

Examining the Internal Kinematics of Interacting Dwarf-Dwarf Galaxy Pairs with SDSS-MaNGA

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Personal Section

My interest in scientific research first developed towards the end of my junior year of high school. After taking AP Physics C that year and developing a passion for physics, I decided to contact two professors in the Department of Physics & Astronomy at Texas Christian University through the Research Apprentice Program about conducting research in their labs. Ultimately, I was unable to contain my childhood curiosity for the cosmos, and I decided to work in the lab of Professor Kat Barger, whose research in observational astronomy focuses on understanding galaxy evolution using spectroscopy.

Before I could start conducting any meaningful research I had a lot to learn. In addition to learning basics of astronomy and spectroscopy, I had to learn computer programming — as all my work would be conducted digitally and remotely. I learned my way around UNIX terminals and had to teach myself the programming language Interactive Data Language (IDL), a language primarily used by astronomers. After picking up the basics, I was given a choice of projects by Dr. Barger, and I opted to study interacting galaxy systems using spatially resolved spectroscopic data from SDSS-MaNGA (Mapping of Nearby Galaxies at Apache Point Observatory) because it gave me the opportunity to take a significant role in an open-ended research project in which I could grapple with important questions about our universe. The acquisition of skills did not stop there. In addition to continually improving my proficiency in IDL, along the way I had to teach myself the basics of vector calculus and to execute queries in SQL as they were necessary to the understanding and execution of the project.

The most important skill which I had to develop was the ability to read and comprehend scientific literature. Upon beginning my project, I quickly realized that in order to provide some new insight into galaxy interactions, I needed to understand what scientists knew about interacting galaxies, what pending questions scientists have about these galaxies, and how I would be able to use integral field data from MaNGA to contribute to these questions. To do this, I would need to consult journals to learn what was happening at the cutting edge of the field. Reading professional scientific journal articles is a daunting task for anyone, particularly a rising senior in high school. They are written by professional scientists with an intended audience of other scientists who have doctorates in similar fields; accordingly they are packed with high-level scientific and mathematical jargon and make plenty of assumptions about the requisite background knowledge of the reader. At first it was very difficult, and I could barely understand

what I was reading. Fortunately, with some helpful guidance from Dr. Barger, I began to realize what I needed to look for and focus on in my reading and began to make progress. After spending a few weeks scouring through the Harvard-Smithsonian Astrophysics Data System and Cornell University's arXiv, openly accessible and comprehensive repositories of scientific articles, which provided an invaluable resource to me, I was able to formulate a plan to compare the motions of the gas and stars within interacting dwarf galaxies. Then the real work began. After countless hours spent selecting a sample of galaxies and writing thousands of lines of code to analyze them, I finally had results.

I submitted my results to the Regeneron Science Talent Search in which I was named a Scholar. I am continuing my research at TCU as part of a larger group effort to analyze other factors such as star formation rates and histories, ionization conditions, and metallicities in these interactions to determine their role in galaxy evolution. We hope to publish our results with data from the most recent MPL-7 Data Release.

The experience of conducting research was enlightening and stimulating and I would encourage any high schooler interested in science to seek it out. It was able to clarify for me how pursuing scientific research is a fundamentally creative pursuit, and I am now excited to pursue a career in some form of basic or applied research,

Finally, I would like to thank Professor Barger, Hannah Richstein, and Jing Sun, as well as my junior year science teachers Mr. Shaen McKnight and Mr. John Cordell for their assistance and support in my scientific endeavors.

Research Section

1 Introduction

Mergers and interactions between neighboring galaxies are a crucial driver behind the processes of galaxy evolution. While they have been extensively observed between more massive galaxies, there have been relatively few efforts to study this phenomenon among dwarf galaxies ($10^7 < M < 5 \times 10^9 M_{\odot}$: galaxies with mass between 10^5 and 5×10^7 times the mass of the sun) Given that low-mass galaxies constitute the majority of galaxies in the universe (Binggeli et al. 1988; Karachentsev et al. 2013), one would expect that most mergers occur between dwarf galaxies. Furthermore, the standard Λ CDM model of cosmology predicts that dwarf galaxy mergers are responsible for the hierarchical formation of larger galaxies, that the large galaxies which we observe in the modern universe are the result of the repeated merging of smaller galaxies earlier in the universe (e.g. Kauffman and White 1993; Anatoly et al. 1999). However, we know little about these occurrences. Because dwarf galaxies are fainter and harder to observe; few studies have been dedicated to their interactions. Stierwalt et al. (2015) conducted the first large-scale observational study of these events as part of the TiNy Titans project. Using spectroscopically resolved observations which only probed the central regions of the galaxies with the Sloan Digital Sky Survey (SDSS), they examined 104 dwarf galaxy pairs and found evidence of enhanced star formation and a significantly larger fraction of starbursts — galaxies with exceptionally high amounts of star formation — than present in a sample of isolated dwarf galaxies. Furthermore, Stierwalt et al. (2017) observed several groups of dwarf galaxies and found direct evidence of hierarchical formation.

