</td>
</tr>
<tr>
<td>EW</td>
<td>equivalent width.</td>
</tr>
<tr>
<td>FGS</td>
<td>Fine Guidance Sensors.</td>
</tr>
<tr>
<td>FITS</td>
<td>flexible image transport system.</td>
</tr>
<tr>
<td>FOV</td>
<td>field of view.</td>
</tr>
<tr>
<td>FPA</td>
<td>focal plane array.</td>
</tr>
<tr>
<td>FWHM</td>
<td>full width at half maximum.</td>
</tr>
<tr>
<td>GASP</td>
<td>gas stripping phenomena.</td>
</tr>
<tr>
<td>GSC2</td>
<td>Guide Star Catalog II.</td>
</tr>
<tr>
<td>HR</td>
<td>Hertzsprung–Russell.</td>
</tr>
<tr>
<td>HRC</td>
<td>High Resolution Channel.</td>
</tr>
<tr>
<td>HST</td>
<td>Hubble Space Telescope.</td>
</tr>
<tr>
<td>ICM</td>
<td>intracluster medium.</td>
</tr>
</tbody>
</table>
IMF initial mass function.
IR infrared.
ISM interstellar medium.
IVM inverse variance map.
JWST James Webb Space Telescope.
KDE kernel density estimation.
MAD median absolute deviation.
MAST Mikulski Archive for Space Telescopes.
MUSE Multi Unit Spectroscopic Explorer.
NIR near-IR.
PSF point spread function.
RMS root mean square.
RPS ram pressure stripping.
SBC Solar Blind Channel.
SF star formation.
SFR star formation rate.
SNR signal-to-noise ratio.
SOAR Southern Observatory for Astrophysical Research.
SSP simple stellar population.
STIS Space Telescope Imaging Spectrograph.
STScI Space Telescope Science Institute.
ULX ultraluminous X-ray source.
UV ultraviolet.
UVIS  ultraviolet-visible.

VLT  Very Large Telescope.

WCS  world coordinate system.

WFC  Wide Field Channel.

WFC3  Wide Field Camera 3.
# LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>Speed Constant (The speed of light in a vacuum unless there is an accompanying subscript)</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational Acceleration</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass</td>
</tr>
<tr>
<td>$p$</td>
<td>Momentum</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
</tr>
<tr>
<td>$u$</td>
<td>Velocity</td>
</tr>
<tr>
<td>$E$</td>
<td>Energy</td>
</tr>
<tr>
<td>$F$</td>
<td>Force</td>
</tr>
<tr>
<td>$L$</td>
<td>Luminosity</td>
</tr>
<tr>
<td>$M$</td>
<td>Mass</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of Particles</td>
</tr>
<tr>
<td>$P$</td>
<td>Gas Pressure</td>
</tr>
<tr>
<td>$R$</td>
<td>Radius</td>
</tr>
<tr>
<td>$S$</td>
<td>Surface Area</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
</tr>
</tbody>
</table>
$V$ Volume

$W$ Work

$Z$ Stellar Metallicity

$\beta$ Wave Number

$\lambda$ Length Scale

$\rho$ Density

$\sigma$ Surface Density

$\tau$ Time Scale

$\omega$ Angular Frequency

$\Phi$ Potential
To Jennifer, Isaiah, and Jonathan
If I find in myself a desire which no experience in this world can satisfy, the most probable explanation is that I was made for another world.

—C. S. Lewis
CHAPTER 1

INTRODUCTION

*The beginning is the most important part of the work.*

—Plato

1.1 Galaxy Clusters

Galaxy clusters are the largest gravitationally collapsed structures in the universe. Rich clusters can contain on the order of a thousand galaxies (e.g., the Virgo cluster) while poor clusters may contain several tens of galaxies (e.g., White et al., 1999). The earliest studies showed that these clusters are extremely massive (Smith, 1936; Zwicky, 1937). The predicted masses of these clusters tended to be much higher than could be measured based on the luminous matter prompting the first suggestions of dark matter populating the cluster (Zwicky, 1933, 1937). Galaxy clusters were later shown to have a hot intracluster medium (ICM) that emits X-rays via free-free (Bremsstrahlung) interactions providing some observation of the missing dark matter though it cannot account for all the dark matter (Gursky et al., 1971). This ICM has since become a signature for studying the depth of the cluster gravitational wells (Kravtsov & Borgani, 2012). Currently, scientists believe that galaxy clusters
are comprised of ∼80% dark matter, ∼17% of this hot ICM, and only ∼3% in galaxies (Feretti et al., 2012).

Many authors have proposed systems to classify galaxy clusters. In addition to classification by richness (population), clusters can also be classified by whether the cluster is regular or irregular (Abell, 1958, 1965), by cluster compactness (Zwicky et al., 1961), the contrast of the brightest member (Bautz & Morgan, 1970), or by the morphological type of the population galaxies (Rood & Sastry, 1971). Galaxy clusters have also been identified by whether the cluster is a radio or X-ray emitter or not (Bahcall, 1977).

Because of the richness of data found in galaxy clusters, they have served as laboratories to study dark matter (Zwicky, 1933; Moore et al., 1999), galaxy evolution (Gunn & Gott, 1972; Dressler, 1980, 1984, see also Section 1.2 below), cosmology (Allen et al., 2011), and high energy physics (e.g., shocks and mergers; Markevitch et al., 1999; Dasadia et al., 2016).

1.2 Galaxy Evolution

It has been long known that the environment where galaxies reside affect their properties and evolution (e.g., Gunn & Gott, 1972; Gallagher & Ostriker, 1972; White, 1976; Dressler, 1980, 1984; Postman & Geller, 1984). Two predominant models were posed to explain the relationship between cluster formation and galaxy evolution (Madau et al., 1998). The first model, monolithic collapse (Eggen et al., 1962), states that large structures (i.e., galaxy clusters) likely formed first from gas clouds collapsing under their own self-gravity. Galaxies then formed out of these collapsing clouds
and evolved slowly as stars formed. The second, widely accepted model (Madau et al., 1998; Feretti et al., 2012; Kravtsov & Borgani, 2012), hierarchical clustering (Peebles & Yu, 1970), states that small structures (i.e., globular clusters and dwarf galaxies) formed first then merged and clustered into galaxies and then galaxy clusters. The hierarchical model suggests a cold dark matter (i.e., dark matter with low velocity dispersion in the early universe) further effects galaxy evolution (Peebles, 1982; Blumenthal et al., 1984; Davis et al., 1985). This latter model paints an interesting picture of galaxy formation and evolution that is explored below.

Per the hierarchical model, galaxy clusters can affect galaxy formation and evolution at the largest scales. For example, Butcher & Oemler (1978) observed that “all centrally concentrated clusters are deficient in spirals” showing the cluster can affect galaxy morphological type. Later, Butcher & Oemler (1984) observed that low-redshift, compact clusters tended to be devoid of blue galaxies and that spirals in low-redshift cluster cores tended to be redder than their field counterparts.

Galaxies can also evolve from certain internal effects. Galactic winds (Lynds & Sandage, 1963; De Young, 1978; Veilleux et al., 2005), for example, can drive gas out of the region quenching star formation. Active galactic nuclei can affect the way a galaxy evolves by supplying energy back to the outer regions of the galaxy (Silk & Rees, 1998; Bower et al., 2006). Dressler (1980) and Postman & Geller (1984) show that the density of the galaxy itself will influence the morphology of the galaxy.

Likewise, galaxies can evolve from external effects with each other or the ICM. Collisions, mergers, and tidal stripping have been shown to shape galaxies (Gallagher & Ostriker, 1972; Richstone, 1976). Galaxies also evolve under the condition of ther-
mal evaporation where a cold body (e.g., the galaxy interstellar medium) can experience mass loss to a hot surrounding medium (Cowie & McKee, 1977; Cowie & Songaila, 1977; McKee & Cowie, 1977; Balbus & McKee, 1982). Galaxy cluster properties such as viscosity, thermal conduction, and turbulence similarly affect galaxy evolution (Nulsen, 1982). Tidal effects on a galaxy by the ICM can also affect a galaxy’s evolution via a process called harassment (Moore et al., 1998). Gunn & Gott (1972) introduced ram pressure stripping (a drag force proportional to the square of the galaxy velocity) as one such mechanism that shapes galaxy evolution. Since ram pressure stripping (RPS) is the stripping mechanism that motivates the study of this thesis, a full treatment on the topic is presented in the subsequent subsections.

1.2.1 Ram Pressure Stripping

The total pressure experienced by an object in a fluid can be described by two primary components. The first component arises from the random motion of the particles in the fluid (i.e., the isotropic pressure). The second component arises from the relative velocity of the object through the fluid (i.e., drag or ram pressure). Pressure is generally considered to be a force per unit area or proportional to the energy per unit volume (i.e., the energy density), or

\[ P = \frac{F}{S} \sim \frac{E}{V} \]  \hspace{1cm} (1.1)

where \( P \) is the pressure, \( F \) is a force normal to a surface \( S \), and \( E \) is the total energy of the fluid in a given volume \( V \) (bound by the surface \( S \)). In either case from
Equation 1.1, the expectation is that the pressure is proportional to $u^2$ where $u$ is a velocity.

Consider the isotropic pressure where $u$ is the velocity of a particle in the fluid. Considering the total energy, $E$, of the fluid is (according to statistical mechanics) related to the average kinetic energy, $K$, of the $N$ particles in the fluid

$$E \sim N \langle K \rangle = \frac{N}{2} m \langle u^2 \rangle$$

for a fluid with particles of mass $m$. The pressure of the fluid is then

$$P \sim \frac{E}{V} \sim N \frac{m \langle u^2 \rangle / 2}{V} = \frac{1}{2} \rho \langle u^2 \rangle$$

where $\rho = N m / V$ is the density of the fluid. This relationship is also evident when considering the force exerted by the gas. According to the principle of work

$$dW = \mathbf{F} \cdot d\mathbf{l}$$

where $dW$ is a differential amount of work done by a force $\mathbf{F}$ along a path $\mathbf{l}$. And, according to the work-energy principle,

$$dW = dK$$

Thus,

$$P = \frac{F}{A} = \frac{\mathbf{F} \cdot d\mathbf{l}}{A d\mathbf{l}} = \frac{dW}{dV} \sim \rho \langle u^2 \rangle$$
for kinetic/thermal isotropic pressure.\(^1\)

This characteristic dependence on \(u^2\) is likewise evident when considering the bulk flow of a fluid with velocity \(u\) relative to some other fluid element or some object (the converse consideration that an object traveling with relative velocity \(u\) through a fluid is also valid). Following the treatment of Clarke & Carswell (2014, Chapter 2), we begin by stating that the rate of change of fluid mass in volume \(V\) is equal to the outward flow of mass across a bounding surface \(dS\), or

\[
\frac{\partial}{\partial t} \int_V \rho \, dV = - \int_S \rho \mathbf{u} \cdot dS = - \int_V \nabla \cdot (\rho \mathbf{u}) \, dV
\]

(1.7)

where the last term in the equation invokes the divergence theorem. The continuity equation for fluid mass conservation is then

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]

(1.8)

in the Eulerian formulation\(^2\). Next, the net force a fluid exerts on a surface in the direction \(\hat{n}\) is\(^3\)

\[
F = - \int_S P \hat{n} \cdot dS = - \int_V \nabla \cdot (P \hat{n}) \, dV.
\]

(1.9)

\(^1\)This relationship can also be derived by integrating the forces that individual particles exert on \(S\). The normal force exerted by a particle is \(F = dp/dt\) where \(p\) is the particle’s momentum perpendicular to \(S\). The change in momentum \(dp \sim u\) and the differential time step \(dt \sim u^{-1}\) yielding the same result that \(F \sim u^2\) and since \(P = F/S\) then \(P \sim u^2\).

\(^2\)The Eulerian formulation studies fluid density, momentum, and energy within a fixed volume rather than the Lagrangian formulation which studies these properties for a particular fluid element (Clarke & Carswell, 2014, Section 1.3).

\(^3\)Note that this similar to the first two terms of Equation 1.1 but in integral form.
From this, the Lagrangian form of the fluid momentum equation can be inferred which states, “the momentum of a fluid element changes as a result of pressure gradients and gravitational forces” (Clarke & Carswell, 2014). The Eulerian form similarly states

\[ \rho \frac{\partial \mathbf{u}}{\partial t} = \rho \mathbf{g} - \nabla P - \rho \mathbf{u} \cdot \nabla \mathbf{u}, \]  

(1.10)
or “the momentum contained in a fixed grid cell within the fluid changes as a result of pressure and gravitational forces, and any imbalance in the momentum flux in and out of the grid cell” (Clarke & Carswell, 2014) where \( \mathbf{g} \) represents the gravitational acceleration. The change of momentum density in an Eulerian cell (in index notation) is

\[ \frac{\partial}{\partial t} (\rho u_i) = u_i \frac{\partial \rho}{\partial t} + \rho \frac{\partial u_i}{\partial t}. \]  

(1.11)
The first term on the right can be transformed by Equation 1.8 and the second by Equation 1.10 such that

\[ \frac{\partial}{\partial t} (\rho u_i) = \rho g_i - \partial_j (\delta_{ij} P + \rho u_j u_i) \]  

(1.12)
where \( \partial_j \equiv \partial/\partial x_j \) and \( \delta_{ij} \) is the Kronecker delta. Returning from index notation, this can be written as

\[ \frac{\partial}{\partial t} (\rho \mathbf{u}) = \rho \mathbf{g} - \nabla P - \nabla \cdot [(\rho \mathbf{u}) \otimes \mathbf{u}]. \]  

(1.13)
The term \( P \) on the right hand side of Equations 1.12 and 1.13 represents the isotropic thermal pressure detailed in the preceding paragraph, and the final term \( (\rho u_j u_i \) and
\( \rho u \otimes u \) in each equation is the pressure that arises from the bulk motion of the fluid (i.e., the ram pressure).

The seminal work by Gunn & Gott (1972) shows that if the ram pressure of the ICM with density \( \rho \) on a galaxy with relative speed \( u \) normal to the cloud surface,

\[
P_{\text{ram}} \approx \rho u^2,
\]

is greater than the gravitational force of the galaxy on its interstellar medium (ISM) then the ISM can be stripped by this ram pressure (see Boselli \textit{et al.}, 2022, Section 2 for more detail). That is, if

\[
\rho u^2 > 2\pi G\sigma_s\sigma_g = \frac{u_r^2\sigma_g}{R}
\]

(where \( G \) is the gravitational constant, \( \sigma_s \) and \( \sigma_g \) are the stellar and total gas surface densities, \( u_r \) is the galaxy rotational velocity, and \( R \) is the galaxy radius) then the galaxy will be stripped by the ram pressure (Gunn & Gott, 1972; Fujita \textit{et al.}, 1999; Yamagami & Fujita, 2011). The removal of the ISM by this process has since been called ram pressure stripping (RPS). Quilis \textit{et al.} (2000) show that this hydrodynamical process is driven by the hot ICM pushing out the cold, galactic ISM (see also Boselli \textit{et al.}, 2022). An additional important note is that RPS leaves the existing stellar population unperturbed considering stars have a small cross section and high internal pressure (Boselli \textit{et al.}, 2022).
1.2.2 Ram Pressure Stripping Observations

The hot ICM / cold ISM interaction detailed above was first observed by Gavazzi (1978) and Shostak et al. (1982) in the radio and H I continuums, respectively. Since then, RPS has been observed extensively across many clusters in many bands (see the extensive review by Boselli et al., 2022, Section 3.2 and Table 2). For example, tails from created from RPS have been observed in the UV and Hα (Gavazzi et al., 2001; Oosterloo & van Gorkom, 2005; Sun et al., 2007; Yagi et al., 2007; Yoshida et al., 2008; Sivanandam et al., 2010; Smith et al., 2010; Yagi et al., 2010; Fossati et al., 2016; Sheen et al., 2017). These observations note that much of the affected galaxy’s gas can be stripped over a short (∼10^7 Myr) time period (Gavazzi et al., 2001; Sivanandam et al., 2010). The stripped gas may be visible after the stripping occurs because the evaporation by the ICM is slow (Vollmer et al., 2001; Oosterloo & van Gorkom, 2005). RPS has also been observed in X-Ray (Wang et al., 2004; Sun & Vikhlinin, 2005; Sun et al., 2006, 2010). Often, these X-Ray observations reveal a long, narrow tail in the soft X-Ray regime. Giovanelli & Haynes (1985), Gavazzi & Jaffe (1987) and Jáchym et al. (2014) have also noted tails associated with ram pressure stripping with radio observations. Although each of these results are presented in different bands the tails for an individual galaxy are often visible and well aligned across multiple bands (Sun et al., 2007; Jáchym et al., 2014). Recently, the gas stripping phenomena (GASP) survey performed an extensive study on RPS galaxies in clusters from 0.04 < z < 0.07 (Poggianti et al., 2017). Boselli et al. (2022)
Figure 1.1: The phase diagram for the gas in RPS tails presented by Boselli et al. (2022, Figure 6). RPS tail data have shown the presence of cold molecular gas, cold atomic gas, warm molecular gas, warm ionized gas, and hot X-ray gas. The region of each phase of gas is clearly marked on the diagram. The grey contours are from simulations by Tonnesen. The simulation data does not include cold molecular nor cold atomic gas, but the warm H$_2$, H$\alpha$, and X-ray peaks are clearly marked with a black contour. The boxes on the top of the diagram highlight the other effects RPS has on galaxy evolution.

present a gas phase diagram that shows the relationship of each of the aforementioned observations on a single diagram which is also displayed in Figure 1.1.

