Methods of Merger Classification

Summer Fellows Final Report

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Introduction

In 2007 an innovative new astronomy project called Galaxy Zoo was launched onto the World Wide Web. Galaxy Zoo's purpose was to enlist the general public to help classify over 900,000 galaxies for astronomical research. Among these classifiable galaxies were mergers, the most dramatic form of galactic interactions: colliding galaxies.

When two or more galaxies collide, it is not a sudden or jarring collision. Galaxies consist of stars, gas, other matter, and a large amount of empty space; thus galactic collisions are more so the exchange and/or reshaping of galactic material over time. Some collisions result in a full merge, where two galaxies become one; others result in dramatically altered morphology (form, structure, composition, and evolution) of both galaxies. There are many factors that contribute to mergers, such as the relative sizes and velocities of the involved galaxies, their alignments and the angle at which they collide.

One of the consequences of galaxy mergers is the accompanying burst of star formation. Galaxies are already the natural birthplaces of hundreds of billions of stars, but mergers elicit massive starbursts due to the inevitable mixing and colliding of gas. Some is already known about this process, but there is still much to learn.

This project therefore focuses on merger morphology and corresponding spectral emissions in an attempt to learn more about the mechanics of such starbursts. As this is still a work in progress, the research described in this paper is only one small aspect of the entire project. Thus, no conclusions or results will be drawn at this point; rather, the emphasis will be on the process of observation and data recording.

Participants in the 2007 Galaxy Zoo project have already identified thousands of mergers using images taken by the Sloan Digital Sky Survey, hereafter abbreviated SDSS. Galaxy Zoo's first data release catalogues every galaxy, including mergers, and so became the starting point.

The data release contained, among other things, a percent-based merger category for an enormous number of galaxies. Galaxies with a vote of 40% or above in that category could conclusively be considered a merger (Lintott et al. 2010), so all galaxies that did not fall within that range were cut. To further organize and, later, limit the list, I asked Dr. Rob Knop, project advisor, to download and insert into the data table the redshift for each remaining merger.

Redshift is the so-called lengthening of a photon's frequency that occurs when distant massive objects move away from each other at great speeds. It is a unitless quantity defined as the change in the photon's wavelength divided by the photon's rest wavelength, and is typically denoted as *z*. Higher *z*-values indicate greater redshift. Redshift also correlates to distance, as closer objects have receded less quickly than more distant objects due to the expansion of the universe, and thus have been redshifted less than the more distant objects. Thus, higher *z*-values also indicate greater distances.

The *z*-values dictated the first pass of data collection. All of the data represented in this paper is from mergers of redshift $0.02 < z < 0.03$, as Dr. Knop and I believed that these would be sufficiently close enough to make out more interesting features. In addition, these mergers fell within the redshift range of the 3003 Galaxy Zoo mergers investigated by D.W. Darg, whose research serves as an important reference point for this project (Darg et al., 2009).

Methods of Data Collection

The methods of observation and data recording used in this project were developed over a period of several weeks before they were implemented. In the initial stages of the project, I drafted a detailed written description of each of the first 80 mergers in the Galaxy Zoo data release, sorted by OBJID (an ID number assigned by the SDSS). These descriptions served the purpose of identifying recurring aspects of merger morphology.

From those first 80 written descriptions, Dr. Knop and I derived a list of features that warranted further investigation. These were tails, including length, direction, and amount of curve; the approximate distance between cores in arcseconds; the brightness ratio of the cores; shells; blobs of material that could not be directly associated with another obvious feature; inclination of each galaxy and their angle to each other; and band distinctiveness. In addition to these characteristics, several other factors were recorded: the brightness ratio error; the pixel x- and y-coordinates for each core; an approximate average sigma value for nearby stars; x- and y-coordinates for two points each on tails; and extra notes. Also found in the table are columns for object ID, RA, DEC,* and redshift, though these were included more for convenience than for observational purposes.

The image-viewing program used throughout the project is "Imview." Coded by Dr. Knop, Imview is a fairly simple program that displays FITS files (the special type of image file obtained from the SDSS database) and can make certain adjustments and measurements. FITS images contain adjustable pixel brightness data, and Imview allows control over the range of brightness (white to black and between) to bring out certain features (*Figure 1*).