A recently emerging and novel method of the observation of galaxies is through Integral Field Unit (IFU) Spectroscopy. Spectroscopy — in contrast to photometry which measures the total brightness or flux of light — allows us to see the amount of light observed at each discrete wavelength within the observed range. Accordingly, since many physical processes are associated with the absorption or emission of light at specific wavelengths, we are able to measure these processes in distant objects through spectroscopy. Historically, spectroscopic galaxy surveys have only taken one single observation from the galaxies' center. IFU surveys take resolved observations throughout the entire galaxy, allowing for the observation of properties in pixels across the area of the galaxy. However, IFU surveys have been historically

biased towards larger galaxies. MaNGA (Mapping of Nearby Galaxies at Apache Point Observatory), a program in the fourth-generation SDSS, provides a unique and unprecedented opportunity for spatially resolved spectroscopy. With an ultimate goal of 10,000 observed galaxies, MaNGA allows for statistically significant IFU studies of less common events in galaxy evolution such as galaxy mergers. Furthermore, since MaNGA aims to study and observe an even distribution of galaxies by mass, the study of dwarf galaxy mergers with IFU spectroscopy is now possible (Bundy et al. 2015; Drory et al. 2015).

In this work, I seek to apply some of the unique forms of analysis permitted by IFU spectroscopy to the phenomena of dwarf interactions. One such innovation which IFU spectroscopy allows for is the examination of 2-dimensional resolved velocity dispersions, maps which display the movements of discrete stellars and gaseous elements within the galaxy. By modeling these velocity fields and extracting the rotation curves using N-Body simulations, Kronberger et al. (2006) have concluded that galaxy mergers and fly-bys will significantly disturb these rotation fields, leading to asymmetries and distortions. In addition, Barrera-Ballesteros et al. (2015) — by observing the stellar and $H\alpha+[NII]$ velocity lines of a large sample of interacting and isolated galaxies from CALIFA, an IFU survey which focused on larger disk galaxies — found evidence of an increased proportion of kinematic decoupling among the interacting galaxies such that the stellar and ionized gas in the galaxies displayed significant differences in their mean rotation by calculating position angles for the galaxies. In this work I search for similar occurrences in dwarf galaxies.

In this paper, I present the first spatially-resolved kinematic analysis specific to dwarf-dwarf galaxy mergers using IFU Spectroscopy. I examine the velocity dispersions and the kinematic decoupling between ionized gas as traced through $H\alpha$ emissions and stars present in pilot samples of isolated and interacting dwarf galaxies using MaNGA data to determine if the kinematic motions of stars and gas diverge as a result of tidal interactions.

2 Observations and Sample

2.1 Observations

MaNGA observations are taken with the SDSS 2.5 m telescope (Gunn et al. 2006) at a spatial resolution of nearly $2''$ (about 1-2 kpc). MaNGA began taking data on 2014 July 1 and will continue to collect observations through 2020. Two dual-channel Baryon Oscillation

Spectroscopic Survey (BOSS) spectrographs, which are used for the MaNGA survey, provide a wavelength coverage in the optical range at about 3,600-10,300 Å (Smee et al. 2013). Data is collected over three dithered fifteen minute exposures. MaNGA targets are selected independently of color, environment, and morphology — allowing for a sample which is representative of the nearby galaxy population. The targets are selected on the basis of finding a sweet spot between several parameters: sample size, spatial coverage, maximized signal to noise ratio, and spatial resolution. In addition the survey seeks to provide a flat distribution of stellar masses between 10^9 and $10^{11} M_{\odot}$, with a total stellar mass range spanning 5×10^8 to $3 \times 10^{11} M_{\odot}$ (Wake et al 2017). In this paper I use data from SDSS Data Release 14 (known internally as MPL-5), which contains all publicly available data cubes reduced and observed by July 2016 for 2,812 MaNGA galaxies of the planned 10,000 (Blanton et al. 2017).