Observations of RPS show more than just the presence of tails in various continuums. Koopmann & Kenney (2004) show that RPS can trigger star formation (SF) in the initial compression of the ISM. After this initial compression (once RPS
has sufficiently removed the gas from the galaxy), SF can effectively be quenched in
the galaxy itself (Boselli et al., 2016). The ISM that is pushed by RPS into the ICM
has been shown to enrich the metallicity of the ICM (Schindler & Diaferio, 2008;
Durret et al., 2011). After the cold galactic gas has been pushed into the ICM, the
gas clouds can collapse and form stars in the tails outside the galaxies (Owen et al.,
2006; Sun et al., 2007; Yagi et al., 2007; Jáchym et al., 2014; Poggianti et al., 2019;
Waldron et al., 2022) which could suggest the presence of cold molecular gas that
has cooled since the RPS began (e.g., Jáchym et al., 2014). Since the discovery of
this phenomenon, the resulting star formation in these tight, blue clumps has become
known as a “fireball” (Yoshida et al., 2008; Kenney et al., 2014; Sheen et al., 2017).
While the RPS effects on dust are often visible (Kenney et al., 2015; Abramson et al.,
2016; Fossati et al., 2016; Poggianti et al., 2019; Waldron et al., 2022), Longobardi
et al. (2020) provide the only detailed study dedicated to RPS dust detection. See
Boselli et al. (2022, Sections 4 and 5) for a detailed review of RPS effects on the
affected galaxies and their environment.

The observations of these star forming regions urged the community to also
observe RPS and the resulting star formation in the broadband optical regime. To
date, no detailed analysis exists for studying the star forming knots within a tail using
broadband optical data. This thesis serves to fill that void by providing a framework
of analysis using ESO 137-001, the prototype RPS galaxy, and a few other galaxies
as the candidates for study. In doing so, we intend to quantify the star formation
rate in the tail and see how much is missed by the H II observations. Likewise, we’ll
compare the distribution of young star clusters within the tail and determine whether there is a correlation between the source age and distance from the galaxy.

1.2.3 Ram Pressure Stripping Simulations

RPS has also been extensively studied via simulation. RPS simulations began with the 2D work on spiral (Farouki & Shapiro, 1980) and spherical galaxies (Gaetz et al., 1987; Balsara et al., 1994). Nulsen (1982) similarly studied the effect of viscosity, thermal conduction, and turbulence of hot gas around a galaxy as a stripping mechanism. Abadi et al. (1999) present the first 3D simulation to study RPS though this was later improved by Quilis et al. (2000) to include viscous/turbulent effects and by Schulz & Strick (2001) to include radiative cooling in the tail. Roediger et al. (2006), Roediger & Brüggen (2007), and Roediger & Brüggen (2008) extended the focus of 3D RPS simulations to the tails. Roediger et al. (2006) and Roediger & Brüggen (2008) identify that observed RPS tails are narrower than simulated tails; however, the radiative cooling considerations by Tonnesen & Bryan (2010) helped match the width of the simulated to tails to those of observed tails. Jáchym et al. (2007) and Jáchym et al. (2009) studied the effect of time-varied ICM wind strength and galaxy inclination on RPS galaxies and tails. Tonnesen et al. (2011) first studied the correlation of H\textsc{i}, H\alpha, and X-ray signatures in RPS tails. Tonnesen & Bryan (2012) further study SF in RPS tails. Tonnesen & Stone (2014), Ruszkowski et al. (2014), and Ramos-Martínez et al. (2018) more recently increase the fidelity of their models by considering magnetic field effects on RPS.
Simulations have also led to interesting observations of the effects of RPS. For example, simulations have shown that RPS can trigger SF (Bekki & Couch, 2003) then later quench it (Quilis et al., 2000) matching the previously mentioned observations by Koopmann & Kenney (2004) and Boselli et al. (2016), respectively. Vollmer et al. (2001) show that RPS can explain H\textsc{i} deficiencies in galaxies by matching their results with observations of the Virgo cluster (Giovanelli & Haynes, 1985; van Gorkom & Kotanyi, 1985). Some simulations have shown a loss of angular momentum in the stripped gas (Schulz & Struck, 2001; Tonnesen & Bryan, 2009; Ramos-Martínez et al., 2018). Boselli et al. (2022), in their review, highlight many more RPS simulations and their results.

1.3 The Nature of Stars

1.3.1 Star Formation

Stars form out of molecular clouds (or sub-regions thereof) collapsing under their own gravity (Rose, 1998). As the cloud collapses, it can fragment as pockets of instability cause sub-collapsing structures to begin forming protostars in their inner regions. The protostar shifts toward the main sequence as the gravitational collapse is balanced by a hydrostatic equilibrium. Finally, the protostar becomes a main sequence star when the core has sufficiently heated to a temperature to ignite nuclear fusion within the core that maintains this hydrostatic equilibrium.

The collapse of the initial cloud can be modeled by a large gas cloud in equilibrium. Following the treatment of Rose (1998), the cloud can be modeled by its
velocity \( (u) \), density \( (\rho) \), temperature \( (T) \), pressure \( (P) \), and gravitational potential \( (\Phi) \) where the subscript 0 denotes an unperturbed/background quantity and the subscript 1 denotes a perturbed quantity. Thus,

\[ \rho = \rho_0 + \rho_1, \]

etc. If the perturbations occur under isothermal conditions, the equations of gas motion are

\[
\frac{\partial \rho_1}{\partial t} + \rho_0 \nabla \cdot \mathbf{u}_1 = 0, \tag{1.16}
\]

\[
\rho_0 \frac{d \mathbf{u}_1}{dt} = -\nabla P_1 - \rho_0 \nabla \Phi_1, \tag{1.17}
\]

\[
\nabla^2 \Phi_1 = 4\pi G \rho_1, \tag{1.18}
\]

and

\[
P_1 = \rho_1 \frac{kT}{\mu m_H} = \rho_1 c_s^2 \tag{1.19}
\]

after retaining the first order of small quantities where \( G \) is the gravitational constant, \( k \) is the Boltzmann constant, \( m_H \) is the mass of a hydrogen atom, \( \mu \) is the molecular weight (e.g., 2 for molecular hydrogen), and \( c_s \) is the isothermal sound speed. Note that Equation 1.16 is the continuity equation similar to Equation 1.8, Equation 1.17 is the momentum equation similar to Equation 1.10, Equation 1.18 is the Poisson equation, and Equation 1.19 is the ideal gas law.
Taking the divergence of Equation 1.17 and combining with the other three equations, we see

\[
\frac{\partial^2 \rho_1}{\partial t^2} = c_s^2 \nabla^2 \rho_1 + 4\pi G \rho_0 \rho_1. \tag{1.20}
\]

Assuming the solution

\[
\rho_1 = A \exp \left[ i (\beta x - \omega t) \right], \tag{1.21}
\]

Equation 1.20 becomes

\[
\omega^2 = \beta^2 c_s^2 - 4\pi G \rho_0. \tag{1.22}
\]

The case when \( \omega^2 > 0 \) gives a wave solution to Equation 1.21, and the case when \( \omega^2 < 0 \) gives an exponentially increasing solution to the perturbed density in Equation 1.21. Thus, the condition for instability (\( \omega^2 = 0 \)) yields

\[
\beta = \frac{2}{c_s} \sqrt{\frac{\pi G \rho_0}{\mu m_H G}}
\]

from which we can express the Jeans length (\( \lambda_J \simeq \beta^{-1} \)) as

\[
\lambda_J = \rho_0^{-1/2} \sqrt{\frac{\pi kT}{\mu m_H G}} \tag{1.23}
\]

for the smallest wavelength of an unstable perturbation (Rose, 1998). From this Jeans length, we can infer the Jeans mass for instability to be

\[
M_J \simeq \rho_0 \lambda_J^3 = \rho_0^{-1/2} \left( \frac{\pi kT}{\mu m_H G} \right)^{3/2}. \tag{1.24}
\]

15
Assuming a uniform initial density distribution for a spherical gas cloud with the equation of motion

\[ \frac{d^2r}{dt^2} = -\frac{GM}{r^2} \]  

(1.25)

(which is just the gravitational acceleration condition), Rose (1998) shows the free fall time for all the mass to reach the origin is

\[ \tau_{ff} = \rho_0^{-1/2} \sqrt{\frac{3\pi}{32G}}. \]  

(1.26)

Assuming, for a molecular hydrogen cloud, the temperature to be 10 K and the density to be \(10^{-22} \text{g cm}^{-3}\) (a number density \(\sim 10^2 \text{cm}^{-3}\)), we find the Jeans length to be \(\sim 3.5 \text{ pc}\), the Jeans mass to be \(\sim 100 \text{M}_\odot\), and the free fall time to be \(\sim 5 \text{ Myr}\). Therefore, if a molecular cloud under these temperature and density conditions has a size and mass greater than these values, the cloud can be reasonably be expected to collapse on the aforementioned time scale.

Of course, many considerations must be added to this simplistic model to understand how clouds collapse to form stars. McKee & Ostriker (2007) note the importance of turbulence in the initial cloud in the role of fragmentation and formation of massive stars. Rose (1973, Section 3.4) notes that, under the simplified conditions, a gas cloud will not collapse unless there is an efficient transport mechanism for the angular momentum (i.e., if all the initial angular momentum remains in the collapsing gas cloud, a star cannot form due to the rapid rotation of the cloud). Therefore, Rose (1973) notes that a present magnetic field provides just such a mechanism to
transport the angular momentum into the surrounding medium. McKee & Ostriker (2007) further review the importance of magnetic fields in modeling cloud collapse.

Star formation can explode under certain conditions creating an entire stellar population on a short timescale (~10^7 yr) through a process called a starburst (Harwit & Pacini, 1975; Rieke & Low, 1975; Balzano, 1983; Moorwood, 1996). These starbursts can be triggered by various factors such as mergers (Barnes & Hernquist, 1991) or ISM compression by the ICM (Bekki & Couch, 2003). Starbursts have also been modeled extensively (Leitherer & Heckman, 1995; Leitherer et al., 1999). Balzano (1983) notes that, during these starburst events, approximately 10^7–10^9 M☉ stars can be formed in about 2 × 10^7 to 10^8 yr implying a star formation rate (SFR) of ~10^{-1} to ~10^2 M☉/yr. A starburst is also an important model in RPS considering increased SF it can trigger (Koopmann & Kenney, 2004; Sun et al., 2007).

1.3.2 Stellar Evolution

Stars are generally categorized by a number of properties (e.g., metallicity, mass, radius, luminosity, and temperature). The mass of the star and its metallicity are two fundamental properties from which many of these other properties can be inferred. Astronomers tend to show the relationship of a star’s properties on the Hertzsprung–Russell (HR) diagram as shown in Figure 1.2. The HR diagram demonstrates a number of key relationships (along the main sequence) of various properties to a star’s mass. First, a star’s surface temperature, radius, and luminosity tends to increase as the mass increases. Second, the lifetime of the star tends to decrease as the mass increases.
Figure 1.2: The HR diagram which maps where stars tend to measure in terms of the luminosity-temperature relationship. Several trends can be identified using an HR diagram. First, per the Stefan-Boltzmann law and the surface area of a spherical body, the stellar radius tends to increase toward the upper-right of the diagram. Also, Equation 1.27 shows that stellar lifetime tends to increase toward the bottom-right of the diagram. Finally, the mass tends to increase as luminosity increases (see Equation 1.28). The two giant branches do not necessarily follow these latter two trends as stars at the end of their lives function differently to maintain equilibrium. White dwarfs must likewise be treated differently considering they no longer burn hydrogen in their cores and therefore maintain outward pressure via thermal energy and electron degeneracy pressure rather than radiative pressure against gravity. Credit: ESO.
As a protostar falls onto the main sequence, its luminosity tends to decrease. While on the main sequence the luminosity of the star remains constant. Then, as the star begins to die, its luminosity greatly increases for a short period of time as the core begins to burn heavier elements. Finally, once the star has died, the luminosity drastically decreases as the star becomes a stellar remnant.

These evolutionary stages in the star’s life do not take the same amount of time, however. The main sequence lifetime of a star can be approximated by

\[ \tau \equiv 10^{10} \frac{M_*}{M_\odot} \frac{L_\odot}{L_*} \text{ yr} \propto 10^{10} \left( \frac{M_\odot}{M_*} \right)^{5/2} \text{ yr} \]  

(1.27)

where \( M \) is the mass, \( L \) is the luminosity, and the last term assumes the mass-luminosity relationship\(^4\) (Rose, 1973, 1998)

\[ L \propto M^{7/2}. \]  

(1.28)

Equation 1.27 therefore affirms the previously discussed inversely proportional stellar mass-lifetime relationship. Consider then, a solar mass star. The main sequence of lifetime of the star, according to Equation 1.27, would therefore be \(~10^{10}\) yr. The protostar collapse, however, only takes \(~10^6\) yr (see Section 1.3.1). Similarly, the stellar death causes a slow increase in luminosity over \(~10^9\) yr. Therefore, for the majority of a star’s life, its luminosity remains constant.

\(^4\)The mass-luminosity relationship assumed here is a geometric average of the values suggested by Rose (1998) for low and high mass stars.
The remaining chapters of this thesis study stellar populations, however, rather than individual stars. Therefore, we seek to understand how the luminosity of an entire population evolves with time. Using the Kroupa (2001) initial mass function (IMF) and a single starburst event with stars ranging from 0.03 M⊙ to 100 M⊙, one can see the trend for luminosity to decrease over time. Although the more massive stars have much higher luminosity (see Figure 1.2 and Equation 1.28), they also have a much shorter lifetime (see Figure 1.2 and Equation 1.27) due to their high hydrogen burn rate to maintain equilibrium in the star. Therefore, the total luminosity for the population should begin to decrease after the first ~10^5 yr and continue to decrease as stars continue to extinguish. We model the total population luminosity of the aforementioned starburst as

\[ L_T \propto t^{-a}, \]

and find the power \( a \approx 0.9 \). The expectation then is that the magnitude of a stellar population falls off by ~2.25 mag every time the population ages by a factor of ten.
Equipped with his five senses,  
man explores the universe around him  
and calls the adventure Science.  
—Edwin Powell Hubble

The Hubble Space Telescope (HST) is a 2.4 m Cassegrain ultraviolet (UV), optical, and infrared (IR) space-based telescope that was launched into orbit in 1990. Its position in low-Earth orbit allows it to take high resolution imagery of the sky without atmospheric distortion and extinction or light pollution effects. Throughout its 30+ year mission, it has revolutionized the scientific understanding of our universe by exploring regions of the cosmos that had been previously unknown (e.g., the Hubble Ultra Deep Field). Its wide instrument array allows for photometric and spectroscopic scientific studies of the local solar system, exoplanets, stars and nebulae and galaxies. A list of HST properties can be found in Table 2.1. HST continues to be a primary space-based scientific telescope though the James Webb Space Telescope (JWST), with its larger mirror, has already become the new flagship telescope for IR scientific discovery.

HST currently has five working instruments that contribute to unique areas of study: the Advanced Camera System (ACS), the Fine Guidance Sensors (FGS),
Table 2.1: HST Optical Tube Assembly properties. Table credit: STScI.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>Ritchey-Chretien Cassegrain</td>
</tr>
<tr>
<td>Aperture</td>
<td>2.4 m</td>
</tr>
<tr>
<td>Wavelength Coverage</td>
<td>90 nm to ~3 μm</td>
</tr>
<tr>
<td>Focal Ratio</td>
<td>f/24</td>
</tr>
<tr>
<td>Plate Scale (on axis)</td>
<td>3.58 arcsec/mm</td>
</tr>
<tr>
<td>PSF FWHM at 5000 Å</td>
<td>0.043 arcsec</td>
</tr>
<tr>
<td>Encircled energy within 0&quot;1 at 5000 Å</td>
<td>87% (60% - 80% at the detectors)</td>
</tr>
</tbody>
</table>

Figure 2.1: HST instruments and control/support systems. Image credit: STScI.

the Wide Field Camera 3 (WFC3), the Cosmic Origins Spectrograph (COS), and the Space Telescope Imaging Spectrograph (STIS). This thesis depends primarily on ACS and WFC3 which are discussed in Section 2.1 and Section 2.2, respectively. The locations and fields of view (FOVs) of each instrument can be seen in Figure 2.1 and Figure 2.2, respectively. Each instrument is equipped with various filters to study different regions of the electromagnetic spectrum. Some HST filter (see Section 2.1
Figure 2.2: The FOVs of various HST instruments. Image credit: STScI.

and Section 2.2) throughput tables are shown in Figure 2.3 with normalized reference spectra for comparison.
2.1 The Advanced Camera System

The Advanced Camera System (ACS) is a third-generation HST instrument that was installed and became operable in 2002 (Ryon, 2022). ACS has two operable channels – Solar Blind Channel (SBC) and Wide Field Channel (WFC) – and an inoperable channel – High Resolution Channel (HRC) – to perform broadband imagery, coronagraphic, polarimetric, and spectral studies. Only the WFC is discussed below as it is the ACS channel used in this thesis.

Figure 2.3: HST filter throughputs with reference spectra. Upper: Filter throughputs for the filter set used in this thesis. Lower: HST calibration stellar spectra for reference. The star name and spectral type are listed in the legend. Each spectrum has been normalized to have a -20 AB mag in F475W. The plots are generated with PySynphot (STScI Development Team, 2013).
The WFC uses two 4096 × 2048 charge-coupled devices (CCDs) covering the 350-1100 nm spectral range. The pair of CCDs are situated such that there is a 750 µm (≈ 50 pix; 2.5 arcsec) chip gap between them. The paired set of smaller CCDs allows for a fewer number of charge transfers. The CCDs have a pixel size of 15 × 15 µm corresponding to a scale of 0.05 × 0.05 arcsec to cover a 202 × 202 arcsec FOV (Ryon, 2022). A full overview of the WFC detector properties can be found in Ryon (2022, Table 3.1) and full details (quantum efficiency, dark current, read noise, etc.) for the detector can be found in Ryon (2022, Section 4.2). The WFC is equipped with 2 long-pass filters, 7 wide-band filters (including F475W and F814W shown in Figure 2.3), 4 medium-band filters, 15 narrow-band filters, 7 polarimetry filters, and 1 grism. Observations made at various wavelengths have an associated point spread function (PSF) and encircled energy percentage (see Ryon, 2022, Section 5.6) that must be considered when performing aperture photometry.