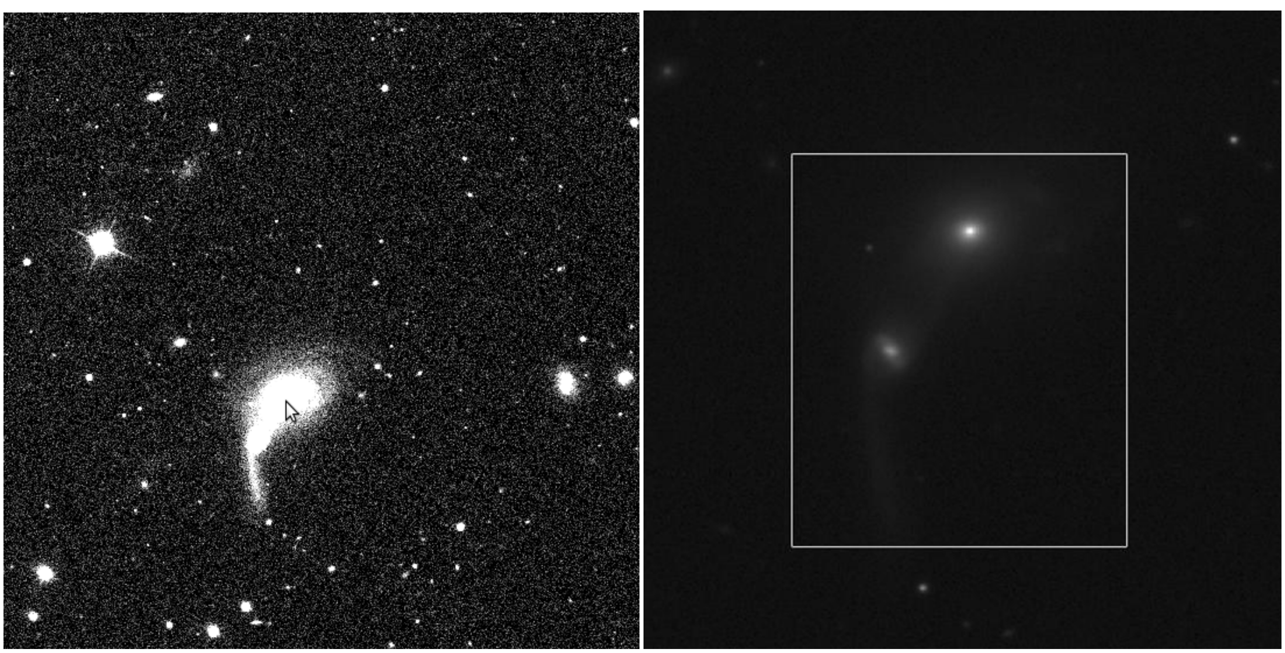

Figure 1. *Left: this image has not been adjusted to bring out features of the merger, indicated by mouse arrow. Right: an enlarged and adjusted version of the same merger. Note that the galactic cores (the bright spots) are visible in the second image, and are distinguishable from other features by differences in brightness. The shape of the object is also clearer.*

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* Right ascension (RA) and declination (DEC) are the two directional coordinates of a point on the celestial sphere. The sphere itself is imaginary, but is described as the heavens projected onto the inside of a sphere of arbitrary radius surrounding the Earth. RA is analogous to longitude on Earth; DEC is analogous to latitude. Both are typically measured in units of degrees, arcminutes, and arcseconds, with a positive or negative attached to DEC to specify which side of the celestial equator (north and south, respectively).

Imview is additionally programmed to calculate certain values such as apparent brightness and distances between selected objects with use of the Photometry tool. It can also display the RA and DEC of any given pixel so that a viewer may locate an object at those coordinates. Its Gaussian Fit tool calculates sigma for selected objects. It can also be set to render color images, though this was never a necessary function.

The goal of this section is to familiarize readers with the reasons and meanings behind the data recorded, and acquaint them with the thought processes required to generate the data. *Figure 2* displays a small sample of each of the data columns, excepting OBJID, RA, DEC, and redshift, as those are not directly pertinent to the methods employed. The purpose of those four columns was merely for correlation between this data table and the original table; identification of and within the images in the database; and reference to redshift.