Information about neighbor galaxies comes from the spectroscopic catalogs of SDSS Data Release 14, which only contain long-slit spectroscopy from the center of the galaxies (Blanton et al. 2017; York et al. 2000). Stellar masses for all galaxies in the samples are derived from SDSS photometry by fitting stellar evolution models in accordance with the methods described in Maraston et al. (2009). Morphological data is taken from the Galaxy Zoo project, which provides crowd-sourced morphological classifications of nearly a million SDSS galaxies (Lintott et al. 2008; Lintott et al. 2011).

2.2 Reductions and Pipeline

All data is processed from observations through the standard pipeline as described extensively in Law et al. (2015). The data reduction software automatically runs for all data in the collaboration on a supercomputing cluster at the University of Utah. This reduction includes sky subtraction, flux calibration, and binning of the dataset to combine individual dithered observations. The reduced dataset is further put through a data analysis pipeline to create data analysis products by fitting the stellar continuum, and stellar absorption-lines are fit with a population synthesis model, and gas emission-lines are fit using a one component Gaussian function. In this paper, I use the data analysis products, which contains information on the stellar and gas kinematics, among other properties. Additionally, I use data binned with the Voronoi binning algorithm (Cappellari et al. 2003). This algorithm corrects for discrepancies in Signal/Noise (S/N) ratio in the 2D velocity dispersions by creating bins with a minimum S/N ratio of approximately 10 and allows for a more precise study of the faint galaxies in the sample.

2.3 Sample

My goal is to select a pilot sample of both interacting and isolated dwarf galaxies, on which I can conduct an analysis of the internal kinematics. I will then compare the two in an effort to determine the effects of interactions with neighbors.

2.3.1 Dwarf Pairs Sample

I define the mass range of dwarf galaxies consistent with the TiNy Titans project ($10^7 < M < 5 \times 10^9 M_{\odot}$). As they showed that interacting galaxies in this mass range have elevated star formation compared to isolated ones when their companion was within a distance of 100 kpc — I select this as the maximum distance cutoff to constitute a pair between two dwarf galaxies. I also choose a maximum difference in line of sight velocity in accordance with TiNy Titans at less than 300 km/s (Stierwalt et al. 2015). In addition, to minimize the environmental effects of additional galaxies, I only examine binary galaxy pairs, defined as having a projected separation of at least 500 kpc to the nearest third galaxy.

I found 30 MaNGA galaxies which met these objective criteria observed and reduced before June 2016 (Blanton et al. 2017). Afterwards I cut down the sample by employing several soft criteria: 1) the galaxy should be sufficiently face-on as to allow for the detailed observation of 2D velocity dispersions; 2) the galaxy should have sufficient signal to noise ratio to either have a large enough percentage of the galaxy with $S/N > 5$ or to contain a sufficient number of bins as to not bias the fitting of position angles; 3) the galaxy should be a rotating system - as observed either morphologically using photometry and Galaxy Zoo observations or by the examination of spectroscopic velocity dispersions; within this criteria, in order to maintain a representative sample not biased by morphological cuts, I include early-type and irregular galaxies which exhibited rotation in 2D dispersion maps; 4) the galaxy and its neighbor should be reasonably close in stellar mass ratio; approximately within a magnitude of 10 of each other; 5) the galaxy should exhibit some $H\alpha$ emissions — typically an indicator of star formation — to allow for the examination of $H\alpha$ velocity dispersions. From those 30, I find 9 galaxies which met these criteria. The sample contains 4 starburst galaxies (defined as having an $H\alpha$ spectrum width of greater than 50 \AA) and 1 pair of galaxies, (MaNGA IDs 1-351790 and 1-351792) for which both components are being observed by MaNGA. Masses of the sample are represented in Figure 1.