WFC suffers from additional degradations such as well saturation, cosmic rays (CRs) and hot pixels, image persistence, vibrations and other anomalies. Each one of these can be combated with various strategies such as dithering (used in the images in this thesis) which can be reduced with the default HST pipeline if the images are taken with a single visit. Changes to the default pipeline or combining images from multiple visits can be accomplished with DrizzlePac (Hoffmann et al., 2021; see Chapter 3).
2.2 The Wide Field Camera 3

The Wide Field Camera 3 (WFC3) is a fourth-generation HST instrument that was installed and became operable in 2009 (Dressel, 2022) and replaced the Wide Field Planetary Camera 2. WFC3 uses two channels – ultraviolet-visible (UVIS) and IR – to cover the UV, optical, and near IR (NIR) parts of the spectrum. WFC3 maintains the long-term HST high-resolution imaging capability and gives some redundancy to the imaging capabilities of ACS.

WFC3 was designed to maximize the FOV, sensitivity, spectrum range, spatial resolution, and photometric performance (Dressel, 2022). This was accomplished with the two aforementioned channels detailed in Dressel (2022, Figure 2.1). The complicated optics and slight offset from the center of the HST optical telescope assembly causes geometric distortions in both the UVIS and IR channels that must be corrected in post-processing. Dressel (2022, Appendix B) provides an overview of the distortions by providing the distortion and pixel area maps which are corrected by the default HST pipeline.

The UVIS channel has a focal ratio of f/31 using two 2051 × 4096 adjacent CCD detectors covering the 200-1000 nm spectral range. The pair of CCDs are situated such that there is a 465 µm (31 ± 0.1 pix; see Dressel, 2022, Figure 5.1) chip gap between them (an improvement over the 50 pix ACS chip gap). The CCDs have a pixel size of 15 × 15 µm corresponding to a scale of 0.0395 × 0.0395 arcsec to cover a 162 × 162 arcsec FOV (Dressel, 2022). A full overview of the UVIS channel detector properties can be found in Dressel (2022, Table 5.1) and full details (quantum
efficiency, dark current, read noise, etc.) for the detector can be found in Dressel (2022, Section 5.4). The UVIS channel is equipped with 6 long-pass/extra-wide filters used for very deep imaging, 12 wide-band filters (including F275W shown in Figure 2.3) used for ISM absorption and broad-band imaging, 9 medium band filters, 34 narrow-band filters (primarily for studying individual transition lines), and 1 grism for slitless spectral analysis covering 2000-4000 Å. Observations made at various wavelengths have an associated PSF and encircled energy percentage (see Dressel, 2022, Section 6.6) that must be considered when performing aperture photometry.

The IR channel has a focal ratio of f/11 using a $1014 \times 1014$ focal plane array (FPA) covering the 800-1700 nm spectral range. The FPA has a larger pixel size of $18 \times 18 \mu m$ corresponding to a scale of $0.135 \times 0.121$ arcsec to cover a $136 \times 123$ arcsec FOV (Dressel, 2022). A full overview of the IR channel detector properties can be found in Dressel (2022, Table 5.1) and full details for the detector can be found in Dressel (2022, Section 5.7). The IR channel is equipped with 5 wide-band filters (including F160W shown in Figure 2.3), 4 medium-band filters, 6 narrow-band filters, and 2 grisms. Like the UVIS channel, PSF and encircled energy considerations must be made when doing aperture photometry (see Dressel, 2022, Section 7.6).

Both the UVIS and IR channels suffer from additional degradations such as well saturation, cosmic rays (CRs) and hot pixels, image persistence, vibrations and other anomalies. Each one of these can be combatted with various strategies such as dithering (used in the images in this thesis), making parallel observations with another instrument, or performing a drift and shift strategy. The first and third strategies can be reduced with the default HST pipeline if the images are taken with
a single visit. Changes to the default pipeline or combining images from multiple visits can be accomplished with DrizzlePac (Hoffmann et al., 2021; see Chapter 3).
CHAPTER 3

DATA REDUCTION PIPELINE

We find them smaller and fainter, in constantly increasing numbers, and we know that we are reaching into space, farther and farther, until, with the faintest nebulae that can be detected with the greatest telescopes, we arrive at the frontier of the known universe.

—Edwin Powell Hubble

This chapter presents the methodology to reduce the HST data to study the star forming regions in a ram pressure stripped tail. While the HST pipeline does drizzle the images from the telescope, some modifications must be made to the default pipeline to maximize the effectiveness in studying the star forming regions in ram pressure stripped tails. Considering the default pipeline only drizzles images from a single visit, an extensible framework such as the one detailed below is needed to drizzle images from multiple visits. We also present the process for making photometric measurements on these reduced images.

3.1 HST Image Data Reduction

The ACS and WFC3 images were first processed through the default CALACS (Lucas & Ryon, 2022) and CALWFC3 (Sahu, 2021) data pipelines, respectively. Each
package in this step performed a combination of data quality estimation, CCD bias correction, CCD anomaly correction, pixels with low signal identification, charge transfer efficiency (CTE) correction, dark current subtraction, post-flash correction, CR identification, and photometry correction. The output of this step produced the baseline flat-field (FLC/FLT for CTE and non-CTE files, respectively) flexible image transport system (FITS) files used in this thesis which were retrieved from the Mikulski Archive for Space Telescopes (MAST). The default MAST data pipeline also uses AstroDrizzle (Hoffmann et al., 2021) to combine images from an HST visit into a final drizzled FITS file (DRC/DRZ for CTE and non-CTE files, respectively) through a process that primarily involves sky subtraction and cosmic ray rejection. Both Lucas & Ryon (2022) and Sahu (2021) cite relevant cases for when manual drizzling may be needed: 1) when there are images from multiple visit – in which image alignment is also needed – and 2) when a non-default drizzle parameters – such as the output pixel scale – are needed to enhance the output image.

Image alignment was performed using TweakReg (Hoffmann et al., 2021) using two different methodologies depending on the number of flat-field images. When the number of flat-field images per filter was low (less than 6 images), an F814W reference image was chosen because of its high signal-to-noise ratio (SNR). Due to the high number of CRs in the flat-field images (see Figure 3.1-top-left), an initial X/Y offset was found using DS9 (Joye & Mandel, 2003) and supplied to TweakReg along with the non-default values listed in Table 3.1 which optimized the match of real sources versus anomalous sources such as the CRs. Additional alignment solution verification was carried out using DS9 (Joye & Mandel, 2003). Alternatively, when the number
Table 3.1: Non-default TweakReg parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Default Value</th>
<th>New Value</th>
</tr>
</thead>
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<tr>
<td>Source Find Threshold</td>
<td>sigma</td>
<td>4.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Search Radius</td>
<td>pixel</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>X/Y Offsets</td>
<td>pixel</td>
<td>0.0</td>
<td>DS9\textsuperscript{a}</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Images were compared using DS9 (Jaye & Mandel, 2003) to find the approximate initial offsets.

of flat-field images per filter was high (greater than 6 images), the aforementioned process is not feasible due to time constraints. Therefore, we modify the process by assuming that flat-field images taken in a single visit are well aligned (generally within 0.1 pixel according to Sahu, 2021) and drizzle all associated flat-field images together which allows for coarse CR rejection. SExtractor (Bertin & Arnouts, 1996) is then run on drizzled images to identify source coordinates. TweakReg is then run on each flat-field image using the source catalog from the associated drizzle file. The first method is advantageous in ensuring each flat field image is well aligned before drizzling while the second method is advantageous when processing many images.

Once the flat-field images were aligned to the same relative astrometry, the images could then be combined using AstroDrizzle (Hoffmann \textit{et al.}, 2021) to remove CRs, performs sky subtraction, reduces background variation, and corrects geometric distortions. Several non-default parameters listed in Table 3.2 were chosen to assist and enhance the photometric measurements. Absolute astrometry was then performed on these drizzled images by aligning to the Guide Star Catalog II (GSC2) (Lasker \textit{et al.}, 2008) using TweakReg with the default parameters. Overall, using this method we were able to align the drizzled images’ world coordinates to within 0\textquoteleft01.
Table 3.2: Non-default AstroDrizzle parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Default Value</th>
<th>New Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>WCS Key</td>
<td></td>
<td>TWEAK</td>
<td></td>
</tr>
<tr>
<td>Context Image</td>
<td>True</td>
<td>False</td>
<td></td>
</tr>
<tr>
<td>Median Combination Type (&gt; 6 images)</td>
<td>minmed</td>
<td>median</td>
<td></td>
</tr>
<tr>
<td># of High Pixel Values to Reject (&gt; 6 images)</td>
<td>0</td>
<td>1 + int(N/10)</td>
<td></td>
</tr>
<tr>
<td>Final Weight Type</td>
<td>EXP</td>
<td>IVM</td>
<td></td>
</tr>
<tr>
<td>Final Rotation</td>
<td>deg</td>
<td>Input Rot</td>
<td>0.00</td>
</tr>
<tr>
<td>Final Pixel Scale</td>
<td>arcsec/pix</td>
<td>Input Scale</td>
<td>0.03</td>
</tr>
</tbody>
</table>

CRs remained in the chip gaps (see Section 2.1 and Section 2.2) of data sets with a low number of flat-field images per filter after drizzling (e.g., ESO 137-001; see Figure 3.1-*top-right* and Figure 3.1-*bottom-left*). These CRs were identified by first using SExtractor (Bertin & Arnouts, 1996) in single image mode with a low detection threshold to identify any potential source. Sources that only appeared in a single frame were flagged as potential CRs. Once a CR candidate was visually confirmed, a region mask was added to a DS9 (Joye & Mandel, 2003) region file which in turn was converted to a image mask. The mask was then used with the IRAF (Tody, 1986) tool “crfix” to remove the indicated CRs. After this process, a few residual CRs remained and were subsequently removed with Astroscrappy (van Dokkum, 2001). The final image from this process is shown in Figure 3.1-*bottom-right*.

### 3.2 Photometry

Due to the high number of sources in each filter, we primarily utilized SExtractor (Bertin & Arnouts, 1996) in dual-image mode to measure the photometry using the F475W image as the detection image. Table 3.3 shows the non-default parameters
Figure 3.1: The comparison of images between the HST image pipeline and the one detailed in this thesis. Each of the image cutouts show the center of ESO 137-001 (see Section 4.1) and its western tail filaments using the F814W filter. Top-Left: The original flat field image covered with CRs. The chip gap between the two detectors is on the right hand side of the figure. Top-Right: The HST pipeline drizzled image. The CRs remain where only one image covered the other’s chip gap. Bottom-Left: The drizzled image from this work. The CRs still remain in the chip gap area. Bottom-Right: The CR corrected drizzled image from this work. There still remain a few CRs in the chip gap, but the remaining number is much more manageable to identify by hand.
Table 3.3: Non-default SExtractor parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Default Value</th>
<th>New Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BACK_SIZE</td>
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<td>128</td>
</tr>
<tr>
<td>BACKPHOTO_THICK</td>
<td>pixel</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>BACKPHOTO_TYPE</td>
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<td>Global</td>
<td>Local</td>
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<tr>
<td>DEBLEND_MINCONT</td>
<td></td>
<td>0.005</td>
<td>0.001</td>
</tr>
<tr>
<td>DEBLEND_NTHRESH</td>
<td></td>
<td>32</td>
<td>64</td>
</tr>
<tr>
<td>FILTER_NAME</td>
<td></td>
<td>default.conv</td>
<td>gauss_3.0_7x7.conv</td>
</tr>
<tr>
<td>GAIN</td>
<td></td>
<td>0</td>
<td>Total Exposure Time(^a)</td>
</tr>
<tr>
<td>PHOT_APERTURES</td>
<td>pixel</td>
<td>5</td>
<td>0\textdegree55, 0\textdegree50, 0\textdegree50, 0\textdegree80(^b)</td>
</tr>
<tr>
<td>PIXEL_SCALE</td>
<td>arcsec/pixel</td>
<td>1.0</td>
<td>0.03</td>
</tr>
<tr>
<td>SATUR_LEVEL</td>
<td>ADU</td>
<td>50000</td>
<td>85000/GAIN</td>
</tr>
<tr>
<td>WEIGHT_GAIN</td>
<td></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>WEIGHT_IMAGE</td>
<td></td>
<td>weight.fits</td>
<td>RMS Image(^c)</td>
</tr>
<tr>
<td>WEIGHT_TYPE</td>
<td></td>
<td>None</td>
<td>MAP,RMS</td>
</tr>
<tr>
<td>WEIGHT_THRESH</td>
<td>ADU</td>
<td></td>
<td>100000</td>
</tr>
</tbody>
</table>

\(^a\) The total exposure time from all flat-field images used in generating each drizzled image.

\(^b\) Aperture sizes in arcseconds for F275W, F475W, F814W, and F160W, respectively.

\(^c\) Created by taking the square root of the inverse of the IVM image.

used when running SExtractor. Due to difficulty in aligning magnitude measurements, the magnitude of each source was calculated manually from the SExtractor (Bertin & Arnouts, 1996) fluxes according to

\[
m = -2.5 \log_{10} (f) + Z - G - \alpha - k
\]  

(3.1)

where \(f\) is the flux measured in e\(^-\)/s, \(Z\) is the HST AB zero point (Oke & Gunn, 1983; Bohlin, 2016), \(G\) is the Milky Way extinction (Schlafly & Finkbeiner, 2011), \(\alpha\) is the aperture correction (Sirianni et al., 2005; Bohlin, 2016), and \(k\) is the k-correction (Humason et al., 1956; Oke & Sandage, 1968; Hogg, 1999; Hogg et al., 2002; Blanton & Roweis, 2007). Likewise, the flux uncertainties were converted to the magnitude
system according to

\[ m_{\text{err}} = \frac{5f_{\text{err}}}{2 \ln(10)f} \]  

(3.2)

where \( m_{\text{err}} \) is the magnitude uncertainty, \( f_{\text{err}} \) is the flux uncertainty, and \( f \) is the flux\(^1\). We corrected the magnitude uncertainty due to the drizzling process using the following correction factor\(^2\).

\[
\sqrt{F_A} = \begin{cases} 
\frac{s}{p} \left(1 - \frac{s}{3p}\right) & s < p \\
1 - \frac{p}{3s} & s \geq p 
\end{cases}
\]  

(3.3)

and

\[ E_C = E / \sqrt{F_A} \]  

(3.4)

where \( p \) is the AstroDrizzle pixel fraction parameter, \( s \) is the factor applied to the original pixel scale, \( \sqrt{F_A} \) is the correction factor, \( E \) is the measured error and \( E_C \) is the corrected error. The photometric parameters vary over time and space and are therefore presented with each observation.

We validate our methodology by first ensuring the image reduction pipeline (Section 3.1) did not change the photometry of various sources. Figure 3.2 shows the photometric flux comparisons between the ESO 137-001 images developed for this thesis and the original/\textit{HST} pipeline images using the F814W filter. The photometry was measured with 0\".5 source circles and background annuli with 0\".6 and 0\".8 inner and outer radii, respectively. The comparison between our images and the flat-field

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\(^1\)See Appendix A for a treatment of magnitude uncertainty propagation.  
\(^2\)https://www.ifa.hawaii.edu/~rgal/science/sexttractor_notes.html
Figure 3.2: A comparison of the measured flux on 10 ESO 137-001 sources in the F814W filter. The photometry was measured with 0\′′.5 source circles and background annuli with 0\′′.6 and 0\′′.8 inner and outer radii, respectively.

Images Figure 3.2-left varies from unity, but the variation can be attributed to the noise in the flat-field images that is corrected by the drizzling process (as is suggested by the comparison of our image to the HST pipeline image in Figure 3.2-right). Ultimately, the measured flux remains conserved across all three images showing that the image reduction pipeline did not change the photometry.

Next, we validate our SExtractor (Bertin & Arnouts, 1996) setup in Figure 3.3. The top row of Figure 3.3 shows a comparison of seven ESO 137-001 tail sources (see Section 4.4.1) using SExtractor between the images developed in this thesis and those created by the HST pipeline. As shown in these two plots, the flux in both F475W and F814W as well as the color between the two are preserved when using SExtractor. The bottom row of Figure 3.3 further validates the use of SExtractor (and our setup thereof) by doing a comparison of the SExtractor results to those made with simple
aperture photometry using the images developed according to Section 3.1. The photometry was measured on the same seven previously mentioned sources. The simple annular photometry was performed with the aperture sizes detailed in Figure 3.2. Likewise, the SExtractor measurements were made with 0\textquotesingle 5 apertures. Making this comparison is difficult considering the differences in background subtraction and SExtractor’s treatment of blended sources. However, for the displayed subset of compact sources in Figure 3.3, there is generally good agreement using the two methods. The one exception is the small extended source that measures much brighter in both bands when using simple annular photometry. Any difference in the flux measurements will propagate to the magnitude calculations; however, the difference is less pronounced when measuring the color between two bands (Figure 3.3: bottom-right).

The photometric process detailed in Sections 3.1 and 3.2 is compared against Hammer et al. (2010) to further ensure we measure the same photometry. Figure 3.4 shows the comparison of a random subset of 15 sources (from over 2000) using SExtractor (Bertin & Arnouts, 1996). Both panels in Figure 3.4 show good agreement of the photometric measurements which further add confidence to our SExtractor setup and results.
Figure 3.3: ESO 137-001 flux and color comparisons for methodological validation. 
Top Row: Flux and color comparisons on a subset of seven ESO 137-001 tail sources (see Section 4.4.1) in the F475W and F814W filters between the images developed in this thesis and those created by the HST pipeline using SExtractor (Bertin & Arnouts, 1996). The two plots show that photometric properties are still conserved across both pipelines (as in Figure 3.2) when using SExtractor. 
Bottom Row: A comparison of photometric measurements between SExtractor and simple aperture photometry on the aforementioned seven sources using the images developed in this thesis. The simple aperture photometry measurements are made in the same way as Figure 3.2. The compact sources generally show good agreement between the two measurement techniques. The one source that appears brighter in both bands when using simple aperture photometry is an extended source that highlights the difference in how the two methods account for the background flux and how they deal with blended sources.
Figure 3.4: Photometric comparisons between the methods presented in this thesis to those presented in Hammer et al. (2010) using SExtractor (Bertin & Arnouts, 1996). The left and right panels show the F475W and F814W magnitude measurements, respectively. The blue markers indicate measurements made with the SExtractor “MAG_AUTO” output parameter, and the orange markers indicate measurements made with a fixed 0.4′ aperture. Both plots show good agreement indicating a good SExtractor setup.
CHAPTER 4

ESO 137-001 RESULTS

I do not feel obliged to believe that the same God who has endowed us with sense, reason, and intellect has intended us to forgo their use.