CORE_DIS	BRI_RAT	RAT_ERR	DIM_CENTX	DIM_CENTY	BRI_CENTX	BRI_CENTY	#TAILS	DIRECTION	CURVE1	CURVE2	LENGTH1	LENGTH2	DIS_BAND
8.22	0.8377	0.0126	643.25	1169.54	634.94	1150.53	0	N/A	N/A	N/A	N/A	N/A	GRIUZ
4.61	0.6395	0.0243	251.25	1027.45	241.81	1034.23	0	N/A	N/A	N/A	N/A	N/A	RGIZU
43.34	0.1509	0.0012	614.15	122.94	583.34	227.97	2	DIFF	SC	VC	SHORT	MEDIUM	RGIZU
43.33	0.0861	0.0018	491.50	554.73	587.06	501.32	1	N/A	NC	N/A	SHORT	N/A	RGIZU
0.00	1.0000	0.0000	1053.72	1313.73	1053.72	1313.73	1	N/A	NC	N/A	SHORT	N/A	IGRUZ
0.00	1.0000	0.0000	218.48	1524.59	218.48	1524.59	0	N/A	N/A	N/A	N/A	N/A	GRIUZ
10.93	0.7340	0.0200	230.48	297.68	255.87	277.14	0	N/A	N/A	N/A	N/A	N/A	GRIUZ
31.21	0.7510	0.0101	970.88	304.86	1020.08	243.31	2	SAME	NC	NC	MEDIUM	MEDIUM	RIGZU
43.34	0.1509	0.0012	614.15	122.94	583.34	227.97	2	DIFF	SC	VC	SHORT	MEDIUM	RGIZU
11.28	0.6621	0.0036	1035.63	1862.81	1015.03	1843.12	1	N/A	VC	N/A	LONG	N/A	RIGZU
5.66	0.0884	0.0041	500.67	1083.38	505.12	1069.78	1	N/A	NC	N/A	SHORT	N/A	RIGZU
9.40	0.3504	0.0034	252.19	1642.68	241.38	1663.85	2	SAME	SC	SC	MEDIUM	MEDIUM	IRGZU
5.51	0.2911	0.0028	1202.30	979.77	1198.40	993.14	2	SAME	NC	NC	SHORT	SHORT	RIGZU
10.27	0.3818	0.0096	1222.32	741.01	1207.87	762.54	0	N/A	N/A	N/A	N/A	N/A	GRIUZ
19.73	0.4050	0.0074	520.05	592.36	516.30	542.99	0	N/A	N/A	N/A	N/A	N/A	GRIZU
13.69	0.6396	0.0026	792.90	90.48	924.48	104.55	0	N/A	N/A	N/A	N/A	N/A	RIGZU
22.48	0.1442	0.0028	391.11	247.09	342.71	217.43	1	N/A	VC	N/A	MEDIUM	N/A	IRGUZ

SHELL	INC_BRI	INC_DIM	BLOBS	STAR_SIG	ANGLE	TAIL1_X1	TAIL1_Y1	TAIL1_X2	TAIL1_Y2	TAIL2_X1	TAIL2_Y1	TAIL2_X2	TAIL2_Y2	NOTES
N	NR	SR	2	1.30	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Messy-ish
N	NR	NR	1	1.21	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
N	SR	NR	0	1.00	90	580.30	130.50	598.70	119.50	628.80	120.90	656.00	142.80	*
N	SR	U	0	1.29	90	538.00	525.70	555.10	507.50	N/A	N/A	N/A	N/A	
N	SR	NR	2	1.16	90	1064.10	1310.10	1070.30	1306.80	N/A	N/A	N/A	N/A	Messy-ish
N	NR	SR	4	1.16	90	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Messy; G and R are
N	U	U	6	1.01	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Messy
N	NR	LI	0	1.39	10	934.40	327.20	958.10	312.90	989.30	292.60	1010.40	275.70	
N	SR	NR	0	1.00	90	580.30	130.50	598.70	119.50	628.80	120.90	656.00	142.80	*Same as 587741707
N	NR	R	0	0.95	N/A	977.90	1665.20	1002.30	1803.40	N/A	N/A	N/A	N/A	
N	SR	SR	0	1.22	20	511.40	1079.60	516.00	1092.20	N/A	N/A	N/A	N/A	
N	R	SR	0	1.24	N/A	228.30	1635.50	243.40	1640.60	261.10	1644.10	275.80	1651.80	*
N	NR	LI	1	1.10	10	1189.50	976.30	1194.70	986.70	1205.60	1000.50	1211.40	1009.70	
N	R	U	4	1.22	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Messy
N	LI	R	2	1.42	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Messy
N	NR	NR	0	1.10	80	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*
N	NR	LI	0	1.38	70	344.90	194.40	353.60	204.80	N/A	N/A	N/A	N/A	

Figure 2*. A sampling of the data table with corresponding column labels, separated into two pieces due to size. Note that the lower portion contains additional data columns rather than a continuation of those in the upper portion. Each row of data corresponds with a specific merger, identified by object ID and RA and DEC (columns not shown).*

CORE_DIS

The first column in the upper portion of *Figure 2* contains values that specify the distance between the cores of two merging galaxies in a given image. Although there is no recorded unit, the values are in arcseconds.* They were calculated within Imview. The values are estimates, since I hand-picked the

* One arcsecond is equivalent to 1/60 of an arcminute, which in turn is 1/60 of a single degree, of which there are 360 in a circle. In astronomy, the distance between two objects is given in arcseconds because the measurement is tiny enough to be projected onto a circular or spherical object of arbitrary radius, such as the celestial sphere.

centers of the cores as accurately as possible using Imview's Photometry tool. Additionally, it is difficult to account for discrepancies in the galaxies' positions if they are *not* exactly the same distance away, because arcseconds only measure tiny angles of an arc. In reality, one galaxy may be further away than its companion, and thus the measure in arcseconds is inaccurate because it assumes both galaxies are on the same surface, so to speak. Nevertheless, it is the best that can be done. In *Figure 3,* the distance measured is between the centers of the two inner circles, which I placed over what I identified as the two galactic cores.