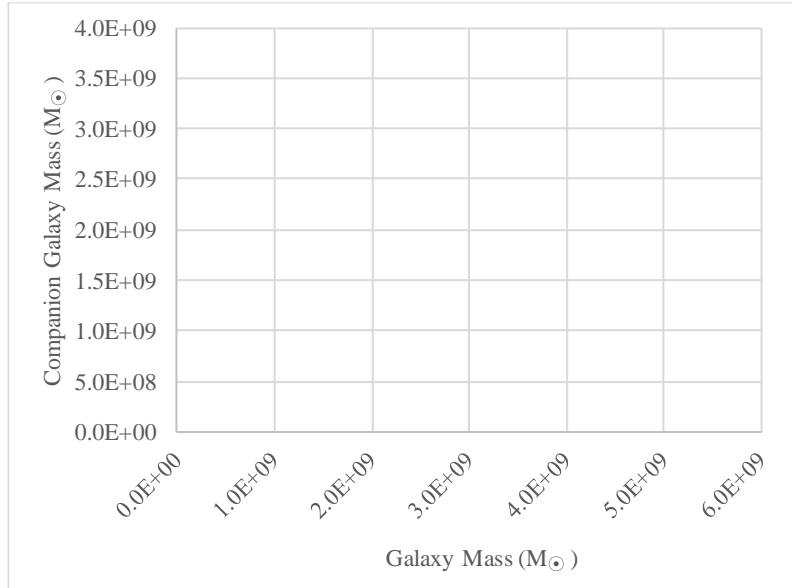


Figure 1: Masses of the interacting sample plotted against their companions. Point size represents the projected separation between the galaxies.

2.3.2 Isolated Sample

As a control, I select a sample of isolated galaxies - chosen within the same stellar mass range as the interacting galaxies - with projected separation of at least 1 mpc from its nearest neighbor and line of sight velocity difference of at least 1000 km/s. In addition, for the aforementioned reasons, I apply the same set of soft criteria as I do in the interacting sample to ensure that: 1) the data is suitable for analysis of position angles, and 2) the sample is representative and similar to the interacting sample to provide a suitable basis of comparison between the two. The sample contains 15 interacting galaxies, 2 of which are starbursts. Masses range from $6.31 \times 10^8 M_{\odot}$ to $2.95 \times 10^9 M_{\odot}$.

3 Methodology

3.1 Kinematic Position Angles

Several different methods have been derived to quantify a galaxy's general kinematics using 2D velocity dispersions. These models often make several assumptions about a galaxy's behavior. For example these models may assume that the galaxy follows a thin disk geometry (Barnes & Sellwood 2003; Epinat et al. 2008) or assume symmetrical radial distortions (Spekkens & Sellwood 2007). Others assume that the velocity fields will naturally follow a cosine law in their odd moments (Krajnovic et al 2006). However, as I aim to examine dispersions which may be significantly perturbed and distorted by tidal interactions and examine rotation on both sides of the galaxy to ascertain more localized disturbances, I choose a method

which makes no assumptions about the galactic behavior and is derived directly from the kinematic data. The methodology I employ creates position angles for the galaxy and is largely based on the methods of Barrera-Ballesteros et al. (2014).

The position angle provides the average orientation of the analyzed velocity fields. I collect three different position angles each for both the stars and the ionized gas defined from north to east: 1) PA_Approaching, the mean alignment of the side of the galaxy with a positive line of sight velocity ranging from 0° - 360° ; 2) PA_Receding, the mean alignment of the side of the galaxy with a negative line of sight velocity ranging from 0° - 360° ; and 3) PA_Global, an aggregate measure of both sides of the galaxy in 180° space. I then calculate the difference between these measurements in stars and gas. Examples are shown in Figure 2.

3.1.1 Kinematic Center

In order to determine the alignment of a galaxy, it is first necessary to determine its center. In an ideal rotating disk, the center of rotation should coincide with the center of the galaxy. Ideally, the center would have zero rotational velocity and would accordingly be the location of the largest velocity gradient in the galaxy. The kinematic center of the galaxy should correspond to the peak of the directional derivative of velocity (Kutdemir et al. 2008; Arribas et al. 1997). I estimate this peak based on the procedures outlined in Garcia-Lorenzo et al. (2015) and Barrera-Ballesteros et al. (2014) by estimating the absolute value of the velocity gradient for each spaxel on the galaxy with respect to the surrounding spaxels. I subsequently select an area of 5×5 arc seconds around the optical nucleus — the point which appears to be the center of the galaxy photometrically — and calculate the average position of the spaxels weighted by gradient. I also allowed for the option to default to the center of the IFU bundle when there appears to be no significant gradient peak. However, while Garcia-Lorenzo et al. (2015) concluded that this methodology resulted in much clearer images of rotation I found that I defaulted to the center of the IFU bundle the majority of the time — since the sample is filled with faint, small, and morphologically irregular galaxies, which made determining an accurate gradient peak far more difficult — and for the times in which I used the gradient peak, the difference was not very significant between the peak and the optical center of the IFU bundle.