—Galileo Galilei

4.1 ESO 137-001 Introduction

ESO 137-001 (see Figure 4.1), a spiral galaxy near the center of the closest rich cluster the Norma cluster (Abell 3627), was first discovered as a galaxy undergoing RPS by Sun et al. (2006) with the Chandra and XMM X-ray data that reveal a 70 kpc long, narrow X-ray tail. Sun et al. (2007) took the narrow-band imaging data with the Southern Observatory for Astrophysical Research (SOAR) telescope to discover a 40 kpc Hα tail that aligned with the X-ray tail. More than 30 H II regions were also revealed, unambiguously confirming SF in the stripped ISM. Sun et al. (2010) further studied ESO 137-001 with deeper Chandra observations and Gemini spectroscopic observations. The deep Chandra data surprisingly revealed that the X-ray tail, now detected to at least 80 kpc from the galaxy, is bifurcated with a secondary branch on the south of the primary X-ray tail. Re-examination of the Sun et al. (2007) Hα data also shows Hα enhancement at several positions of the secondary tail. Sun et al.
(2010) also presented the *Gemini* spectra of over 33 H\textsc{ii} regions and revealed the imprint of the galactic rotation pattern in the tail.

Sivanandam *et al.* (2010) presented *Spitzer* data on ESO 137-001 that reveals a 20 kpc warm (130-160 K) H$_2$ tail which is co-aligned with the X-ray and the H\textalpha{} tail (note that the extent of the H$_2$ tail is limited by the field of view of the *IRS* instrument). The large H$_2$ line to IR continuum luminosity ratio suggests that SF is not the main excitation source in the tail. Jáchym *et al.* (2014) used *APEX* telescope to observe ESO 137-001 and its tail at four positions. Strong CO(2-1) emission is detected at each position, including the middle of the primary tail that is 40 kpc from the galaxy, indicating abundant cold molecular gas in the tail. On the other hand, the SF efficiency in the tail appears to be low. Jáchym *et al.* (2019) further observed ESO 137-001 and its tail with an *ALMA* mosaic to obtain a high-resolution view of the cold molecular gas. The resulting map reveals a rich amount of molecular cloud structure in the tail, ranging from compact clumps associated with H\textsc{ii} regions, large clumps not closely associated with any H\textsc{ii} regions, to long filaments away from any SF regions.

Spatially resolved studies of warm, ionized gas have been revolutionized with the the *Multi Unit Spectroscopic Explorer (MUSE)* on the *Very Large Telescope (VLT)*. As the first science paper with *MUSE*, Fumagalli *et al.* (2014) presented results from the *MUSE* observations on ESO 137-001 and the front half of the primary tail. The work demonstrates the great potential of *MUSE* on studies of diffuse warm, ionized gas as often seen in stripped tails. The early *MUSE* velocity and velocity dispersion maps suggest that turbulence begins to be dominant at $> 6.5$ Myr...
Figure 4.1: The RGB image (blue: F275W; green: F475W; red: F814W) of ESO 137-001 with zoom-ins on 40 regions (Large Image Credit: STScI; zoom-ins are from this work). We include the following zoom-in regions: H$	ext{II}$ regions defined in Section 4.4.1 shown by the white, dashed circles with a radius of 0′′.40, X-ray point sources from Sun et al. (2010) shown by the cyan, dotted circles with a radius of 0′′.50, bright CO sources from Jáchym et al. (2019) shown by the magenta, solid contours (contour levels of 0.03, 0.06 and 0.12 Jy km/s per beam), and blue star clusters defined from this work. The blue star clusters shown were selected with these criteria: F275W-F475W < 2, F475W-F814W < 1 and F475W < 25.6. Some isolated blue sources are not included in zoom-ins but they are all studied in this work. The arrow on each cutout represents 0.25 kpc. Caption continued in next figure.
Figure 4.2: Continued from Figure 4.1. The bold numbers emphasize regions that align with an H\textsc{ii} source, and italicized numbers emphasize regions that do not. Regions 30, 31, 32, 33, and 40 lie outside the large STScI image and are shown for reference on Figure 4.7. Region 40 is not covered by F275W so the blue source associated with the H\textsc{ii} region appears green. The correlation of H\textsc{ii}, blue HST star clusters, CO clumps and X-ray sources is discussed in Section 4.4.
after stripping. Fossati et al. (2016), with the same MUSE data that Fumagalli et al. (2014) used, presented a detailed study of line diagnostics in ESO 137-001’s tail. Their results also called for better modeling of ionization mechanisms in stripped tails. Sun et al. (2021) presented a new MUSE mosaic to cover the full extent of ESO 137-001’s tail, revealing very good correlation with the X-ray emission. This new set of MUSE data provides a great amount of data for detailed studies of kinematics and line diagnostics (Luo et al. in preparation).

As discussed above, ESO 137-001 has become the RPS galaxy with the richest amount of supporting data and multi-wavelength analysis. In this context, a detailed study with the HST data adds important information on this multi-wavelength campaign, which is the focus of this chapter. Table 4.1 summarizes the properties of ESO 137-001. As in Sun et al. (2010), we adopt a luminosity distance of 69.6 Mpc for Abell 3627 and 1" = 0.327 kpc.

### 4.2 ESO 137-001 Observations

The data for this work was collected using WFC3 and ACS on HST, from proposals 11683 and 12372 (PI: Ming Sun). Details of the observations are summarized in Table 4.2. All observations focus on the tail of ESO 137-001 described in Sun et al. (2006, 2007). The F275W data are especially sensitive to recent star formation in the last several $10^7$ years and the F275W - F475W color measures the strength of the 4000 Å break. The data from F475W and F814W add a broad spectrum of light to identify dim, diffuse features, while the F160W data present the view of the
Table 4.1: Properties of ESO 137-001

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heliocentric velocity (km/s)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4647 (-224)</td>
</tr>
<tr>
<td>Offset (kpc)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>180</td>
</tr>
<tr>
<td>Position Angle</td>
<td>~9°</td>
</tr>
<tr>
<td>Inclination</td>
<td>~66°</td>
</tr>
<tr>
<td>W1 (Vega mag)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>12.31</td>
</tr>
<tr>
<td>$L_W1$ ($10^9 L_\odot$)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.489</td>
</tr>
<tr>
<td>W1 − W4 (Vega mag)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>6.99</td>
</tr>
<tr>
<td>$m_{F160W}$ (AB mag)&lt;sup&gt;d&lt;/sup&gt;</td>
<td>13.16</td>
</tr>
<tr>
<td>Half light semi-major axis (kpc)&lt;sup&gt;d&lt;/sup&gt;</td>
<td>4.91</td>
</tr>
<tr>
<td>$M_\star$ ($10^9 M_\odot$)&lt;sup&gt;e&lt;/sup&gt;</td>
<td>5-8</td>
</tr>
<tr>
<td>$M_{mol}$ ($10^9 M_\odot$)&lt;sup&gt;f&lt;/sup&gt;</td>
<td>~1.1</td>
</tr>
<tr>
<td>$L_{FIR}$ ($10^9 L_\odot$)&lt;sup&gt;g&lt;/sup&gt;</td>
<td>5.2</td>
</tr>
<tr>
<td>SFR ($M_\odot$/yr) (Galaxy)&lt;sup&gt;h&lt;/sup&gt;</td>
<td>1.2</td>
</tr>
<tr>
<td>$M_\star$ ($10^6 M_\odot$) (Tail)</td>
<td>2.5 - 3.0</td>
</tr>
<tr>
<td>SFR ($M_\odot$/yr) (Tail)</td>
<td>0.4 - 0.65</td>
</tr>
<tr>
<td>Tail length (kpc)&lt;sup&gt;i&lt;/sup&gt;</td>
<td>80 - 87 (X-ray/Hα)</td>
</tr>
</tbody>
</table>

<sup>a</sup> The heliocentric velocity of the galaxy from our study on the stellar spectrum around the nucleus (Luo et al. 2022). The velocity value in parentheses is the radial velocity relative to that of Abell 3627 (Woudt et al., 2004).

<sup>b</sup> The projected offset of the galaxy from the X-ray center of A3627.

<sup>c</sup> The WISE 3.4 μm magnitude, luminosity and the WISE 3.4 μm - 22 μm color. The Galactic extinction was corrected with the relation from Indebetouw et al. (2005).

<sup>d</sup> The total magnitude and the half light semi-major axis at the F160W band. The axis ratio is 2.27 and the positional angle is 9.0° east of the North.

<sup>e</sup> The total stellar mass estimated from Sun et al. (2010).

<sup>f</sup> The total amount of the molecular gas detected in the galaxy from Jáchym et al. (2014).

<sup>g</sup> The total FIR luminosity from the Herschel data (see Waldron et al., 2022, Section 5.1).

<sup>h</sup> The average value from the first estimate (0.97) based on the Galex NUV flux density and the total FIR luminosity from Herschel with the relation from Hao et al. (2011), and the second estimate (1.4) based on the WISE 22 μm flux density with the relation from Lee et al. (2013). The Kroupa initial mass function (IMF) is assumed.

<sup>i</sup> The tail length for ESO 137-001 from Sun et al. (2010).
Table 4.2: HST ESO 137-001 Observations (PI: Sun)

<table>
<thead>
<tr>
<th>Filter</th>
<th>Instrument</th>
<th>Mode</th>
<th>Dither¹</th>
<th>Date</th>
<th>Exp</th>
<th>Mean λ / FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>F275W</td>
<td>WFC3/UVIS</td>
<td>ACCUM</td>
<td>3 (2.4&quot;)</td>
<td>02/08/2009</td>
<td>3 x 978.0</td>
<td>2719/418</td>
</tr>
<tr>
<td>F475W</td>
<td>ACS/WFC</td>
<td>ACCUM</td>
<td>2 (3.01&quot;)</td>
<td>02/08/2009</td>
<td>2 x 871.0</td>
<td>4802/1437</td>
</tr>
<tr>
<td>F814W</td>
<td>ACS/WFC</td>
<td>ACCUM</td>
<td>2 (3.01&quot;)</td>
<td>02/08/2009</td>
<td>2 x 339.02</td>
<td>8129/1856</td>
</tr>
<tr>
<td>F160W</td>
<td>WFC3/IR</td>
<td>MULTI</td>
<td>3 (0.605&quot;)</td>
<td>17/07/2011</td>
<td>3 x 499.2</td>
<td>15436/2874</td>
</tr>
</tbody>
</table>

¹ Number of dither positions (and offset between each dither).

Table 4.3: ESO 137-001 Photometric Parameters

<table>
<thead>
<tr>
<th>Filter</th>
<th>ApSize</th>
<th>AB Zero Point</th>
<th>Extinction</th>
<th>ApCor²</th>
<th>K-Correction</th>
<th>√(F_A)³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F275W</td>
<td>0.55</td>
<td>24.1713</td>
<td>1.158</td>
<td>0.122871</td>
<td>0.019457</td>
<td>0.5625</td>
</tr>
<tr>
<td>F475W</td>
<td>0.50</td>
<td>26.0604</td>
<td>0.689</td>
<td>0.100013</td>
<td>0.033213</td>
<td>0.4800</td>
</tr>
<tr>
<td>F814W</td>
<td>0.50</td>
<td>25.9489</td>
<td>0.322</td>
<td>0.096447</td>
<td>0.004671</td>
<td>0.4800</td>
</tr>
<tr>
<td>F160W</td>
<td>0.80</td>
<td>25.9462</td>
<td>0.108</td>
<td>0.176453</td>
<td>0.022268</td>
<td>0.2130</td>
</tr>
</tbody>
</table>

² The aperture correction to account for the encircled energy within the aperture.
³ The magnitude error correction divisor from using AstroDrizzle (Hoffmann et al., 2021).

The galaxy least affected by the dust extinction. Together, these four filters can be used to constrain the stellar age of star clusters found in the galaxy and the tail. Abell 3627 lies near the galactic plane which means the Milky Way extinction and foreground clutter is high: 1.158 mag for F275W, 0.689 mag for F475W, 0.332 mag for F814W, and 0.108 mag for F160W (Schlafly & Finkbeiner, 2011). We estimate the point source detection limits (as 3-σ of the background rms) as 29.2 mag for F275W, 30.6 mag for F475W, 29.9 mag for F814W, and 31.3 mag for F160W (all corrected for the Galactic extinction). The table of photometric parameters (detailed in Equation 3.1) used for this observation can be found in Table 4.3.
4.3 ESO 137-001 Properties

4.3.1 Morphology & Light Profiles

A composite RGB image of ESO 137-001 is shown in Figure 4.1 which includes zoomed in areas of interesting regions that will be discussed later this paper. Figure 4.3 presents the central galaxy region in each of the four HST filters. ESO 137-001’s upstream is nearly devoid of dust from RPS while dust trails extend from the nucleus into the downstream regions. This suggests that RPS has nearly cleaned out the eastern half of the galaxy of dust but that RPS is still occurring around the nucleus and western half. Figure 4.3 also shows the outer Hα contour from the MUSE data that reveal the current stripping front that is only $\sim 1.2$ kpc from the nucleus. One can also see a large dust feature downstream has an associated large molecular cloud detected by the Atacama Large Millimeter Array (ALMA).

We quantitatively examine the galaxy structure by deriving the surface brightness profiles in all four bands along the major axis, minor axis and in elliptical annuli centered at the nucleus (Figure 4.4). The galaxy center is set at the nuclear position defined in Waldron et al. (2022, Section 3.3). The major axis has a position angle of 9.0° (measured counterclockwise from North). The total F160W light measured from the galaxy is 13.16 mag (without correction from intrinsic extinction) and the half-light radius is $4.91 \pm 0.05$ kpc in F160W. This half-light radius in F160W can also be compared with the half-light radius of 4.74 kpc and 4.58 kpc at B band and I band respectively from the SOAR data (Sun et al., 2007).
Figure 4.3: The central regions of the galaxy in the four HST bands. One can see strong dust features downstream of the galaxy (vs. smooth light distribution upstream) and enhanced SF in the central part of the galaxy. The dashed blue contour is the outer Hα edge from the full MUSE mosaic image (Sun et al., 2021), which shows the stripping front in the galaxy. The red contours show the CO emission from Jáchym et al. (2019). There is a large CO clump downstream of the galaxy, at ~2.3 kpc from the nucleus where dust attenuation is significant (especially apparent in the F475W image) and lacks bright star clusters and strong Hα emission. This downstream region may be the “deadwater” region, or the stagnant part of the wake that is close to the moving body. Other smaller CO clumps are typically around young star complexes. The green circle (with a radius of 0.5′′) shows the nucleus. The scale bar is 1 kpc.
Figure 4.4: ESO 137-001 surface brightness profiles. Top-Left: The surface brightness profiles of ESO 137-001 along its minor axis (a 6'' width and a 0.5' step size). The vertical dashed line shows the position of the nucleus (also the same for other panels in this figure). The east (E) region is upstream because the major axis of the galaxy is almost NS. One can clearly see the upstream-downstream asymmetry especially in UV and blue bands. Note that the bin width is doubled for distances greater than 5 kpc from the nucleus. Top-Middle: The surface brightness profiles of ESO 137-001 along its major axis (a 3'' width and a 0.5' step size). One can see the light profiles along the major axis are much more symmetric than those along the minor axis. Note that the bin width is doubled for distances greater than 5 kpc from the nucleus. Top-Right: The radial surface brightness profiles of ESO 137-001 in elliptical annuli (with the same proportions as the elliptical galaxy region in Figure 4.6). The x-axis represents the semi-major axis. Bottom Row: The F275W - F475W and F475W - F814W profiles in the relevant regions from the upper panels.
The light profiles along the minor axis are shown in Figure 4.4. The profiles are measured in a series of rectangle regions each with a width of 40″ and a step size of 0″5. Likewise, the profiles along the major axis are also shown. The profiles are measured in a series of rectangular regions each with a width of 20″ and a step size of 0″5. The elliptical profiles are measured in annuli with a width of 0″15 along the major axis and have an axis ratio of 0.44. It is worth noting the asymmetry of the F275W profile along the minor axis (Figure 4.4, top-left). The profile shows the faintness of the ultraviolet light in the galaxy upstream regions and an excess of ultraviolet light in the downstream. Since dust in the galaxy is mainly in the downstream region, the intrinsic E-W contrast on the F275W - F475W color is in fact larger than shown in Figure 4.4. This demonstrates the quenched SF upstream and enhanced SF downstream in the near tail. The radial profile also shows an F275W-F475W color gradient (Figure 4.4, bottom-right) where the galaxy is bluer in the central regions than it is in the outer regions. The F475W-F814W color profiles (Figure 4.4, bottom row) shows little change along each axis in these wide bins.

We also derive the structural parameters of ESO 137-001 in the F160W band (least affected by intrinsic extinction) using the two dimensional fitting algorithm GALFIT (Peng et al., 2002). For this case, we used a single Sérsic model, as well as a double component model (bulge fitted by a Sérsic model while disk fitted by an exponential component) to fit the galaxy image. The fitted parameters are listed in Table 4.4. In the case of a single Sérsic model, there is a degeneracy between the Sérsic index and the effective radius. A double component model also fits the F160W image reasonably well. However, as shown in Figure 4.1 and Figure 4.3, there is no clear
evidence for the existence of a bulge. The fits also suggest that any bulge component, if it exists, must be small. We note that both the total F160W light and the half-light radius from profile fitting (Table 4.1) are similar to the double Sérsic model results with GALFIT (Table 4.4). Overall, the derived Sérsic indexes are in good agreement with results from large surveys like GAMA (e.g., Lange et al., 2015) for galaxies similar to ESO 137-001. Based on the light profiles and the GALFIT results (Table 4.4), we measure the inclination angle of ESO 137-001 to be 66° with the classic Hubble formula (assuming a morphological type of SBc), which is the same as the result from HyperLeda (Makarov et al., 2014). As the motion of ESO 137-001 is towards the east and mostly on the plane of sky, we conclude that the near side of the galaxy is towards the east, as the stripped dust clouds need to be located between the disk and us the observer to make the downstream dust features significant. Another way to conclude the east side as the near side is from the spiral arm winding (Figure 4.5). As almost all spiral arms are trailing, ESO 137-001’s spiral arms are rotating counter-clockwise. As the south side of the galaxy is rotating away from us relative to the nucleus (Fumagalli et al., 2014), the east side must be the near side.