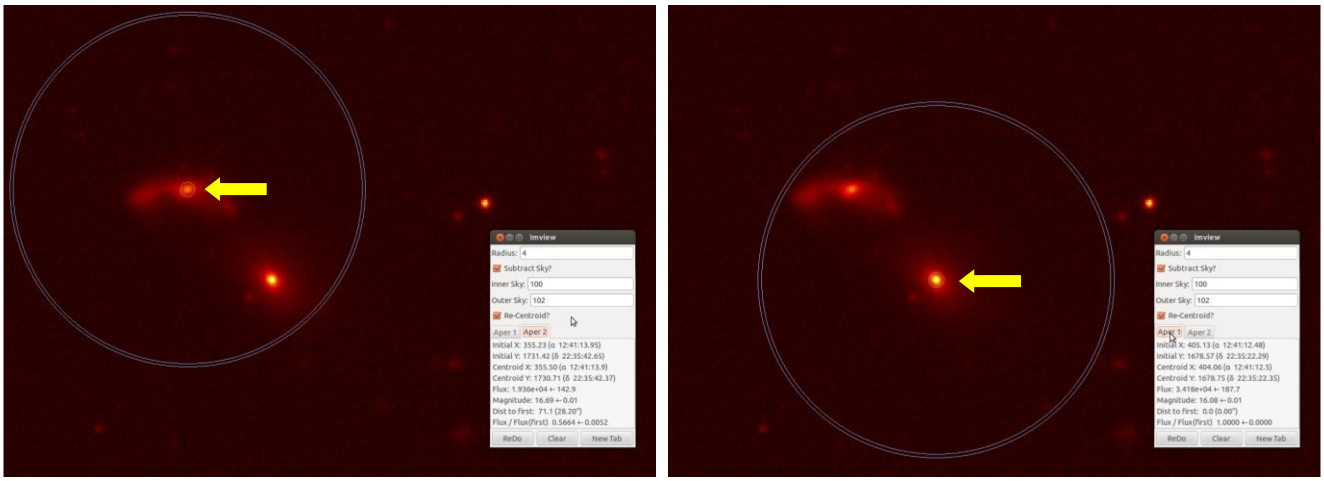

Figure 3. *Images of the sky limit circles and core locations, from the Photometry tool in Imview. The yellow arrows point to the inner circles, which are difficult to see at this size. These inner circles surround the cores, and the locations are what determine the distance. Left is "Aperture 2;" right is "Aperture 1." The brighter core was always made Aperture 1 so that flux ratio was no larger than 1. The more visible outer circle is actually comprised of two circles, which define the sky limit.*

BRI_RAT and RAT_ERR

Referring back to *Figure 2,* the second column depicts brightness ratio (flux ratio). Flux, or apparent brightness, is a measure of how bright an object appears. It is dependent upon the object's luminosity, which is its energy output in watts, and the distance from the object at which the measurement is made. A flux ratio is simply a comparison of two fluxes.

The values were calculated with the Photometry tool using the average flux of the inner circles shown in *Figure 3:* $\frac{Aperture\ 2}{Aperture\ 1}$. The ratios are approximate, since even a slight variation in the placement of an inner circle can change the calculated average flux of that core, thus changing the flux ratio. Variations tended to be fairly small, though.

Note that the flux ratio is recorded from *only* the r-band.* This was done for consistency and ease of comparison throughout the observations, and because the r-band is consistently very clear and thus easiest to work with. The fluxes and flux ratios are almost certainly different in the other bands.

The calculations were done solely by Imview. I could have done the flux ratio calculations by hand if necessary, but this way saved much time.

The third column merely denotes the small amount of error present in Imview's calculation of the brightness ratio.

* See DIS_BAND section for an explanation of "bands" like the r-band.

DIM_CENTX, DIM_CENTY, BRI_CENTX, and BRI_CENTY

These four columns specify x- and y-coordinates in pixels of identified core centers in the image. “DIM” refers to the dimmer core, while “BRI” refers to the brighter. Again, these were recorded only from the r-band. The coordinates come from the placement of the inner circle of the Photometry tool (*Figure 3*), and therefore may not represent the precise core centers. I was usually able to determine visually which core was dimmer and which was brighter, but whenever it was questionable I used the Photometry tool to identify which had the lesser and greater flux before making any related observations.

#TAILS

This column indicates the number of tails present in the merger. On occasion, the number reported may not be fully accurate, as there are a small number of mergers that had a possible third or even fourth tail. In those cases, the number of tails was reported as 2, the most obvious tails were used in recording data, and a secondary note was made in a separate column (NOTES).

DIRECTION

This column describes whether the tails curved in the same or different directions. When there were no tails, the response was N/A. A response of 1 tail in the previous column also generated N/A in this column. For two tails, however, the response could be either SAME or DIFF (*Figure 4*). SAME refers to tails that curve in the same direction, either clockwise or counterclockwise, while DIFF refers to one tail curving clockwise and the other curving counterclockwise.