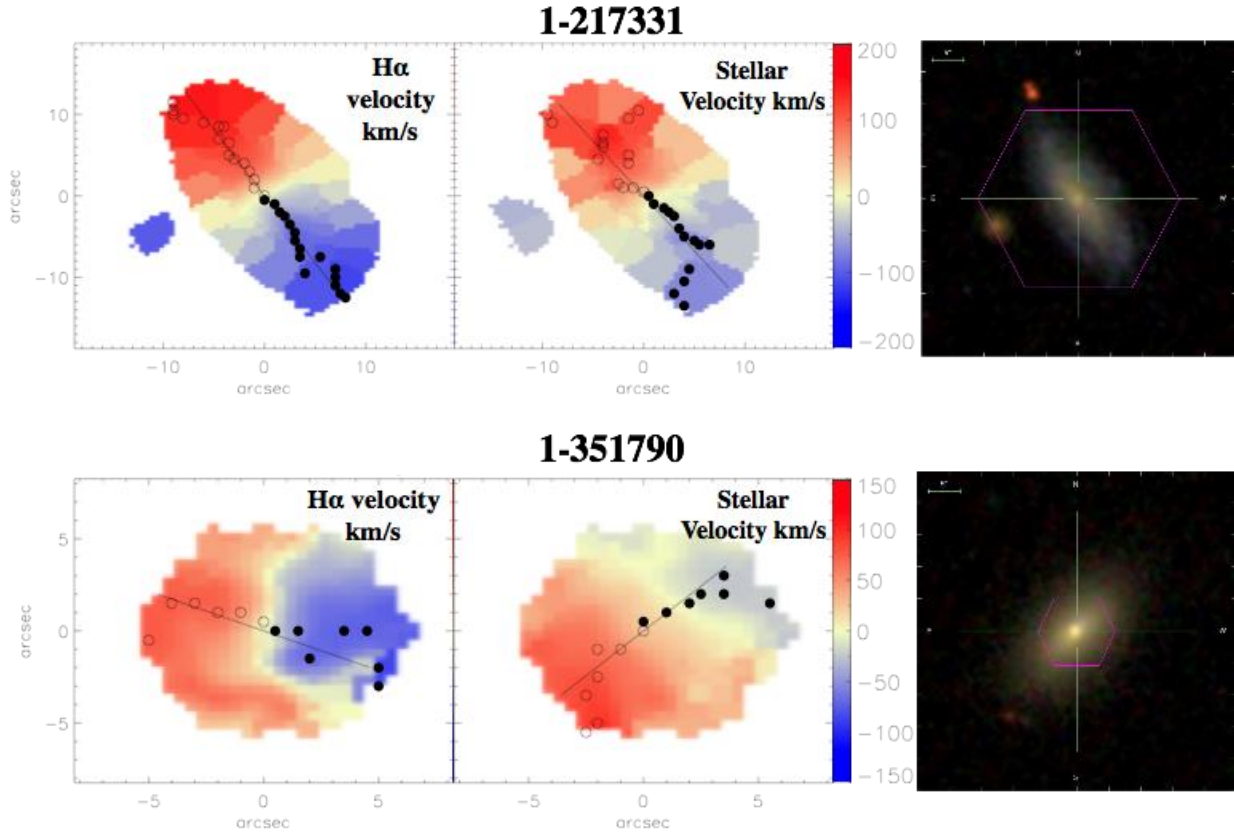


Figure 2: 2D velocity dispersion maps and SDSS photometry for the isolated galaxy 1-217331 and the misaligned interacting galaxy 1-351790. The filled circles represent the points used to calculate $\Delta PA_{\text{Receding}}$ and the open circles $\Delta PA_{\text{Approaching}}$. Overlaid on the diagrams are the global position angles.