4.3.2 Dust Features

To better show the dust features in the galaxy, we also used GALFIT to produce a residual image with a single Sérsic model in the F475W image. Prior to the analysis, foreground stars are masked. The residual image is shown in Figure 4.5. It shows some prominent dust features downstream of the galaxy (also see Figure 4.3).
Table 4.4: GALFIT fits on the F160W image of ESO 137-001

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single ($\chi^2=5.323/6.293$)</th>
<th>Double ($\chi^2=5.206$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bulge-Sérsic</td>
<td>Disk-Exp</td>
</tr>
<tr>
<td>Total mag</td>
<td>12.68/13.78</td>
<td>15.77</td>
</tr>
<tr>
<td>$r_e$ (kpc)</td>
<td>9.78/2.74</td>
<td>0.91</td>
</tr>
<tr>
<td>Sérsic index</td>
<td>2.97/(1.0)</td>
<td>1.02</td>
</tr>
<tr>
<td>Axis ratio</td>
<td>0.436/0.469</td>
<td>0.351</td>
</tr>
<tr>
<td>PA (deg)</td>
<td>8.81/8.22</td>
<td>14.3</td>
</tr>
</tbody>
</table>

Note: The axis ratio is the ratio between the minor axis and the major axis. The position angle is measured relative to the north and counter-clockwise. For the single Sérsic model, the fit with the index fixed at 1.0 (for an exponential disk) is also shown. Parameters in parentheses are fixed.

The spiral pattern of the galaxy is also better shown after a smoothed component removed. Some dust features downstream of the galaxy can also be seen clearly.

We also attempted to quantify the dust extinction in the galaxy with an E(B-V) map, using the F475W and F814W data. We assume that the F475W-F814W color of the galaxy is symmetric around the nucleus, between upstream and downstream (see Figure 4.4). Since the upstream is mostly dust-free, we can use the upstream color as the color in the mirror position of the downstream without intrinsic extinction. The Voronoi binning method (Cappellari & Copin, 2003) was used to adaptively bin the F475W & F814W image with a minimum S/N of 50 with the same choice of bins. The binned data is then used to create the reddening map by applying the extinction law $A_\lambda = k_\lambda E(B-V)$ with $R_V = 4.05$ from Calzetti et al. (2000). First, we measure the magnitude $m$ on bins in each image as

$$m = -2.5 \log_{10}(f) + Z - G - \kappa - A_\lambda$$  \hspace{1cm} (4.1)
Figure 4.5: ESO 137-001 extinction images. Left: The residual F475W image of ESO 137-001, after subtracting the one-Sérsic model fit obtained with GALFIT (Table 4.4). Spiral arms, dust features downstream of the galaxy and some blue streams composed of young stars can be seen. The galactic nucleus (see Waldron et al., 2022, Section 3.3) is marked with the small green circle in both panels. The footprint of the E(B-V) image on the right is indicated by the cyan rectangle. Right: The E(B-V) map in the Voronoi binning around ESO 137-001. The E(B-V) image is derived from the F475W - F814W color image, assuming that the upstream region is dust free and an extinction law from Calzetti et al. (2000). The E(B-V) values are shown in the scale-bar beneath. Bright foreground stars were masked in dashed-line circles. The red contours show the CO emission from Jáchym et al. (2019) as shown in Figure 4.3. The E(B-V) values are indeed enhanced around the large CO clump at ∼2.3 kpc downstream of the nucleus.
where $f$ is the flux, $Z$ is the zero point, $G$ is the Milky Way extinction, $\kappa$ is the k-correction, and $A_\lambda$ is the intrinsic extinction. Letting $\mu$ be the first four terms on the right hand side of (4.1), we derive

$$E(B-V) = -\frac{(m_1 - m_2) - (\mu_1 - \mu_2)}{k_1 - k_2}$$

(4.2)

where $(m_1 - m_2)$ is the measured color in the downstream, $(\mu_1 - \mu_2)$ is the measured color in the corresponding upstream position, taken as the color without intrinsic extinction, and $(k_1 - k_2)$ is the extinction strength difference between the F475W and F814W filters. The resulting E(B-V) map is shown in Figure 4.5, which indeed shows strong extinction at the positions of dust clouds in the downstream. However, the E(B-V) values in at least some regions of the downstream can be under-estimated if there is enhanced SF in the downstream region, as implied by the enhanced F275W emission (Figure 4.4, top-left).

4.4 Young Star Clusters in the Tail

4.4.1 Regions of Interest and Source Sample

While Sun et al. (2007) defined a sample of H II regions in the ESO 137-001 tail from the SOAR narrow-band imaging data, the recent full MUSE mosaic (Sun et al., 2021, more detail in Luo et al. in preparation) provides much better data to select H II regions. We selected H II regions from the extinction-corrected MUSE Hα surface brightness map with SExtractor. Sixty-four candidates are identified by selecting for CLASS STAR > 0.8 (point-like sources) and the ellipticity ($e$) < 0.55. We relaxed the
criteria on $e$ (Fossati et al. (2016) used $e < 0.2$) as several HII regions are mixed with the stripped Hα filaments, which will enhance the ellipticity obtained by SExtractor. We further applied a limit for the integrated Hα flux of the candidates as $2.1 \times 10^{-16}$ cm$^{-2}$ erg s$^{-1}$ to avoid the selection of faint Hα clumps in the tail. In addition, the [NII]/Hα emission-line ratio was also required to be less than 0.4 to confirm the ionization characteristic of the HII candidates. We finally selected 43 HII regions in the stripped tail of ESO 137-001. As shown in Figure 4.6, 42 of them are covered by the F275W data, while the other one is just off the F275W FOV but covered by the F475W/F814W data. Sun et al. (2007) presented a sample of 29 HII regions, plus 6 more candidates. 27 of these 29 sources are also selected by MUSE. The other two are also shown as compact Hα sources in the MUSE data. They would have been selected with a lower flux limit than what was adopted. For the 6 candidates in Sun et al. (2007), 3 are MUSE HII regions. Two others are also shown as compact Hα sources but fainter than the chosen threshold. One is not confirmed with the MUSE data. This comparison shows the robustness of the HII regions selected in Sun et al. (2007). The new MUSE HII region sample also adds 13 new HII regions compared with Sun et al. (2007). These new ones are typically fainter than HII regions selected by Sun et al. (2007) and they are generally close to bright stars. The Sun et al. (2007) selection is essentially based on Hα equivalent width (EW) so these faint ones that are close to bright stars were not included in Sun et al. (2007).

With the HII regions defined from the MUSE data, we define four regions of interest (Figure 4.6) for the subsequent analysis: small red circles — MUSE HII regions defined in this work (each represented by a circle with a radius of 1.4′); the
green ellipse — the galaxy region; the large blue ellipse (but within the thick black line to show the common FOV of the F275W, F475W and F814W data) — the tail region; the area outside of the green and blue ellipses but still within the thick black line — the control region. There is common area shared by different regions so it is defined that the galaxy region is the green ellipse excluding small red circles. The tail region is the blue ellipse (but within the thick black line) excluding green ellipse and small red circles. The sky areas for each of the four regions after removal of bright stars are 0.065, 0.313, 3.123, and 2.001 arcmin$^2$ for the H II, galaxy, tail, and control regions, respectively.

For the HST photometry studies of individual sources, we define the baseline sample of sources as sources covered by the F275W, F475W, and F814W data. The baseline source selection is defined as follows. First, spurious sources from wrong alignment, scattered light from bright stars and residual CRs close to the edges were removed. This leaves 3803, 12293 and 10783 sources in F275W, F475W and F814W respectively with SExtractor. Second, only sources detected in at least two adjacent bands were kept. This includes sources detected in all three bands, sources detected in F275W and F475W, and sources detected in F475W and F814W. From this selection, 713 were detected in all three bands, 144 were detected in F275W/F475W, and 4882 were detected in F475W/F814W. After taking the union of these three sets, 5739 sources remain. Third, stars in the the GSC2 (Lasker et al., 2008) were removed. The number of sources was dropped to 5422. Fourth, sources that were brighter than 19.45 mag in F475W, 20.40 mag in F814W, and 21.1 mag in F160W were removed. The F475W magnitude cuts are one magnitude brighter than the
Figure 4.6: Regions of interest to be studied in this paper are shown here using the F475W image as a reference. The small, red circles denote the 43 H II regions identified from the full MUSE data (see Section 4.4.1). The green ellipse centered at the nucleus defined in Waldron et al. (2022, Section 3.3), angled at 9.0° from the North and with semi-axes (31.00, 13.64), defines the galaxy region. The galaxy region also excludes the six H II regions that fall in the green ellipse. We also measure the photometry of the galaxy region in 14 smaller regions in 7 radial bins, with each bin divided into the upstream and downstream portions. The largest, blue ellipse indicates the tail regions and is defined by an ellipse centered at (16:13:12.1968, -0:44:36.495) rotated to 34.7° above the RA axis with axes (137.137, 72.560). The exception to this tail region is that we exclude the upstream sources which are defined as anything to the east of the major axis of the galaxy, as well as the galaxy region and H II regions. The control region is therefore defined as the area outside the tail and galaxy regions. Note that our analysis is limited to the field covered by F275W, F475W and F814W observations together, which is marked by the solid, black line. The smaller dotted, gray line indicates the WFC3/F160W FOV. Finally, the gray contours show the Chandra X-ray emission reported in Sun et al. (2010). Only the near part of the ∼80 kpc X-ray tail is covered by HST.
Table 4.5: Baseline $HST$ sources and their properties.

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<td>1</td>
<td>16:13:20.56</td>
<td>-60:46:11.75</td>
<td>24.59 ± 0.09</td>
<td>-0.21 ± 0.23</td>
<td>-0.73 ± 0.28</td>
</tr>
<tr>
<td>2</td>
<td>16:13:24.82</td>
<td>-60:46:09.76</td>
<td>23.35 ± 0.04</td>
<td>1.02 ± 0.21</td>
<td>-0.27 ± 0.07</td>
</tr>
<tr>
<td>3</td>
<td>16:13:24.84</td>
<td>-60:46:09.00</td>
<td>23.97 ± 0.06</td>
<td>0.55 ± 0.24</td>
<td>-0.03 ± 0.10</td>
</tr>
<tr>
<td>4</td>
<td>16:13:19.77</td>
<td>-60:46:11.02</td>
<td>24.81 ± 0.11</td>
<td>0.27 ± 0.44</td>
<td>0.16 ± 0.18</td>
</tr>
<tr>
<td>5</td>
<td>16:13:24.70</td>
<td>-60:46:08.58</td>
<td>23.62 ± 0.04</td>
<td>0.99 ± 0.25</td>
<td>-0.15 ± 0.08</td>
</tr>
<tr>
<td>6</td>
<td>16:13:23.45</td>
<td>-60:46:08.83</td>
<td>25.75 ± 0.26</td>
<td>-0.18 ± 0.65</td>
<td>-0.20 ± 0.54</td>
</tr>
<tr>
<td>7</td>
<td>16:13:22.97</td>
<td>-60:46:08.63</td>
<td>24.55 ± 0.09</td>
<td>1.60 ± 0.99</td>
<td>1.46 ± 0.10</td>
</tr>
<tr>
<td>8</td>
<td>16:13:21.68</td>
<td>-60:46:08.44</td>
<td>25.48 ± 0.21</td>
<td>-0.29 ± 0.47</td>
<td>0.11 ± 0.34</td>
</tr>
<tr>
<td>9</td>
<td>16:13:24.73</td>
<td>-60:46:06.99</td>
<td>23.95 ± 0.06</td>
<td>0.52 ± 0.23</td>
<td>0.04 ± 0.10</td>
</tr>
<tr>
<td>10</td>
<td>16:13:23.57</td>
<td>-60:46:06.98</td>
<td>25.17 ± 0.15</td>
<td>-0.34 ± 0.35</td>
<td>-0.38 ± 0.35</td>
</tr>
<tr>
<td>11</td>
<td>16:13:16.44</td>
<td>-60:46:07.06</td>
<td>26.38 ± 0.45</td>
<td>-0.71 ± 0.84</td>
<td>0.69 ± 0.59</td>
</tr>
<tr>
<td>12</td>
<td>16:13:21.47</td>
<td>-60:46:06.90</td>
<td>25.99 ± 0.31</td>
<td>0.17 ± 1.02</td>
<td>-0.80 ± 1.04</td>
</tr>
<tr>
<td>13</td>
<td>16:13:24.29</td>
<td>-60:46:06.18</td>
<td>25.04 ± 0.13</td>
<td>-0.50 ± 0.28</td>
<td>-1.55 ± 0.82</td>
</tr>
<tr>
<td>14</td>
<td>16:13:23.16</td>
<td>-60:46:05.78</td>
<td>26.04 ± 0.35</td>
<td>-0.47 ± 0.71</td>
<td>1.34 ± 0.38</td>
</tr>
<tr>
<td>15</td>
<td>16:13:24.04</td>
<td>-60:46:05.01</td>
<td>24.00 ± 0.06</td>
<td>2.02 ± 0.90</td>
<td>1.99 ± 0.06</td>
</tr>
</tbody>
</table>

The brightest star cluster in ESO 137-001 and its tail while the F814W and F160W cuts were chosen based on the color-magnitude diagram discussed in Section 4.4.4. Fifth, red sources with F275W-F475W > 2.90 mag and F475W-F814W > 2.00 mag are removed (see Figure 4.9 for the corresponding ages). The above two steps decreased the source number to 908. Sixth, sources with individual mag error greater than one mag were removed, which further decreased the source number to 520. This final sample includes 127 in the H\textsuperscript{II} regions, 201 in the tail, 139 in the galaxy and 34 in the control region. The sources defined in the baseline sample are shown in Figure 4.7 which presents the sources identified in the H\textsuperscript{II} regions in red and other sources identified within the tail. We also include an abridged table of baseline sources in Table 4.5. The full table can be found online in Waldron \textit{et al.} (2022).
Figure 4.7: The H\textsc{ii} (red) and blue tail sources (blue) plotted in Figure 4.6 are shown on the \textit{MUSE} H\textalpha{} image from Sun \textit{et al.} (2021). The solid black line again indicates the field covered by F275W, F475W, and F814W, as shown in Figure 4.6. The galaxy nucleus is marked with a green circle on the left. The missing zoom-in regions from Figure 4.1 are plotted using green dashed squares.
Figure 4.8: ESO 137-001 source position KDEs. Left: The unweighted KDE of the source coordinates shown in Figure 4.7. Right: The F475W flux weighted KDE of the source coordinates shown in Figure 4.7. Both: The KDEs were estimated with a Gaussian kernel with a bandwidth (effective standard deviation) of 250 pixels. The figures show the same MUSE image and area as Figure 4.7.

Figure 4.8 shows the Gaussian kernel density estimations (KDEs) (using a 250 pixel bandwidth; effective standard deviation) of the source coordinates in Figure 4.7. Figure 4.8-left shows the unweighted KDE while Figure 4.8-right shows the F475W flux weighted KDE. The MUSE image introduced in Figure 4.7 is shown on the background as a comparison between the MUSE data and the likelihood of source positions defined here. There is no major difference between the unweighted and weighted KDEs. The H II source contours align to the Hα sources defined in Sun et al. (2007) and to the MUSE sources detailed above. The tail source contours do, in general, follow the MUSE source filaments; however, the tail source contours do show a few areas of source abundance where there is little MUSE luminosity.
4.4.2 Color - Color diagram

We present the color-color (F475W-F814W versus F275W-F475W) results of this baseline sample in Figure 4.9 to determine the characteristics of the young star complexes in and around ESO 137-001.\(^1\) The figure presents a large number of sources that meet the above criteria within the H\(_{\text{II}}\) and tail regions and, a smaller number of sources within the galaxy and control regions. However, the KDEs suggest that the galaxy has a higher number of sources per square arcminute than the tail.

Figure 4.9 also indicates that the majority of sources in the H\(_{\text{II}}\) regions tend to be bluer than those in the galaxy. While there is some overlap between the two sets, the two are distinct regions on the color-color diagram. The sources in the H\(_{\text{II}}\) and tail regions are also bluer than the sources in the control region. We also compared the KDE of the H\(_{\text{II}}\) and tail regions in Figure 4.9. The high source number density in the H\(_{\text{II}}\) regions is mainly from its small area by definition. After removing the background contribution estimated from the control region, there are only \(\sim 18\%\) more sources in the tail region than in the H\(_{\text{II}}\) regions and it is also found that sources in the H\(_{\text{II}}\) and tail regions have very similar color distributions, which suggests them both as young star complexes.