In some cases, one tail was straight. However, these would often have a slight bias towards one direction, or an angular bias in which the tail emerged from the galaxy at an angle. These situations helped determine direction as well.

Figure 4. *Far left: bottom galaxy shows tails curving in the same direction. Center left: bottom galaxy shows tails curving in different directions. Center right: top galaxy provides example of a straight tail with a slight directional bias. Far right: bottom galaxy, top tail, provides example of straight tail with slight angular bias.*

CURVE1 and CURVE2

These two columns describe each tail's amount of curviness. There are four possible responses: N/A, which occurs only in the absence of a tail; NC, or "no curve," which applies to straight or only slightly curved tails, up to 15 or 20 degrees of curve; SC, or "somewhat curved," which applies to tails with 20 to 90 degrees of curve; and VC, "very curved," which applies to 90 degrees and above, and includes tails that curve all the way around the galaxy in a ring (*Figure 5*).

Figure 5. *Far left: top galaxy displays tail classified NC and LONG. Center left: smaller galaxy's lower tail was classified SC and MEDIUM. Center right: lower galaxy's bottom tail was classified VC and MEDIUM. Far right: an example of a LONG and VC tail that forms a ring around the merger. It is not the distinct circle around the larger galaxy; rather, the ring tail is the fainter ellipse that appears to intersect the upper galaxy and drop below the lower.*

For mergers that had no tails, both columns were marked N/A; for mergers with only one tail, CURVE2 was marked N/A but CURVE1 reported data. When there were two tails, one was somewhat arbitrarily assigned to CURVE1 while the other was assigned CURVE2. There is admittedly little quantifiable method to these choices, except that I tried to assign the tail closest to the left side of the image to CURVE1 whenever possible, for consistency.

LENGTH1 and LENGTH2

These two columns correspond directly with the two that identified curve. The numbers 1 and 2 in both columns refer to the same tail; that is, columns for CURVE1 and LENGTH1 contain data on the same tail. There are four possible responses for lengths: N/A if there is no tail; SHORT if the tail is less than or equal to the approximate width of the galaxy; MEDIUM if the tail is between equal to and twice the approximate galactic width; and LONG if the tail exceeds twice the approximate width.

These responses are not precisely measured. Rather, they are approximated by the eye.

DIS_BAND

This column indicates band distinctiveness; that is, which wavelengths show the clearest features. There are five different filters, or bands: ultraviolet (u), green (g), red (r), infrared (i), and beyond infrared (z, longer wavelength than infrared). There are additional wavelengths labeled with other letters, but ugriz is the standard filter system used by the SDSS. Consequently, all of these mergers have five different images: one for each band. Each image shows the merger and other celestial objects radiating in that particular wavelength; not all wavelengths radiate the same amount, so the images often look different from band to band (*Figure 6*).