3.1.2 Calculating the Position Angles

Once the kinematic center is derived, a polar coordinate system is imposed with the origin at the kinematic center. Afterwards every spaxel on the galaxy is sorted into radial bins with a range of 1 arc second each. Within each radial bin, the spaxels, in which the maximum and minimum line-of-sight velocity are found, are selected to trace the most strongly rotating portion of the galaxy. Excessive outliers — which most likely occur due to faint data with low S/N ratio and bin resolution at the edges of the galaxies — are removed manually, if they have not already been culled in the binning or data reduction pipeline. I then average the polar coordinates of the minimums and the maximums respectively. These averages respectively represent the position angles for the approaching and receding sides of the galaxy. The approaching side has motions moving toward the observing and the receding side away from the observer with respect to the systemic velocity of the galaxy. In addition, afterwards, I shift the position angle of the far side

of the galaxy by 180 degrees and average the two together to determine a global position angle for the galaxy in 180 degree space. This procedure is repeated for both stars and the H α ionized gas to calculate three differences: $\Delta\text{PA}_{\text{Approaching}}$, the difference between the two receding sides of the galaxy; $\Delta\text{PA}_{\text{Receding}}$, the difference between the approaching sides, and $\Delta\text{PA}_{\text{Global}}$, the difference between the combined global position angles.

4 Discussion and Results

Here I report the results and seek to contextualize them with other works, which have had some overlap in their scientific objectives.

4.1 General Trends

In the interacting sample, the mean difference between the ionized gas and stars on the approaching side of the MaNGA galaxies is 44.8° degrees. On the approaching side the mean difference is 34.4° degrees, while the mean $\Delta\text{PA}_{\text{Global}}$ is 27.4° degrees. Using the definition of misalignment of Jin et al. (2016), who defined it as $\Delta\text{PA} > 30^\circ$, I find 5/9 galaxies with local misalignments on the approaching side, 3/9 with misalignments on the receding sides, and 4/9 with global misalignments. 6/9 galaxies possess a misalignment on either side. I observe that in general, all the galaxies exhibit dispersions consistent with normal rotation in the H α ionized gas. The misalignments are represented in Figure 3.

The isolated sample has fewer misalignments. The mean differences are 11.7° on the approaching side, 12.9° on the receding side, and 9.2° degrees globally. Applying the threshold of $\Delta\text{PA} > 30^\circ$, I find 1/15 misalignments on the approaching side, 2/15 on the receding side, and one global misalignment. 2/15 galaxies possess a misalignment on either side.

4.2 Starburst Galaxies

One prevalent feature in the sample of interacting galaxies is the presence of starbursts, with 4/9 interacting galaxies being classified as such. Observationally, two of these galaxies (MaNGA IDs 1-351792 and 1-147496, (see Figure 4) exhibit a significant departure from normal rotation in their stellar dispersions — while remaining fairly normal in the ionized gas — such that the position angle is ineffective as a measurement of the global orientation of the galaxy. Increased excitation in the stellar population would be logical in the starbursts, but, due to the potentially confounding environmental factors and the small sample size of 6 total starbursts between both samples, it is impossible to conclude the causes of this phenomenon.

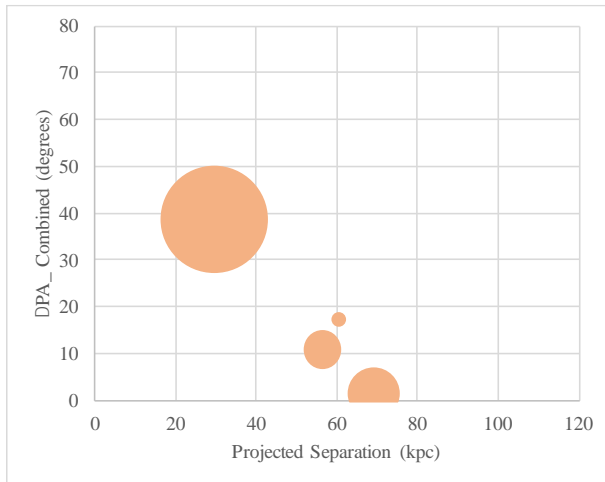
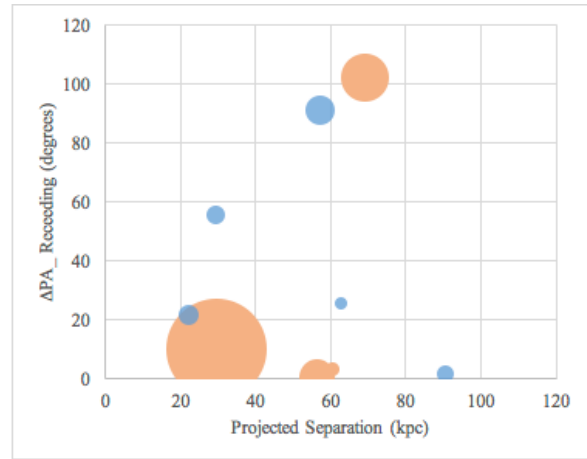
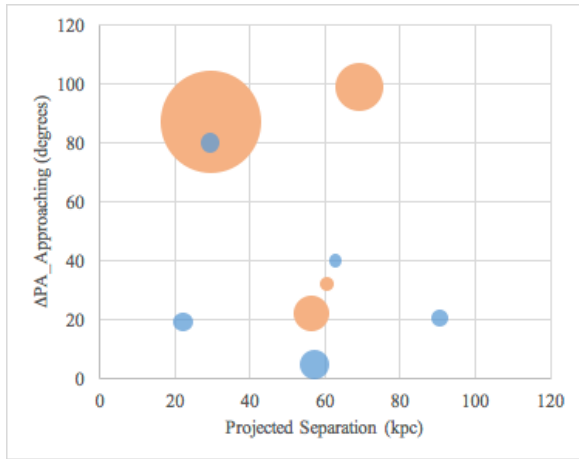