Figure 4.9 also compares the colors of the HST sources to a Starburst99 (Leitherer et al., 1999) track and a Starburst99 + Cloudy (Ferland et al., 2017) track (see detail in Section 4.4.3). We apply an intrinsic extinction of \(E(B-V) = 0.08\) to each track using the Calzetti et al. (2000) extinction law. The rationale to adopt this

\(^{1}\text{We do not include the F160W data in the analysis of tail sources for its poorer angular resolution than other HST bands and the general faintness of young star complexes at the NIR.}\)
Figure 4.9: The colors of the HST sources detected in the regions defined in Figure 4.6. Sources with a marker matching the one in the legend were detected in all three bands. Sources with a right arrow were detected in F475W and F814W but not F275W. Sources with a down arrow were detected in F275W and F475W but not in F814W. No genuine sources detected in F275W and F814W but not in F475W were identified. Only sources with a photometry error of less than 1 AB magnitude in each filter were selected for studies here. The line plots on the top and right of the figure are the Gaussian KDEs ($\sigma = 0.497$ AB mag which is median combined error of the data) of the three band detections plus the relevant axis two band detections that have been normalized by the search area of each region (see Section 4.4.1). The total number of sources for the H II, tail, galaxy, and control regions are 127, 201, 139 and 34, respectively. (Caption continued on following page.)
Figure 4.9: Continued. The F275W-F475W median errors for each region are 0.20, 0.47, 0.52, and 0.70 AB magnitudes, and the F475W-F814W median errors are 0.15, 0.26, 0.20, and 0.16 AB magnitudes, for H\(\text{II}\), tail, galaxy and control regions respectively. The median error of all sources is plotted in the bottom-right of the main figure. The text markers represent each of the seven radial upstream/downstream galaxy sub-regions defined in Figure 4.6 where the number in each annotation represents the radial bin (“1” at the nucleus) and the “u” and “d” represent the upstream and downstream regions, respectively. The Starburst99 + Cloudy track (the solid, black line) is superposed. The Starburst99 track is the Genv00 model (Ekström et al., 2012) with a Kroupa (2001) IMF and \(Z = 0.014\). The ticks on each track represent ages of 1, 3, 5, 7, 10, 30, 50, 100, 200, and 500 Myr (1 Myr with the bluest F475W - F814W color as marked and 500 Myr at the other end). The gray dashed line at ages of less than 10 Myr represents the track with the Starburst99 model only. An intrinsic extinction value of \(E(B-V) = 0.08\) (see Section 4.4.3 for detail) has been applied to the tracks according to the Calzetti et al. (2000) extinction law. The arrow on the figure shows this \(E(B-V) = 0.08\) extinction effect on the track. We also show the 20% KDE contours for sources in these three regions.

Intrinsic extinction value is discussed in detail in the next section. The figure also includes a 20% KDE contour for each data set. The contours show the \(HST\) sources are concentrated along the younger end (less than 50 Myr) of the two tracks.

4.4.3 Comparison with SSP tracks

While in principle we can use the color-color relation in combination with the simple stellar population (SSP) track to constrain the age of young star complexes, intrinsic extinction in young star complexes needs to be corrected first. We can determine the intrinsic extinction in H\(\text{II}\) regions defined from the \(MUSE\) data, with the classic Balmer decrement method (e.g., Fossati et al., 2016). As shown in Figure 4.10, the median \(A_V\) is 0.73 mag for 40 H\(\text{II}\) regions. If the six regions in the galaxy region is excluded, the median \(A_V\) is 0.67 mag. If the same extinction law as used in Poggianti et al. (2019) is instead used, the \(A_V\) decreases by \(~9\%)%. Thus, the median \(A_V\) of H\(\text{II}\)
Figure 4.10: The MUSE Hα EW and intrinsic extinction measurements for 40 H II regions. The grey points are H II regions where bright stars are detected within 1″5 or the MUSE spectrum shows strong Hβ absorption at ~ zero velocity. The MUSE spectra of these H II regions have elevated continuum from bright stars so the Hα EW is under-estimated, while the AV results are still valid. The red points are H II regions without bright stars within 1″5 and without strong Hβ absorption at ~ zero velocity in the MUSE spectrum. The black diamond shows the median values (EW=151 Å and AV=0.73 mag) for all 40 sources, while the black circle shows the median values for red points (EW=304 Å and AV=0.80 mag). If the six H II regions in the galaxy region are excluded, the median AV becomes 0.67 mag for the remaining 34 regions in the tail.

regions in ESO 137-001’s tail is comparable to the median value of 0.5 mag found in the star-forming clumps in the tails of gas stripping phenomena galaxies (Poggianti et al., 2019).

With the intrinsic extinction of these 43 H II regions constrained, we can compare their HST colors with the SSP track, which is done in Figure 4.11 as discussed in the following. For each H II region, since colors of nearby HST sources tend to be similar (see Section 4.5 and Figure 4.16), and considering MUSE’s much lower
Figure 4.11: Colors of MUSE H\textsc{ii} regions on the Starburst99 track (dashed line) and the Starburst99 + Cloudy track (solid line) with different intrinsic extinction values. In each of the three plots, the scatter points in orange represent the combined photometry for all the HST sources detected in each H\textsc{ii} region. The median, minimum and maximum errors on each of these scatter points is 0.14, 0.04, and 0.73 AB magnitude, respectively. Each plot also contains a Starburst99 track (gray, dashed line) created with the Genv00 model (Ekström et al., 2012), a Kroupa (2001) IMF and $Z = 0.014$. The ticks on each track are the same as those in Figure 4.9. Likewise, the Starburst99 + Cloudy track is presented as solid, black line. The big cross in each panel is the median uncertainty for the source colors, with different values of extinction adopted. Left: No intrinsic extinction is applied on the colors of the H\textsc{ii} regions. Middle: The intrinsic extinction, determined from the MUSE spectra of nebular emission, is applied on individual H\textsc{ii} region. Right: The same intrinsic extinction as used in the middle panel, but with a stellar-to-nebula extinction ratio of 0.44 (Calzetti, 1997), is applied on individual H\textsc{ii} regions. This choice of intrinsic extinction provides the best match between the HST colors and the model. This plot also shows that the blue star clusters detected by HST are indeed young with ages of < 10 Myr.

angular resolution than the HST images, we combine all HST sources within the aperture to derive the colors of the total light. The left panel of Figure 4.11 shows the HST colors of the H\textsc{ii} regions, without the correction for the intrinsic extinction. The comparison with the SSP tracks shows, not surprisingly, that the observed colors (especially F275W - F475W) are generally too red, as it is expected that most of these H\textsc{ii} regions are younger than $\sim$7 Myr.
It should be noted that the Starburst99 SSP models do not include nebular emission from the warm and ionized gas, which can be significant for young stellar populations (e.g., age < 10 Myr). We ran the development version of the photoionization code Cloudy, last reviewed by Ferland et al. (2017), to add nebular emission to the stellar component of the radiation field reported by Starburst99. Cloudy does a full ab initio simulation of the emitting plasma, and solves self-consistently for the thermal and ionization balance of a cloud, while transferring the radiation through the cloud to predict its emergent spectrum. We assumed a nebula of density 100 cm$^{-3}$, and metallicity of 0.7 solar, surrounding the stellar source and extending out to 1 kpc from it. For the inner radius of the cloud, we experimented with two values (1 pc and 10 pc), but found that the predicted colors do not depend on that choice. We also imposed a lower limit of 1% on the electron fraction to let the calculation extend beyond the H$\text{II}$ region, into the photo-dissociation region. The Cloudy modification is only important for star clusters younger than 10 Myr (Figure 4.11) but does help to explain the F475W - F814W color for some sources.

The middle panel of Figure 4.11 shows shows the colors of H$\text{II}$ regions, after the correction for the intrinsic extinction derived from the MUSE data. The same tracks as on the left panel, Starburst99 and Starburst99 + Cloudy, are also plotted. While this comparison does suggest these H$\text{II}$ regions are young (e.g., age < 7 Myr), the F275W - F475W colors are typically too blue.

One way to alleviate this discrepancy is to consider the extinction difference between stars and nebulae. It has been known that the measured extinction on the stellar light can be different from the measured extinction on the warm gas (e.g.
Calzetti et al., 1994; Calzetti, 1997; Koyama et al., 2019). Calzetti (1997) gave an average relation of \( E(B-V)_{\text{star}} / E(B-V)_{\text{gas}} = 0.44 \) (also see Calzetti et al., 1994, 2000). This difference may suggest the spatial decoupling of the ionized gas and the young stellar population and other geometry effects (e.g. Calzetti et al., 1994; Charlot & Fall, 2000). There have been some works to study the relation between this ratio and specific star formation rates, redshift and stellar mass (Wild et al., 2011; Wuyts et al., 2011; Price et al., 2014; Reddy et al., 2015). Most recently, Koyama et al. (2019) has shown that this ratio generally increases with increasing specific star formation rate while it decreases with increasing stellar mass, although the scatter is substantial. In this work, we simply apply the ratio of 0.44 as suggested by Calzetti (1997). With this factor included, as shown in the right panel of Figure 4.11, the match between the HST colors and the Starburst99 + Cloudy model is improved.

To summarize, we include two corrections, adding the Cloudy nebular emissions and considering the different extinction for stars and gas, to alleviate the initial discrepancy between the HST broad-band colors and the SSP tracks. Given the uncertainty on the HST colors, the intrinsic extinction on young stars, the Balmer decrement and the Starburst99 models, the colors of these HII regions are consistent with the expectation for young stellar populations at age of \(< 10\) Myr. Therefore, in this work, we simply adopt an intrinsic extinction of \( E(B-V) = 0.08 \) (derived from \( A_V=0.73 \) mag) for all the HST sources in the tail.

We also compare the age determined from the HST broad-band colors with the age determined from the Hα EW especially since the EW is not affected by the intrinsic extinction. The Starburst99 model gives the direct relation between the SSP
We also predicted the age of sources using the HST colors. The age was determined by matching the colors of sources in Figure 4.11-right to the track using the shortest euclidean distance. The age error is estimated from Monte Carlo simulations with the errors of colors considered. As shown in Figure 4.12, the consistency between two age estimates is generally good, when we only include H II regions with robust EW measurements. The best-fit relation is also close to the unity line. Thus, with all the uncertainty discussed above, we conclude that the HST broad-band colors can present good constraints of the SSP age. Although the $\chi^2$ test of the data to the unity model fails, no sources of error were identified for the difference.

### 4.4.4 Properties of the HII regions

We also analyzed the correlation between the source distance from the major axis of the galaxy and the color of that source. Figure 4.13-left shows that there is no strong evidence for the change of the F275W - F475W color with the distance to the galaxy, with the large scatter of the colors observed.

Figure 4.13-right shows the color along three different blue filaments within the tail. This approach was chosen to ensure no information was lost in the ensemble method shown in Figure 4.13-left. All light within the filament regions (less the bright foreground sources) is integrated for this second figure to see how the color changes along an individual filament. Although it is not significant, there is a slight trend from red to blue for filament 1 as the distance increases. Filament 3 has an interesting
Figure 4.12: ESO 137-001 Hα EW / broadband age comparison. Left: The Hα EW/age relationship according to the Starburst99 model used in Figure 4.11. Right: The SSP age derived from the HST broad-band colors as shown in Figure 4.9 vs. the SSP age derived from the Hα EW. Both sets of age estimates were predicted using the Starburst99 + Cloudy model. We limit the comparison to H II regions without bright stars within 1′.5. The marker styles match those from Figure 4.10. The best-fit relation is close to the unity line which suggests a general good consistency between these two age estimates, given the current uncertainty. A $\chi^2$ analysis of the data to the displayed unity model (dashed line) indicates that model must be rejected. No sources of error were identified upon checking the data, and the calculated error must increase by a factor of 16.5 in order to not reject the model. However, considering the consistency of measurements to other studies in Section 4.7.1 and that the age difference for all but two sources is less than a factor of two, we believe the analysis to be a good match overall.

discontinuity where the color goes from blue to red then to blue again as the distance increases.

We also present the Color-Magnitude diagram in Figure 4.14 which gives us a constraint on the masses of the young star clusters if the age is determined from e.g., the color-color diagram. The color-magnitude diagram suggests that the star forming regions have a mass of $10^4$-$10^5$ M$_\odot$ if younger than $\sim$100 Myr. The diagram on the left also delineates the detection threshold near the bottom, between the F475W
Figure 4.13: ESO 137-001 color-distance relationship. **Left:** The F275W - F475W color vs. distance relation for a subset of sources in the H II and tail samples established in Section 4.4.2. We restrict the sources to have an error of less than 0.4 mag here rather than 1.0 mag as in Section 4.4.2. The median colors plotted include both H II and tail sources. The x error bars indicate the bin size and the y error bars indicate the 1-σ scatter in the bin. There is no clear change on the average source color with the distance to the galaxy. **Right:** The same relation for three different filaments extending from ESO 137-001. Filament 1 corresponds to the filament with regions 25 and 26 in Figure 4.1, Filament 2 corresponds to the filament with regions 23 and 27-30 in Figure 4.1, and Filament 3 corresponds to the filament with regions 17, 18 and 21 in Figure 4.1. Although the uncertainties are still large and the intrinsic extinction is not applied, at least two filaments become bluer further away from the galaxy.

The luminosity distribution is presented in Figure 4.15. The figure shows H II and tail sources (see Section 4.4.1) that were detected in all three bands (red) and F475W/F814W detections + F275W upper limit (light red). We model the data in Figure 4.15 according to a luminosity function of \( dN/dL \sim L^{-a} \) where \( dN \) is the number counted per luminosity bin \( dL \), \( L \) is the luminosity and \( a \) is the power law.
Figure 4.14: The color-magnitude diagram for the sources in the H II and tail regions, with the absolute magnitude also shown on the right side. The same tracks as in Figures 4.9 and 4.11 are also shown (for a total mass of $10^4 \, M_{\odot}$). The markers on tracks are also the same (note star clusters become dimmer as they get older so small ages start from the top). From these tracks, the mass of these young star clusters is $10^4 - 10^5 \, M_{\odot}$ if younger than $\sim 100$ Myr.

We can relate the distribution in Figure 4.15 to the luminosity function when we consider

$$\frac{dN}{dL} \sim L^{-a}$$

(4.3)

where $N$ is the number of sources with luminosity $L$. We can then relate the luminosity to the absolute magnitude $M$ as

$$L \sim 10^{-M/2.5}$$

(4.4)
which gives
\[ dM \sim \frac{dL}{L}. \]  
(4.5)

We can rearrange (4.3) as
\[ dN \sim L^{-a} dL. \]  
(4.6)

Now, dividing (4.6) by (4.5), we get the relation
\[ \frac{dN}{dM} \sim L^{1-a} \sim 10^{(a-1)M/2.5}. \]  
(4.7)

The three band detections (for sources brighter than -9.5 mag) correspond to \( a = 2.0 \pm 0.1 \) while the addition of upper band detections correspond to \( a = 2.3 \pm 0.1 \).

4.4.5 Relationship with the Chandra X-ray sources

Sun et al. (2010) discovered some X-ray point sources around ESO 137-001’s tail with the Chandra data. Some of them were suspected to be associated with star forming regions in the tail. We zoom in around some Chandra sources close to blue star clusters in Figure 4.1. Particularly, sources C6, C8, C9, C10, C11 and C12 are close to young star clusters. All of them are downstream and still close to the galaxy. If associated with ESO 137-001, they would be ultraluminous X-ray sources (ULXs). The offset between the X-ray source and the young star clusters observed here, typically within several hundred pc, is also normal for ULXs (e.g., Poutanen et al., 2013).
Figure 4.15: The luminosity distribution for sources detected in the H\textsc{ii} and tail regions defined in Section 4.4.1 with the exception that a F275W - F475W color cutoff of 2.5 is chosen. The control sample has been subtracted from each distribution. The darker distribution represents the sources detected in three bands whereas the lighter distribution include F275W upper limits. Note that the upper limit distribution has been offset for display only.

4.5 Clump Colors

We measured the colors of individual sources found in the clumps defined in Figure 4.1. The results are found in Figure 4.16. The majority of sources shown lie within the H\textsc{ii} regions defined by Sun \textit{et al.} (2007) and in this work. As is shown in the figure, many of the sources in each of the respective clumps do have similar color within uncertainty regardless of their source category (i.e., H\textsc{ii}, tail, or galaxy) although there are a few exceptions. The red tail source in Region 2 is due to the red
Figure 4.16: The colors of individual sources in the clumps defined in Figure 4.1. Regions selected for CO emission but without any detected HST blue sources are not included here. One can see sources in proximity to each other typically have similar colors.

(likely background) source in the NW part of the cutout just west of the westernmost H II region which was just under the color cutoffs defined in Section 4.4.1. The strong F814W tail source in Region 4 is the source that appears pink just SW from the center of the cutout. The high variance of galaxy sources in Region 13 is likely due to the dust gradient in that clump.
4.6 Quantitatively Selected Source Analysis

We also performed analysis on a subset of sources that were chosen quantitatively rather than by region to better determine if H II sources are distinct from non-H II sources. We initially follow the same process as detailed in Section 4.4.1 with a few small adjustments. First, spurious sources from wrong alignment and residual CRs close the edge were removed leaving 3803, 12293 and 10783 sources in F275W, F475W and F814W respectively with SExtractor. Second, only sources detected in at least two adjacent bands were kept. This includes sources detected in all three bands, sources detected in F275W and F475W, and sources detected in F475W and F814W. From this selection, 713 were detected in all three bands, 144 were detected in F275W/F475W, and 4882 were detected in F475W/F814W. After taking the union of these three sets, 5739 sources remain. Third, stars in the GSC2 catalog (Lasker et al., 2008) were removed. The number of sources was dropped to 5422. Fourth, sources with high error were removed dropping the number of sources to 1040. Fifth, we imposed a color cut of 1.25 AB mag in both the F275W-F475W and F475W-F814W colors dropping the number of sources to 450. Finally, for comparison, we divide the sources into those that lie in the H II regions from Section 4.4.1 and those that do not. This final sample includes 126 H II sources and 324 non-H II sources the coordinates of which can be found in Figure 4.17. The sky areas for the H II and non-H II regions are 0.065 and 6.222 arcmin², respectively.

We present the color-color (F475W-F814W versus F275W-F475W) results of this quantitatively selected sample in Figure 4.18 to determine the degree of intermix-
**Figure 4.17:** The H\ II (red; see Figure 4.6) and blue non-H\II sources (cyan) are shown on the *MUSE* H\alpha image from Sun *et al.* (2021). The solid black line again indicates the field covered by F275W, F475W, and F814W, as shown in Figure 4.6. The galaxy nucleus is marked with a green circle on the left.
ing between the H II and non-H II star forming regions in and around ESO 137-001. The figure presents a large number of sources that meet the above criteria.

We also present the Color-Magnitude diagram in Figure 4.19. The diagram on the left also delineates the detection threshold near the bottom, between the F475W magnitude and the F275W-F475W color. The displayed track is the same as the ones used in Figures 4.9 and 4.14.

Comparing the H II and non-H II sources in Figure 4.18 shows that the two displayed colors (F475W-F814W and F275W-F475W) do not make for good indicators between the H II and non-H II sources due to the high degree of intermixing between the sources. Interestingly, there are a higher number of bright (Abs F475W mag < -11) H II sources than non-H II sources, and there are a higher number of dim (Abs F475W mag > -8.5) non-H II sources than H II sources. However, this is also a poor classification feature between the H II and non-H II sources considering the high degree of intermixing between the two classes in intermediate F475W magnitudes.