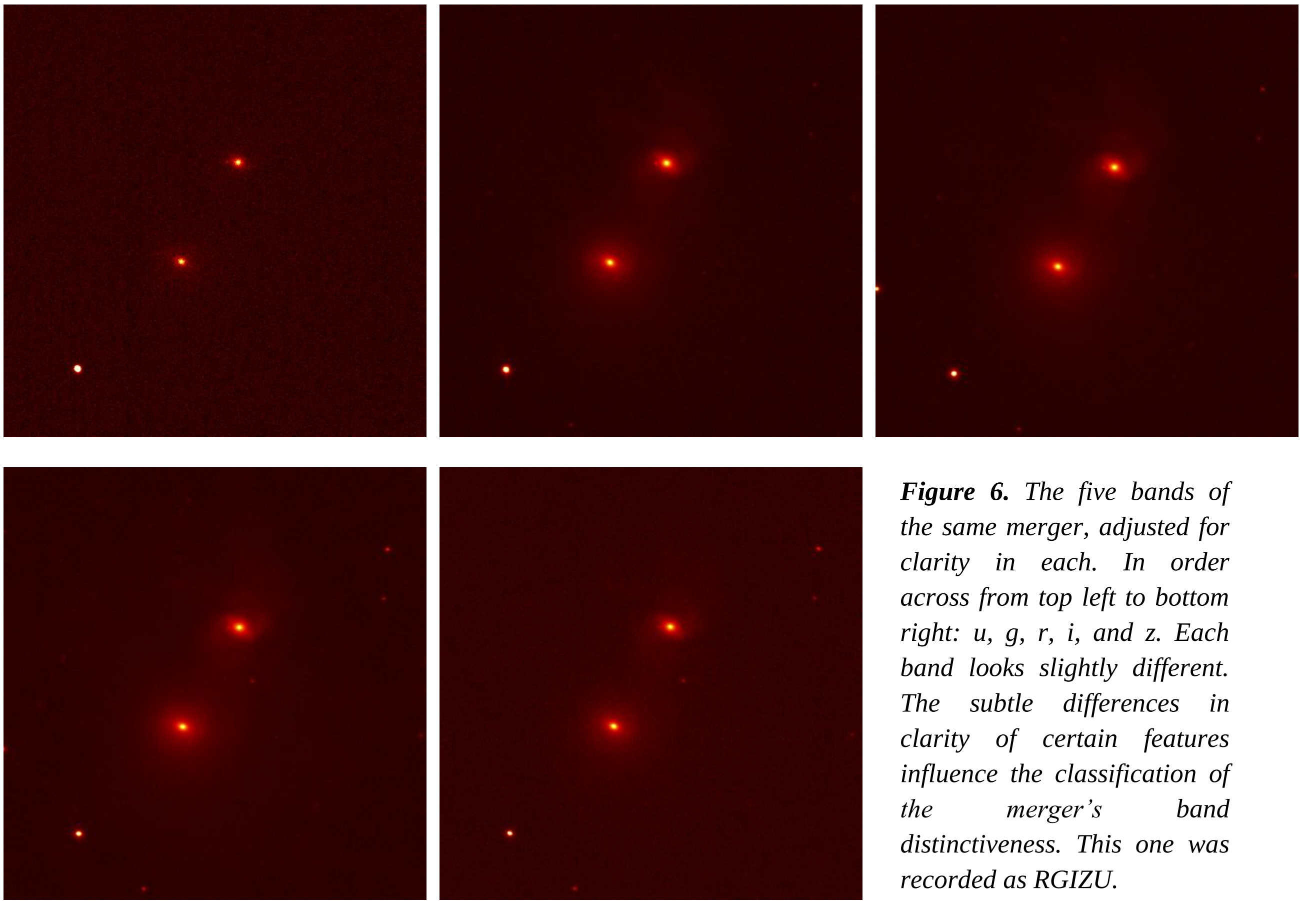

Figure 6. *The five bands of the same merger, adjusted for clarity in each. In order across from top left to bottom right: u, g, r, i, and z. Each band looks slightly different. The subtle differences in clarity of certain features influence the classification of the merger's band distinctiveness. This one was recorded as RGIZU.*

The responses in this category vary greatly, but all are ordered from most distinct to least distinct. For example, a response of GRIUZ indicates that the g-band (green) is the most distinct and the z-band (beyond infrared) is the least distinct, with the r-, i-, and u-bands falling in between, in order.

The band distinctiveness column is also partially color-coded (*Figure 7*). All mergers labeled GRIUZ were shaded green, and certain variations like RGIUZ and GRIZU became a lighter green. The lighter green was typically reserved for any variation of GRIUZ that was only one letter out of place. In addition, any merger shaded in this column received an accompanying comment in the NOTES column: either Messy, Messy-ish, or Not messy. "Messy" refers to a galaxy that has lots of blobs, indistinct shapes, and/or general disorganization. "Messy-ish" is the same thing but to a lesser extent. "Not messy" applies to mergers that did not fit either of the first two criteria. In the case of "Messy" galaxies, the NOTES column was shaded green; "Messy-ish" received the lighter green; and "Not messy" received orange. Furthermore, galaxies identified as "Messy" or "Messy-ish" but *not* labeled GRIUZ or one of its variations were shaded orange in the DIS_BAND column. Mergers that displayed none of these characteristics (such as one labeled RIGZU and "Not messy") are not color coded.

GRIZU	N	LI	NR	1	0.94	70	463.00	1570.90	50.80	1563.50	N/A	N/A	N/A	N/A	*Messy
GRIUZ	N	SR	U	2	1.25	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Messy
RIGUZ	N	NR	LI	0	1.30	40	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
IGRUZ	N	SR	NR	0	1.50	60	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Not messy
GRIUZ	N	R	U	1	1.25	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Messy; G and R are very close to equally bright
RGIZU	N	SR	NR	0	1.08	50	687.30	373.20	676.00	458.60	703.40	484.40	717.10	511.80	*
GIRZU	N	NR	SR	0	1.18	40	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
GIRUZ	N	SR	U	1	1.35	N/A	21.70	1245.20	47.90	1224.10	39.00	1192.20	49.20	1182.60	Messy-ish; dimmer tail splits into two about halfway do
RGIZU	Y	NR	NR	0	1.23	60	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*Same as 587732769978777642; Shell is a maybe for t
GRIZU	N	LI	NR	1	0.94	70	463.00	1570.90	50.80	1563.50	N/A	N/A	N/A	N/A	*Same as 587742549602599058; Messy
GRIUZ	N	NR	U	2	1.15	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Messy
GRIZU	N	NR	LI	0	1.55	50	151.00	286.00	137.50	442.60	234.30	601.30	235.50	772.50	Not messy
RGIZU	N	SR	NR	0	1.12	30	603.40	1303.10	614.40	1300.00	634.70	1313.70	644.90	1311.90	*
RIGZU	N	NR	U	1	1.20	N/A	314.70	1596.50	334.10	1644.00	N/A	N/A	N/A	N/A	Messy
RGIZU	N	SR	NR	0	1.08	50	687.30	373.20	676.00	458.60	703.40	484.40	717.10	511.80	*Same as 587741722819493915
GRIUZ	Y	NR	NR	0	1.12	50	608.60	439.20	619.00	437.50	616.30	427.10	626.70	426.60	Not messy; Tails appear ONLY in u-band!
RIGZU	N	SR	R	0	1.32	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
GRIZU	N	NR	U	2	1.05	N/A	363.10	623.70	368.00	614.20	N/A	N/A	N/A	N/A	Messy; G and R are very close to equally bright
															Image cut off; can't see enough of galaxy
GRIZU	Y	SR	NR	0	1.32	0	498.50	1616.70	492.10	1592.50	509.30	1574.00	495.30	1554.80	Not messy
GRIUZ	N	NR	U	0	1.06	N/A	596.50	748.30	604.80	753.80	N/A	N/A	N/A	N/A	Messy-ish