Figure 3: The three ΔPA values as a function of projected separation in the interacting sample. The orange circles represent starburst galaxies. The dot size represents the mass ratio of the companion galaxy to the MaNGA galaxy.

The isolated sample also contained 2 starburst galaxies. However, while one does possess a global misalignment significant enough to pass the threshold of $\Delta PA > 30^\circ$, neither possesses a velocity signature like 1-351792 and 1-147496, which have no global rotational velocity field detected in the stellar population.

Although my sample size is quite small, my sample is consistent with the findings of Stierwalt et al. (2015). In a much larger sample of dwarf-dwarf mergers, they found that starbursts occur in 20% of paired dwarfs - while only occurring in 6-8% of isolated dwarf galaxies. In my sample, they occurred in 44% of the interacting galaxies and 13% of the control sample. It is important to note that my sample was selected with no bias towards starbursts.

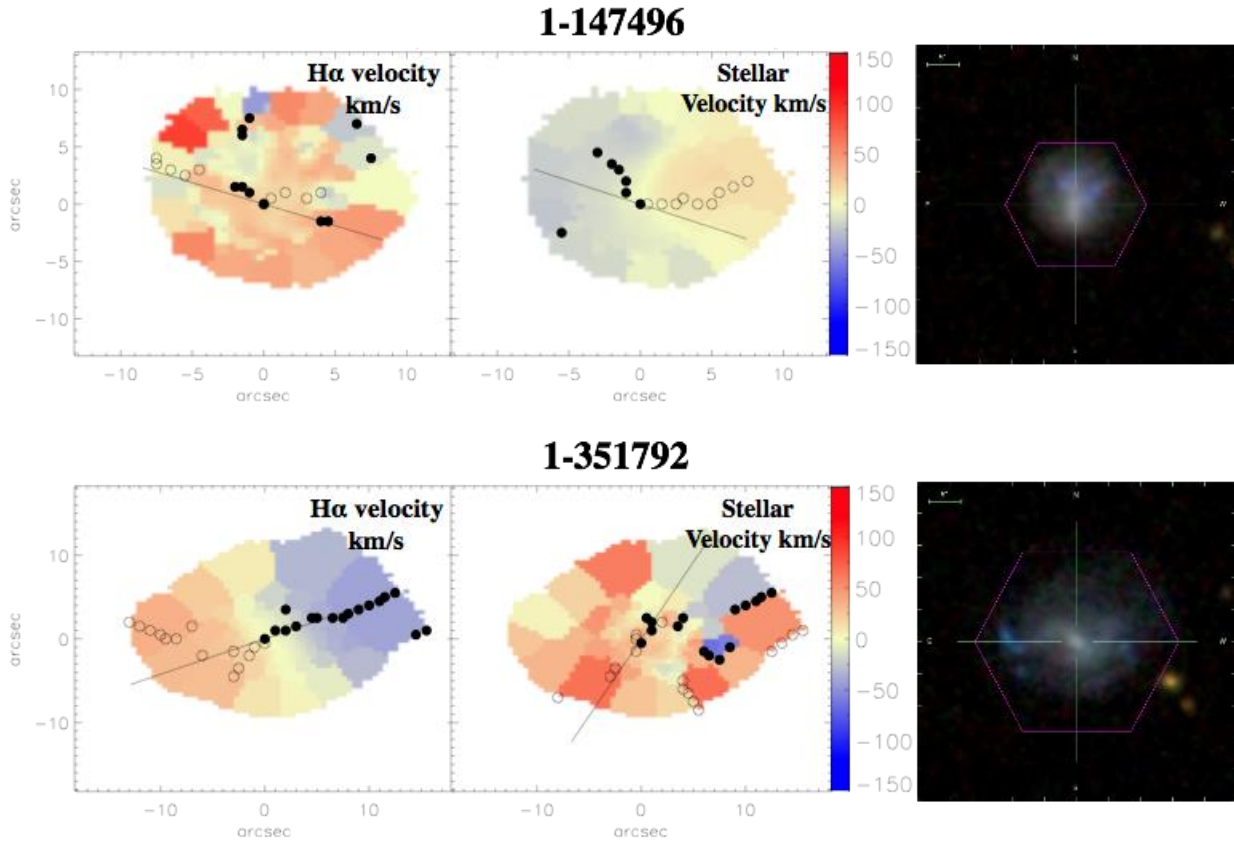


Figure 4: 2D dispersions, photometry, and global position angles for galaxies 1-147496 and 1-351792

It is necessary to control the measurements of positional angles for the whole sample to account for the fact that starbursts may be responsible for some of the misalignments - and that several of the position angles are rendered in such a way that no rotation is evident in the stellar velocity dispersions. While examining only galaxies not classified as starburst, in the interacting sample I find a mean $\Delta PA_{Approaching}$ of 32.7° , a mean $\Delta PA_{Receding}$ of 38.9° , and a mean ΔPA_{Global} of 35.6° . In the isolated sample, I find a mean $\Delta PA_{Approaching}$ of 11.1° , a mean $\Delta PA_{Receding}$ of 9.6° , and a mean ΔPA_{Global} of 7.0° . Furthermore, it is appropriate to consider — although mathematically it lacks a global position angle misalignment — MaNGA galaxy 1-147496 as misaligned (See Figure 4) on both sides due to its significantly disturbed stellar velocity, and accordingly 5/9 of the interacting galaxies should be considered to have a global kinematic misalignment $\Delta PA > 30^\circ$.

4.3 Conclusions