Upon deeper analysis of MUSE data, some of the identified sources are aligned to faint H II regions not reported in Sun et al. (2007). The other sources may be young star clusters or unrelated objects altogether.

4.7 Discussion

4.7.1 Star formation in the tail

Star formation in the tail can be constrained from the Hα data. As discussed in Section 4.4.1, we defined 43 H II regions in the tail region, including 37 beyond the
Figure 4.18: The colors of the quantitatively selected HST sources shown in Figure 4.17. Sources with a marker matching the one in the legend were detected in all three bands. Sources with a right arrow were detected in F475W and F814W but not F275W. Sources with a down arrow were detected in F275W and F475W but not in F814W. No genuine sources detected in F275W and F814W but not in F475W were identified. Only sources with a photometry error of less than 1 AB magnitude in each filter were selected for studies here. The line plots on the top and right of the figure are the Gaussian KDEs ($\sigma = 0.462$ AB mag which is median combined error of the data) of the three band detections plus the relevant axis two band detections that have been normalized by the search area of each region (see Section 4.4.1). The total number of sources are 126 and 324 for H II and non-H II, respectively. The Starburst99 + Cloudy track (solid black line) from Figure 4.9 is also shown for reference.
Figure 4.19: The color-magnitude diagrams for the quantitatively selected HST sources shown in Figure 4.17, with the absolute magnitude also shown on the right side. The same tracks as in Figure 4.9 are also shown (for a total mass of $10^4 \, M_\odot$). The markers on tracks are also the same (note star clusters become dimmer as they get older so small ages start from the top).

galaxy region. The total H\(\alpha\) flux of each region, within a circular aperture with a radius of 1.4", is measured, after correcting for both the Galactic extinction and the intrinsic extinction. The total H\(\alpha\) luminosity for 43 H\(\text{II}\) regions is $8.1 \times 10^{40}$ erg s\(^{-1}\). Excluding the six in the galaxy region, the total H\(\alpha\) luminosity is $4.0 \times 10^{40}$ erg s\(^{-1}\). With the H\(\alpha\) — SFR relation from Hao et al. (2011) assuming a Kroupa IMF, the corresponding SFR is 0.45 and 0.22 M\(_\odot\)/yr, respectively. These SFR values are similar to the estimate from Sun et al. (2007) (0.59 M\(_\odot\)/yr) for 29 H\(\text{II}\) regions assuming a Salpeter IMF and $A_V = 1$ mag.
Star formation in the tail can also be constrained from the \textit{HST} broad-band photometry data as discussed in Section 4.4. We used the Starburst99 + Cloudy model in Figure 4.9 to estimate the ages and masses of star clusters. The age was estimated by comparing the F275W-F475W and F475W-F814W colors to the track in Figure 4.9, taking the value at the closest distance from the track. This process was performed with a Monte Carlo simulation using 50,000 samples where the F275W, F475W, and F814W magnitudes were assumed to be normally distributed using the measured magnitude as the mean and the measured uncertainty as the standard deviation. Again, the assumed intrinsic extinction is $E(B-V) = 0.08$ as discussed before. Once an age is determined, we estimate the mass of the source by matching the F475W magnitude to the corresponding track in the color - magnitude relation in Figure 4.14. Once the age and mass are known, we can estimate the SFR. We simply estimate the SFR of each source by dividing the mass by the age and sum up the individual SFR values for all sources to get the total SFR in each Monte Carlo iteration. If only sources younger than 10 Myr are counted, the median SFR is $0.199 \, \text{M}_\odot/\text{yr}$ and $0.083 \, \text{M}_\odot/\text{yr}$ for the H\textsc{ii} and tail sources, respectively. If instead all sources younger than 100 Myr are included, the SFR is $0.210 \, \text{M}_\odot/\text{yr}$ and $0.117 \, \text{M}_\odot/\text{yr}$ for the H\textsc{ii} and tail sources, respectively. The Monte Carlo uncertainty on these values is 0.7% and 6.4% for the H\textsc{ii} and tail sources, respectively, according to the median absolute deviation (MAD). While this estimate of the SFR for H\textsc{ii} regions is only about half the estimate from the H\textalpha data, it is emphasized that we assumed $E(B-V)_{\text{star}} / E(B-V)_{\text{gas}} = 0.44$ here. If no such a correction is applied (or assuming a ratio of 1), the median SFR is $0.463 \, \text{M}_\odot/\text{yr}$ and $0.153 \, \text{M}_\odot/\text{yr}$ for the H\textsc{ii} and tail sources.
respectively, for an age upper cut of 10 Myr; or 0.468 M⊙/yr and 0.188 M⊙/yr for the H II and tail sources respectively, for an age upper cut of 100 Myr. The Monte Carlo uncertainty on these values is 0.8% and 15.7% for the H II and tail sources, respectively, according to the MAD. Given all the uncertainties, we conclude that both the estimate with the Hα luminosity and the estimate with the HST broad-band photometry give the total SFR in the H II regions of \( \sim 0.2-0.45 \, M_\odot/yr \) and the blue star clusters identified by the HST data add additional \( \sim 40\% \) of SF activity. While the contribution of the background sources in the H II regions is small (Figures 4.9 and 4.14), such a contribution in the tail region is estimated to be \( \sim 1/4 \) from KDEs in Figure 4.14. Thus, the total SFR in the whole tail region is \( \sim 0.3-0.6 \, M_\odot/yr \), which is \( \sim 40\% \) of SFR of the galaxy.

The total SFR in Figure 4.20 was fit to the source distance \( (d) \) (dark-gray dotted line in bottom panel) according to

\[
SFR = a \exp (-d/\delta). \tag{4.8}
\]

The resulting fit gives \( a = 0.53 \, M_\odot \, \text{yr}^{-1} \) and \( \delta = 6.7 \, \text{kpc} \), which again shows the SFR in the tail decreases fast with the distance to the galaxy. Cramer et al. (2019) noted this trend in D100. This trend is also noted for some other galaxies in RPS (e.g., George et al., 2018; Poggianti et al., 2019; Boselli et al., 2022).

With \( E(B-V)_{\text{star}} / E(B-V)_{\text{gas}} = 0.44 \), the total stellar mass in the tail is \( \sim 2.7 \times 10^6 \, M_\odot \). With the above ratio equal to 1, the total stellar mass remains about the same, \( \sim 2.9 \times 10^6 \, M_\odot \). Figure 4.20 shows the Monte Carlo median mass,
Figure 4.20: The mass, age, and SFR for sources younger than 100 Myr as estimated with the Starburst99 + Cloudy model. For the age distribution, the median values (filled markers for three-band detections and empty markers for two-band detections) and 1σ scatter are also shown. The histograms in the top and bottom panels represent the median summed masses and SFRs of both regions within the respective distance bin, with the uncertainty also shown. The scatter points with error bars in the middle panel show the median age of the sources with the MAD as the error bars. The dashed histograms and filled green scatter points are for the same quantities but for the 3 band detections only. The dotted line in the bottom panel shows an exponential fit of the total SFR to the source distance (see Section 4.7.1).
age, and SFR for sources less than 100 Myr old as a function of distance from the galactic major axis for the three band and two band young star clusters identified in Section 4.4.1. Likewise, the graphic shows the median summed masses, median ages, and median summed SFRs for four distance bins. The individual sources do not show any significant trend regarding how these properties change with distance. However, the summed and median statistics do show that the total mass and the total SFR decrease with distance from the galaxy while the median age of the sources increases with distance from the galaxy but with large scatter. However, any age trend is limited by our sensitivity to old (> 100 Myr) sources as discussed later in this section.

About 95% of SF in the tail is within 20 kpc from the galaxy. The SF beyond 20 kpc is still observed but very weak.

Figure 4.20 shows that sources older than 40 Myr are mostly close to the galaxy (within 13 kpc). There is a lack of old sources beyond 15 kpc from the galaxy. There are several factors that can contribute to this result. First, assuming a galaxy total mass of $5 \times 10^{10} M_\odot$, the free fall time from 30 kpc to the galactic plane is $\sim 350$ Myr. Considering, the actual fall-back time to any height above the galactic plane would be some fraction of this value, it is conceivable that some old sources that are close to the galaxy (< 10 kpc) formed further away from the galaxy, but have had sufficient time to fall back toward the galaxy. Second, the intrinsic extinction may be underestimated for some old sources that are close to the galaxy, which would result in over-estimate of their ages. Third, the faint, old (or red) sources have a larger contamination from background sources (see the KDEs in Figure 4.9).
Figure 4.21: The mass and SFR with the source age for sources younger than 100 Myr as estimated with the Starburst99 + Cloudy model. The marker and histogram styles are the same as in Figure 4.20. The empirical mass limit that can be reached with our data is shown as the dotted line in the top plot.

Figure 4.21 shows the estimated mass and SFR as a function of the source age (for sources younger than 100 Myr) for the three band and two band young star complexes identified in Section 4.4.1. Likewise, the graphic shows the summed median masses and SFRs for four age bins. On the face value, Figure 4.21 suggests that most SF in the tail happened within the recent 3-10 Myr. However, as sources become fainter when they age, it is clear that the current data present a lower mass detection
limit increasing fast with the source age (also evident in Figure 4.21). We then derived the empirical mass limit in Figure 4.21 to better understand this limitation. The displayed limit is calculated by requiring the error of the F275W - F475W color less than 1 and also assuming the Starburst99 + Cloudy track in Figure 4.9 and the median extinction reported in Figure 4.10. As shown in Figure 4.21, the displayed limit does well to predict the limiting mass at each age helping explain why we do not measure high age / low mass sources. A few sources do exist below this empirical limit, however they tend to be sources detected in two bands (and are therefore likely to not be detected in F275W at all). We fit the mass limit for ages greater than 3 Myr according to a power law with an index of 1.3.

Even with this limitation, if we assume the observed mass function is the same in each age bin, we can correct for this incompleteness. With the mass function determined in the 3-10 Myr bin, it is estimated that the total mass is increased by a factor of 1.6 in the 30-100 Myr age bin and 3.4 in the 30-100 Myr age bin, respectively. For simplicity, we conclude that the SFR for each bin should increase accordingly. As for Figure 4.20, we estimate that this correction roughly translates to a mass and SFR normalization increase by a factor of ~2, which also applies to Equation 4.8. With this correction, we also estimate the new total stellar mass to be $\sim 5.0 \times 10^6 M_{\odot}$ and the total SFR in the tail increases by $\sim 15\%$. This correction factor may be overestimated, however, considering the observed mass function would likely shift toward the higher masses as the age increases. Even with these correction factors, the conclusions from Figure 4.21 are not changed with most SF happened in the last 3-10 Myr, although
the bulk of the stellar mass in the tail likely comes from stellar populations older than 10 Myr with this correction.

Figure 4.21 also reveals a population of young (< 10 Myr) tail sources that are not associated with an H II region. The total mass of these sources sums to $3 \times 10^5 M_\odot$. However, some of these sources are near H II regions (see Figure 4.7) although they are not in the H II regions of interest detailed in Section 4.4.1. We therefore measure the mass of these tail sources that are within 0.7 kpc of H II regions to be $1.5 \times 10^5 M_\odot$. For the remaining sources, they are typically within 1.2 kpc of the selected H II regions, especially for bright or massive sources.

We also present the SFR spatial distribution in Figure 4.22. The figure highlights a few pockets of higher SF (primarily close to the galaxy center) while the majority of sources only make a small contribution to the total SF. Although not shown in Figure 4.22, the mass distribution is nearly identical to the displayed SFR distribution.

Figure 4.22 also marks the three zones in the tail defined by the Hα data from MUSE, north, central and south zones (more detail in Luo et al. 2022). Figure 4.23 shows the same analysis as Figure 4.20 but for these three tail zones. This further analysis was motivated by the different morphology in each of the three zones. In the north zone, stripping is in an advanced stage as the galaxy region is nearly cleared. H II regions are detected to the largest distance to the galaxy in this zone. In the south zone, stripping may be in a little less advanced stage than in the north zone, as the south side of the galaxy is more on the leading size to the ICM wind while the north side of the galaxy is more on the trailing side. The majority of H II regions
Figure 4.22: The SFR distribution in the tail of ESO 137-001 plotted on the MUSE Hα image. The green contours are generated using a spatial KDE using the SFR of each source as the sample weight. The figure highlights a few pockets of high SF (primarily close to the galaxy center) while the majority of sources only make a small contribution to the total SF. The solid, black lines show the F275W FOV, and the dark-gray dotted lines show the division of the north, central, and southern tail zones from top to bottom. The galaxy region defined in Figure 4.6 is shown as the black ellipse.
**Figure 4.23:** The mass, age, and SFR for sources younger than 100 Myr as estimated with the Starburst99 + Cloudy model and divided by the tail zones shown in Figure 4.22. The plot format is identical to Figure 4.20 with the exception of the division by tail zone.
in the southern zone are within \( \sim 10 \text{kpc} \) of the galaxy major axis. The remaining sources in this zone tend to have the same mass distribution as the rest of the zone but tend to have a higher age distribution. For the central zone, stripping is still ongoing around the nuclear region from the X-ray, H\( \alpha \) and CO data. All H\( \text{II} \) regions are within \( \sim 15 \text{kpc} \) of the major axis. There is a lower density of non-H\( \text{II} \) sources within this zone that tend to have the same age as the rest of the sources in this zone, though they do tend to be low-mass. In the end, the results in these separated zones are similar to those in Figure 4.20.

### 4.7.2 Stripping history of ESO 137-001

What is the geometry of stripping in ESO 137-001? The \textit{HST} data give the distribution of dust that can constrain the geometry of stripping. Four special examples of a disk galaxy undergoing RPS and the expected signature of dust distribution are shown in Figure 4.24. ESO 137-002 is close to case iv (Laudari \textit{et al.}, 2022) and NGC 4921 is close to case ii (Kenney \textit{et al.}, 2015). ESO 137-001 has an inclination of \( \sim 66^\circ \) so it is viewed closer to edge-on than face-on. The eastern side of the galaxy is the leading side to ram pressure and is also the near side to us as discussed. If ESO 137-001 is moving on the plane of sky, the ICM wind angle with the disk plane is \( \sim 66^\circ \). As ESO 137-001 has a small velocity component towards us (relative to the cluster system velocity), the ICM wind angle with the disk plane is less than \( \sim 66^\circ \). Based on the tail direction, Jáchym \textit{et al.} (2019) estimated an ICM wind angle of \( \sim 47^\circ \), which makes stripping in ESO 137-001 about the midway between edge-on and face-on.
What do the HST data inform us on the stripping history of ESO 137-001?

As discussed in Section 4.3, dust is detected around the nucleus and the downstream region immediately behind the nuclear region. RPS started from outside of the galaxy and has now progressed into the central region of the galaxy. SF is still ongoing around the nucleus and the downstream region behind the nucleus, as there is still abundant cold molecular gas around the nucleus (Figure 4.3). On the other hand, an ideal outside-in model of stripping is too simple. One has to consider the actual
distribution of the multi-phase ISM that is often porous so stripping can happen at multiple radii at the same time. The presence of a galactic bar may also cause a relative deficit of gas at intermediate radii. As shown in Figure 4.4, the colors along the major axis of the galaxy are mostly constant, while an ideal outside-in stripping and quenching may produce a continuous color gradient, as observed in D100 (Cramer et al., 2019). More detailed analysis on the stripping/quenching in ESO 137-001 is required in the future with the optical spectroscopic data from e.g., MUSE.

A detailed inventory study of the ISM in ESO 137-001 was done by Jáchym et al. (2014). About 80%-90% of the original ISM in ESO 137-001 has been removed from the galaxy, presumably by RPS. At least half of the removed ISM is accounted for in the tail, mostly in the molecular gas. While more data are required to better constrain the mass the multi-phase gas in ESO 137-001’s tail (e.g., H\textsc{i} and improved H\textalpha estimates from the MUSE data), the biggest uncertainty seems to be on the diffuse cold molecular gas as the ALMA 12m + ACA data on CO(2-1) still miss $\sim$70% of CO flux from the single-dish data by APEX (Jáchym et al., 2019).
CHAPTER 5

OTHER RESULTS

Everything has beauty,
but not everyone sees it.

—Confucius

The methods introduced in Chapters 3 and 4 are not only applicable to ESO 137-001. Rather, these methods can be generalized to HST data of any other galaxy. Laudari et al. (2022) and Laudari (2022) demonstrate some of the same methods on ESO 137-002 and IC 3418. Likewise, we show the applications of these methods on other galaxies.

5.1 NGC 5044

NGC 5044 (Figure 5.1-left) is a low-redshift ($z = 0.00928$, 31.2 Mpc; Tonry et al., 2001) E0 galaxy. NGC 5044 is the central and brightest member of a galaxy group by the same name (Mendel et al., 2008; Spavone et al., 2017) with an estimated stellar mass of $5.7 \times 10^{11} \, M_\odot$ (Spavone et al., 2017). Colbert et al. (2001) report dust features near the center of NGC 5044 which can be seen to the NW and SE of Figure 5.1-right. NGC 5044 and its galaxy group exist in a complex, multiphase X-ray environment with cool gas cavities embedded in the hot surrounding gas (Buote
Figure 5.1: Images of NGC 5044. Left: NGC 5044 in the WFC3 F665N (H\(\alpha\)) band. The reduced image was created with eight flat-field images. The cutout shows the inner 39\farcs6 of the galaxy. Right: The inner 10\farcs8 of the galaxy with a different image scale to highlight the dust features near the nucleus. The top of each image points to the NW.

et al., 2003; Gastaldello et al., 2009; Schellenberger et al., 2020). Lakhchaura et al. (2018) also report the NGC 5044 has cool gas H\(\alpha\)+[N II] emission luminosity of 6.0 \times 10^{40} \text{erg s}^{-1}. The methods detailed in Chapter 3 were used to reduce the \textit{HST} H\(\alpha\) image of NGC 5044 shown in Figure 5.1. These studies of the \textit{HST} \(h\alpha\) data trace the warm, ionized gas (\(T \sim 10^4\) K) which is correlated against studies of the hot gas (\(T \sim 10^7\) K) and helps us understand the connections to active galactic nucleus (AGN) feedback.
Table 5.1: HST D100 Observations (PI: Puzia & Sun)

<table>
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<tr>
<th>Filter</th>
<th># Exp</th>
<th>Total Exp ( \text{sec} )</th>
<th>Pivot ( \lambda / \text{Width} ) ( \text{Å} )</th>
<th>AB Zpt ( \text{mag} )</th>
<th>Extinction ( \text{mag} )</th>
<th>( \sqrt{F_A} )</th>
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<td>4747/1458</td>
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<td>0.4800</td>
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<td>8046/2511</td>
<td>25.94</td>
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5.2 D100

5.2.1 D100 Introduction

D100 (Dressler, 1980, also called GMP 2910, MRK 0060 NED01) is a spiral galaxy in the Coma cluster (Abell 1656) and is located at \( z = 0.01784 \) (\( \sim 83.5 \) Mpc; Yagi et al., 2007). The galaxy is approximately 240 kpc from the center of Coma cluster and has a 60 \( \times \) 1.5 kpc wide H\( \alpha \) tail (Cramer et al., 2019) believed to be caused by RPS (Jáchym et al., 2017). The H\( \alpha \) tail is shown with the galaxy in Figure 5.2.