Figure 7. *A portion of the data table that shows some of the color-coding.*

The color-coding helps keep track of a certain pattern. Early in my observations I noticed a possible correlation between messy galaxies and the GRIUZ band distinctiveness pattern. While it may not ever reveal anything significant, I developed this system of color-coding to keep tabs on both components of the pattern.

Classifying band distinctiveness required careful visual scrutiny. Occasionally two bands would be very close to the same clarity, and when this occurred I made a note of it in a separate column and used my best judgment to decide.

SHELL

This specific type of galactic feature (*Figure 8*) is not very common among the mergers in this data set, but common enough to warrant a specifying column. Classification is simple: if there appeared to be a shell, the response was Y (yes). If not, the response was N (no).

Figure 8. *Left: NGC 474, an example of a typical shell galaxy (photo from NASA). It was not part of this project. Center and right: two different shell galaxies (top in both) seen and catalogued in this project.*

INC_BRI and INC_DIM

Inclination, for these two columns, is similar to shape, and describes how the galaxy appears. As before, "BRI" and "DIM" refer to brighter and dimmer galaxies. The five possible responses for these columns are R (round), SR (somewhat round), NR (not round), LI (linear), and U (undefined). U was used only for galaxies too messy to fit any of the other four categories, or when it was difficult to find or see.

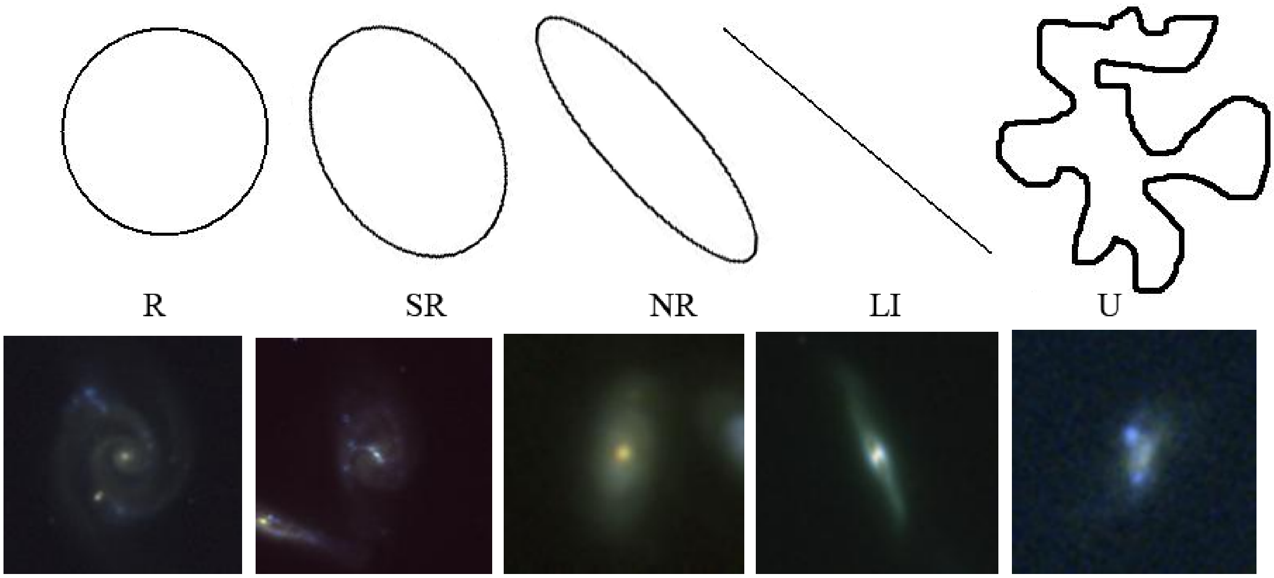

Figure 9. *Top: labeled drawings of the general criteria for each type of inclination. Bottom: actual examples of each type, in the same order as the drawings.*

Some of these classifications correspond directly to “face-on” (round) or “edge-on” (linear) galaxies, but the use of my own classification system allowed for better and easier distinction between different inclinations.