Jin et al. (2016), who specifically aimed to understand the causes behind kinematic misalignment in MaNGA galaxies, suggested that they found no evidence — although in a sample with even fewer interacting galaxies than mine — that paired galaxies were a force behind kinematic misalignments. My sample suggests a significant difference. This discrepancy could likely stem from several causes: 1) small sample size; 2) they calculated their position angles differently using the methodology of Krajnovic et al., which made several underlying assumptions about the galaxies behavior (2006); 3) sample selection: they selected galaxies specifically based on the presence of a kinematic misalignment and compared them to a sample of aligned galaxies which were selected to be similar in stellar mass and star formation, while I examined dwarf galaxies with no *a priori* knowledge of their PA alignments.

Barrera-Ballesteros et al. (2015) examined kinematic misalignments in a sample of 103 interacting CALIFA galaxies. They found that 42% of the interacting sample exhibited a misalignment between the stars and the ionized gas at $\Delta PA > 16^\circ$, compared to 10% in their control sample. Using that value as a threshold in my interacting sample, I find that 8/9 display misalignments on the approaching side and 5/9 on the receding side, with 6/9 displaying global misalignments, with all 9 galaxies displaying a misalignment on at least one side; in my control sample, I find 5/15 misalignments on the approaching side, 3/15 on the receding, and 2/15 globally, with 5/15 exhibiting a misalignment on either side. My results — while examining a significantly different galaxy population — appear to be consistent with their finding of an increased percentage of misalignments in interacting galaxies.

Although my sample size is small, the differences in both the fractions and the mean values of misalignments are significant. These results are promising, and I recommend expanded studies with the new MaNGA data products that have been observed, reduced, and made available. In addition, I suggest the study of other properties in this sample, including but not limited to star-formation rates, star-formation histories, and ionization conditions to further understand what is happening inside these galaxies. In addition, more investigation is recommended into spatially resolved starburst galaxies – as they exhibited far greater misalignments than the rest of the sample.

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