5.2.2 D100 Observations

The data for this work was collected using WFC3/UVIS and ACS/WFC on HST in ACCUM mode from proposals 14182 (PI: Thomas Puzia) and 14361 (PI: Ming Sun). The detail of the observations and a few photometric parameters are summarized in Table 5.1.

5.2.3 D100 Results

We worked with Cramer et al. (2019) to refine the process detailed in Chapter 3 by studying in detail 9 regions in the tail of D100. Specifically, we assisted their work...
Figure 5.2: The composite image of D100 presented by Cramer et al. (2019). The false-color image is created with HST F814W as the red channel, F475W as the blue channel, and F475W/F814W average as the green channel. The bright red overlay shows the Hα tail as imaged with the Subaru Suprime-Cam (Yagi et al., 2007). Image Credit: NASA, ESA, Hubble, Subaru Telescope, STScI, Cramer et al., Yagi et al..

by following the process of comparing the photometry of these sources in the flat field, HST pipeline, and manually reduced images detailed in Section 3.2. The initial results of that work are displayed in the color-color diagram in Figure 5.3. The photometry was measured with elliptical apertures (using PhotUtils; Bradley et al., 2022) assumed to be large enough to encircle all the energy for each source. The subtracted background was modeled using a 2D SExtractor (Bertin & Arnouts, 1996) in Photutils using a 3σ clipping function, a 75 × 75 pixel window, and a 3 × 3 median
Figure 5.3: The color-color diagram of the initial results for D100. The track represents a Starburst99 (Leitherer et al., 1999) with a Padova AGB ($Z = 0.02$; Vázquez & Leitherer, 2005) model using a Kroupa IMF (Kroupa, 2001) and is scaled for a cluster mass of $10^3 M_\odot$. The markers on the track represent ages of 3, 5, 7, 10, 30, 50, 100, 200, and 500 Myr. The arrow in the top-right corner shows the effect of an arbitrary extinction on the track.

The displayed evolutionary track represents a Starburst99 (Leitherer et al., 1999) run with a Padova AGB ($Z = 0.02$; Vázquez & Leitherer, 2005) model using a Kroupa IMF (Kroupa, 2001). These results were further improved for a wider, systematic selection of sources in Cramer et al. (2019, see Figures 15 and 16) using SExtractor.
Table 5.2: HST M87 Observations (PI: Renzini & Shara)

<table>
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<tr>
<th>Filter</th>
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<th>Total Exp</th>
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<th>AB Zpt</th>
<th>Extinction</th>
<th>ApCor</th>
<th>√F_a</th>
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<td>179</td>
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<td>24.17</td>
<td>0.126</td>
<td>0.121</td>
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<tr>
<td>F606W</td>
<td>106</td>
<td>37948</td>
<td>5889/2189</td>
<td>26.10</td>
<td>0.057</td>
<td>0.080</td>
<td>0.5625</td>
</tr>
</tbody>
</table>

* For 0.55 apertures.

5.3 M87

5.3.1 M87 Introduction

M87 (Figure 5.4) is a nearby elliptical galaxy (∼16.8 Mpc/z = 0.004283; Blakeslee et al., 2009; Bird et al., 2010; Cappellari et al., 2011; Cantiello et al., 2018; Event Horizon Telescope Collaboration et al., 2019b) within the Virgo cluster with an AGN that emits as a strong radio jet (Curtis, 1918; Bolton et al., 1949; Owen et al., 2000) which measures ∼80 kpc across (de Gasperin et al., 2012). M87 has also been studied extensively in other bands. M87 is one of the most massive galaxies in the nearby universe. Murphy et al. (2011) estimate the mass of M87 to be $M = 5.7^{+1.3}_{-0.9} \times 10^{12} M_\odot$ within a radius of 47 kpc. M87 has recently gained popularity due to the study and imaging of its super massive black hole – $M = (6.5\pm0.7) \times 10^9 M_\odot$ – at its center (Event Horizon Telescope Collaboration et al., 2019a,b).

5.3.2 M87 Observations

The data for this work was collected using WFC3/UVIS on HST in ACCUM mode, from proposals 12989 (PI: Alvio Renzini) and 14618 (PI: Micheal Shara). The detail of the observations and a few photometric parameters are summarized in Table 5.2.
Figure 5.4: M87 false color image with F606W image as R and G channels and F275W as B channel.
5.3.3 M87 Results

Figure 5.4 shows the brilliance of deep *HST* imaging and highlights the data reduction techniques detailed in Chapter 3. For the *HST* photometry studies of individual sources, we define the baseline sample of sources as sources covered by the F275W and F606W data. The baseline source selection is defined as follows. Sources are detected using SExtractor with the setup detailed in Chapter 3 with the exception that $4\sigma$ and $10\sigma$ detection thresholds are used for F275W and F475W, respectively. With this criteria, 839 sources are detected in F275W and 2722 are detected in F606W. From this selection, 179 were detected in F275W alone, 2026 were detected in F606W alone, and 660 were detected in both F275W and F606W (leaving 2901 unique sources). Next, sources with magnitude error greater than 1 mag were removed dropping the number of sources to 1834.

We present the color-magnitude diagram of these M87 sources in Figure 5.5. The displayed evolutionary track represents a Starburst99 (Leitherer et al., 1999) run with a Padova AGB ($Z = 0.02$; Vázquez & Leitherer, 2005) model using a Kroupa IMF (Kroupa, 2001) and is scaled for a cluster mass of $10^3 M_\odot$. The plot shows two distinct detection thresholds for those detected in F275W versus those detected in F606W. The figure also suggests a unique set of sources whose F275W - F606W color is greater than $\sim2.5$ mag that appear to background sources. More analysis in these and at least one more *HST* is needed to further constrain the SF properties for sources in M87.
Figure 5.5: The color-magnitude diagram of the sources measured in M87 using the F275W and F606W images. Blue circles indicate sources detected in F275W, red squares indicate sources detected in F606W, and the green diamonds represent sources detected in both F275W and F606W. All detected sources with magnitude error less than 1 mag are presented. Those sources with F275W - F606W color greater than $\sim 2.5$ mag primarily appear to be background sources. The track represents a Starburst99 (Leitherer et al., 1999) with a Padova AGB ($Z = 0.02$; Vázquez & Leitherer, 2005) model using a Kroupa IMF (Kroupa, 2001) and is scaled for a cluster mass of $10^3 M_\odot$. The markers on the track represent ages of 3, 5, 7, 10, 30, 50, 100, 200, and 500 Myr. The arrow in the top-left corner shows the effect of an arbitrary extinction on the track.
Now, this is not the end.
It is not even the beginning of the end.
But it is, perhaps, the end of the beginning.

—Winston Churchill

6.1 Pipeline Conclusions

We present the value and utility of an optimized data pipeline for studying the broadband photometric properties of RPS galaxies. We demonstrate the use of this on ESO 137-001, NGC 5044, D100, and M87. Additionally, Laudari et al. (2022) utilized many of the techniques presented here in their work in ESO 137-002. The main results of this pipeline are as follows.

1. The pipeline is useful for combining data multiple from multiple visits from HST. This pipeline does an exceptional job of removing CRs in data-starved scenarios.

2. The pipeline preserves photometric features of detected sources.
6.2 ESO 137-001 Conclusions

We present a detailed analysis of ESO 137-001, an archetypal RPS galaxy, with the HST ACS and WFC3 data in four filters (F275W, F475W, F814W and F160W).

1. The galaxy has clear, asymmetric light and dust distribution indicative of ongoing RPS (Figures 4.1, 4.3 and 4.4). The eastern side of the galaxy is the near side to us, also the leading side to ram pressure. The stripping is about the midway between edge-on and face-on stripping. The light profile effectively shows that SF has been quenched in the upstream regions and the current SF is mainly around the nucleus and downstream regions. The dust images show stripping near the nucleus of the galaxy where the dust has been pushed to the downstream side of the galaxy. We derived the E(B-V) map (Figure 4.5) that shows the strong dust extinction downstream. There is also an enhanced dust feature at ∼2.3 kpc downstream, corresponding to a large CO clump. We suggest it is around the “deadwater” region. Stripping happens outside-in generally and has progressed into the inner ∼1.5 kpc radius of the nucleus, and as detailed in Waldron et al. (2022), there is no evidence for an AGN in ESO 137-001 from the HST and X-ray data.

2. HST data reveal active SF in the downstream gas stripped (Figures 4.1, 4.7 and 4.9). We derived the color-color (F275W - F475W vs. F475W - F814W) diagram for sources identified in different regions of interest, including the galaxy, H II, the tail and the control regions (Figure 4.6). The galaxy, tail and H II
regions all show significant excess of blue sources compared with the control region. We conclude these blue sources are young star complexes formed in the stripped ISM and HST can pick up faint young star complexes no longer hosting bright H II regions.

3. H II regions in the stripped gas are well correlated with young, blue star clusters but not with CO clumps. As shown in Figure 4.1, the correlation between the HST blue star clusters and the H II regions is very good, with all MUSE H II regions having at least one HST blue star cluster within 0.2 kpc. Other HST blue sources typically have faint Hα clumps associated. On the other hand, only about a quarter of H II regions have associated CO clumps within 0.3 kpc, while half of H II regions do not have nearby CO clumps detected at all. Some CO clumps are also not associated with any activity of SF. We conclude that the parent molecular clouds get disrupted quickly after the initial SF. Some molecular clouds are not forming stars at the moment. The comparison between the HST and the Chandra images also suggests up to six ULXs in the tail region.

4. Ages derived for the Hα EW are consistent with those derived from the HST broadband colors (Figures 4.11 and 4.12). We applied a SSP model with Starburst99 on these blue star clusters. For those associated with H II regions with the MUSE data, we can compare the age derived from the SSP model (or with broadband colors) with the age derived from the Hα EW. While the initial analysis shows a significant discrepancy between two estimates, we conclude that these two estimates can be brought back into agreement if a) allowing
different extinction between the nebular and stellar components for young star complexes around H II regions (particularly we adopted E(B-V)$_{\text{star}}$ / E(B-V)$_{\text{gas}}$ = 0.44 from previous studies); and b) nebular emission is included in the SSP tracks for ages of less than 20 Myr.

5. The SFR in the tail can be quantitatively constrained from the HST broad band colors, with a consistent result as that from the H II regions selected from MUSE, especially if different extinction levels are allowed for gas and young stars in H II regions (Figures 4.20 and 4.21). We showed that the average mass of the sources detected have a mass of 10$^3$-10$^4$ M$_{\odot}$ and that the ages of most sources is younger than approximately 100 Myr. We measure the total SFR of the H II regions to be 0.2-0.45 M$_{\odot}$/yr and other blue sources in the tail region add about 30% more SFR, all for sources younger than 100 Myr. The total SFR in the tail is substantial, about 40% in the galaxy. We measure the total stellar mass in the tail to be $\sim 2.7 \times 10^6$ M$_{\odot}$. The H II and tail regions combined have a luminosity function ($dN/dL \sim L^{-a}$) for $a \approx 2.1$ (Figure 4.15). We also showed the HST data have limited sensitivity on the star clusters older than 10 Myr (Figure 4.21) and attempted to correct for this incompleteness for the above results.

6. We also examined the F275W - F475W color of selected sources in the H II and tail regions as a function of distance from the galaxy (Figure 4.13) but no trend is found. The trend is also not clear for color changes along blue streams. While naively it is conceivable that the gas furthest from the galaxy was pushed
out before the gas near the galaxy, the ages of young star complexes does not indicate this trend. Possible explanations include the distribution of the delay time between stripping and SF, different SF history for different star clusters.

The *HST* data are not deep, especially for F275W. Therefore, future broadband optical work on the tail of ESO 137-001 will benefit from the *JWST* and the *Nancy Grace Roman Space Telescope*. These instruments will have better resolution and sensitivity which means we can better constrain the values presented here.

### 6.3 Other Conclusions

Beyond the analysis performed with the ESO 137-001 data, we also used the methodology detailed in Chapter 3 to study three addition galaxies. The work on these additional galaxies helped us generalize our pipeline and laid the foundation for other and future work on the galaxies.

### 6.4 Future Work

The work that is presented in this thesis can benefit from additional work. Proposed further work is detailed below.

1. This work only worked to prepare images for NGC 5044 and M87, and did a preliminary photometric analysis on M87. The field would benefit from a broadband photometric study of each of these additional galaxies.

2. As stated previously in Section 6.2, future broadband optical work on the tail of ESO 137-001 will benefit from the *JWST* and the *Nancy Grace Roman Space Telescope*. 
Telescope. These instruments will have better resolution and sensitivity which means we can better constrain the values presented here.

3. As astronomers seek to better understand galaxy evolution in the galaxy cluster environment, this work would benefit from further generalization of the image reduction and photometric pipelines in order to integrate them into an automated machine learning pipeline to search for and analyze additional RPS galaxies. This could be done in conjunction with a similar pipeline to scrape the ALMA, MUSE, and Chandra archives to add data from other bands.
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APPENDICES
Here I show that the Root-Sum-Squared (RSS) is a valid calculation for the propagation of errors for logarithmic units such as magnitude measurements.

From statistics, we know that the error propagation for a random variable can be calculated by

$$\sigma^2_X = \sigma^2_u \left( \frac{\partial F}{\partial u} \right)^2 \bigg|_{\mu_u} + \sigma^2_v \left( \frac{\partial F}{\partial v} \right)^2 \bigg|_{\mu_v} + 2\sigma^2_{uv} \frac{\partial F}{\partial u} \bigg|_{\mu_u} \frac{\partial F}{\partial v} \bigg|_{\mu_v}. \quad (A.1)$$

The problem at hand is to calculate the error $\sigma_m$ for a difference in magnitudes where,

$$m = m_1 - m_2 = -2.5 \log_{10}(f_1) + 2.5 \log_{10}(f_2) = -2.5 \log_{10} \left( \frac{f_1}{f_2} \right). \quad (A.2)$$
Using (A.1), we can directly calculate the error propagation on the third term of (A.2) when we assume $\sigma_{f_1 f_2}^2 = 0$.

$$\sigma_m^2 = \sigma_{f_1}^2 \left( \frac{\partial m}{\partial f_1} \right)^2_{f_{1}^{\mu_{f_1}}} + \sigma_{f_2}^2 \left( \frac{\partial m}{\partial f_2} \right)^2_{f_{2}^{\mu_{f_2}}} = \sigma_{f_1}^2 \left( -\frac{\beta}{f_1} \right)^2 + \sigma_{f_2}^2 \left( -\frac{\beta}{f_2} \right)^2 = \beta^2 \left( \frac{\sigma_{f_1}^2}{f_1^2} + \frac{\sigma_{f_2}^2}{f_2^2} \right)$$ (A.3)

where

$$\beta = \frac{2.5}{\ln(10)}.$$ (A.4)

Indeed, if we consider the individual magnitude errors on the fluxes $\sigma_{m_1} = \beta \sigma_{f_1} f_1$ and $\sigma_{m_2} = \beta \sigma_{f_2} f_2$ we arrive at the same conclusion from evaluating the error propagation on the second term of (A.2). The error on this value is then

$$\sigma_m^2 = \sigma_{m_1}^2 + \sigma_{m_2}^2 = \left( \beta \sigma_{f_1} f_1 \right)^2 + \left( \beta \sigma_{f_2} f_2 \right)^2 = \beta^2 \left( \frac{\sigma_{f_1}^2}{f_1^2} + \frac{\sigma_{f_2}^2}{f_2^2} \right).$$ (A.5)

Finally, we calculate the error from the right hand side of (A.2). The error on this quantity is

$$\sigma_m = \beta \frac{\sigma_x}{x} = \beta \sqrt{\frac{\sigma_{f_1}^2}{f_1^2} + \frac{\sigma_{f_2}^2}{f_2^2}}$$ (A.6)

where $x = f_1 / f_2$. 

117
Therefore, we conveniently see that calculating the error directly is equivalent to calculating the error from the derived quantities.
APPENDIX B

SIMPLE STELLAR POPULATION MODELS

Due to the distance to ESO 137-001, we have to model the observations as SSPs which represents star forming clusters. Checking our results against well established models allows us to ensure the validity of our results as well as tying the results back to physical quantities such as age and mass. We primarily modeled against Starburst99 (Leitherer \textit{et al.}, 1999) which provided a good baseline comparison. We also compared Starburst99 to GALEV (Kotulla \textit{et al.}, 2009) and BPASS (Eldridge & Stanway, 2016) which allowed further validation of our results. Figure B.1 shows the comparison between the three models. As is visible in the figure, the three models correspond well with one another with the exception of the early BPASS track therefore our choice of model does not greatly impact our results. Each one of these tracks was created with a metallicity of $Z = 0.008$ and the Kroupa (2001) IMF.
Figure B.1: Comparison of tracks between Starburst99, GALEV, and BPASS. The markers on each track appear at 3, 10, 30, 100, 300 and 1000 Myr.