BLOBS

Some galaxies, particularly “Messy” ones, had blob-like features that could not be considered part of a tail, an extension of a disturbed core, or part of a shell. This column thus represents the number of such blobs within the merger. Some of them may be foreground stars, and in cases where I was sure of that, I made note of it in a separate column.

STAR_SIG

This column records an approximate average sigma value for stars near the merger in the image. Very basically, sigma in this context is a number that indicates atmospheric seeing conditions. A lower sigma value like 0.90 suggests good seeing conditions, while a higher value such as 1.20 suggests poorer seeing conditions. Atmospheric distortion is one of the major problems facing astronomers, as it can change the way a distant celestial object looks. Therefore, it was important to note how much distortion may be present in each image.

Sigma values are also helpful in that stars across an image tend to have a fairly consistent sigma value, while galaxies have noticeably different ones. In cases where I was unsure if something was a star or galaxy, I could check the star sigma and compare.

The values were calculated by Imview via the Gaussian Fit tool, and were taken only in the r-band for consistency. Sigma values in other bands are undoubtedly different. I checked sigma for four to seven or eight different stars to determine the approximate average value.

ANGLE

Although not specified in the table, this column is reported in degrees and indicates the angle at which two galaxies are oriented. For any merger with one or both galaxies classified as R or U, the angle is marked N/A. For all other mergers, the angle was calculated with a protractor using the major axis on both, and rounded to the nearest 10 between 0 and 90. No galaxy is ever an exact, perfect line to measure, so these measurements will always be approximations.

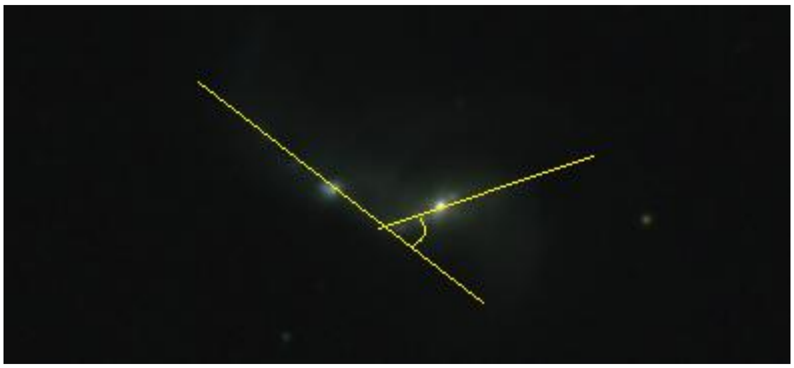

Figure 10. *A diagram showing how one may measure the angle between two galaxies. The acute angle's value is recorded, so that the number is less than 90. Although these example galaxies are sharing material at the intersection of the two lines, that is not a necessary requirement for an angle to be measured.*

TAIL1_X1 to TAIL2_Y2

The values in these columns are not directly pertinent to the research project at hand, but were recorded in the event of a side project or further extrapolation of tail data at the request of Dr. Knop. Each value is a pixel coordinate on a tail present in the merger. N/A was recorded if there were no tails. TAIL1 corresponds with the same tail used in CURVE1 and LENGTH1. Each tail has two separate x- and y-coordinates, usually selected from opposite ends of the tail. X1 and Y1 for TAIL1 were usually located near the end not attached to the core, with the next two coordinates at points closer to the core on either tail and the fourth at the far end of the other tail.

NOTES

This column, while color-coded in relation to band distinctiveness and galactic messiness (see *Figure 7* and the DIS_BAND subsection), also contains information best stated in words. This includes comments about questionable third or fourth tails; notes on two bands of similar distinctiveness; particularly unique or interesting shapes or features; clarification about noted features; and occasional yellow-highlighted technical problems. Also in this column are occasional asterisks, which denote when an object ID refers to the same merger as another object ID. These duplicates are marked * if it is the first of the two, and *Same as [other object ID] if it is the second. All data for duplicates was copied and pasted from the first image.

<u>Further Comments</u>

Other than recurring styles of tails, shells, and other morphological features characteristic of mergers, there is little more to say regarding observations thus far. As discussed in the DIS_BAND subsection, I have noticed some connections between the GRIUZ band distinctiveness pattern and the relative messiness of galaxies. Messy galaxies may have a significant amount of star formation occurring, as their structures indicate vastly mingling galactic material. Why they tend to shine brightest in the visible bands of green and red is as of yet unknown to this researcher. Finally, results, discussion, and an extensive lit review are yet to come; for those, my Keystone will hopefully provide answers.

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