Detection of Double Nuclei Galaxies in SDSS

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ABSTRACT

It is now well established that galaxy interactions and mergers play a crucial role in the hierarchical growth of structure in our universe. Galaxy mergers can lead to the formation of elliptical galaxies and larger disk galaxies, as well as drive galaxy evolution through star formation and nuclear activity. During mergers the nuclei of the individual galaxies come closer and finally form a double nuclei galaxy. Although mergers are common, the detection of double-nuclei galaxies (DNGs) is rare and fairly serendipitous. Their detection is very important as their properties can help us understand the formation of supermassive black hole (SMBH) binaries, dual active galactic nuclei (DAGN) and the associated feedback effects. There is thus a need for an automatic/systematic survey of data for the discovery of double nuclei galaxies. Using the Sloan digital sky survey (SDSS) as the target catalog, we have introduced a novel algorithm GOTHIC — Graph-boosTed iterated Hill Climbing[13] — that detects whether a given image of a galaxy has characteristic features of a DNG (ASCL entry 2707). We have tested the algorithm on a random sample of 100,000 galaxies from the Stripe 82[2] region in SDSS and obtained a maximum detection rate of 4.2% with a careful choice of the input catalog.

1 Introduction

A galaxy is a system of stars, interstellar gas, dust and dark matter bounded by gravitational forces. Based on their morphology galaxies are categorized as spiral, irregular or elliptical. Galaxies are not usually isolated systems but are instead clustered into galaxy groups and large galaxy clusters [18]. Hence, galaxies often interact tidally at a distance with each other or undergo mergers with one another. During these interactions the gravitational field of one galaxy affects the other one. If the two galaxies do not have enough momentum to continue to travel after interacting, they will finally collide and merge, leading to the formation of a galaxy merger remnant [5].Galaxy mergers are common in our universe and are one of the main drivers of galaxy evolution [7, 1].

The outcome of galaxy mergers depends on the mass ratio of the merging galaxies. In the cases where one galaxy is much more massive than the other one, the more massive galaxy remains more or less intact whereas the smaller galaxy is tidally stripped of a large fraction of its mass and finally becomes part of the larger galaxy. Such mergers are called galaxy accretion events or minor mergers. When the colliding galaxies are similar in mass and size, it is called a major merger event. Major mergers usually lead to the formation of elliptical galaxies. Another classification system for galaxy mergers depends on the presence of cold interstellar gas. When one or both the galaxies are gas rich, the merger is said to be a wet merger and when both galaxies are gas free, as in ellipticals, the merger is said to be a dry merger. However, wet or dry, major or minor, all mergers can lead to the formation of a single envelope containing two nuclei. Such dual nuclei systems represent the final stage of galaxy mergers [15].
As the galaxies merge, the supermassive black holes (SMBHs) in their nuclei come closer and may start accreting mass. Such accreting SMBHs are called active galactic nuclei (AGN) and give out large amounts of energy over the whole electromagnetic spectrum and can be detected using optical, radio or X-ray telescopes [31]. Alternatively, the large gas infall into the nuclear regions can trigger starburst activity. Thus double nuclei galaxies can host AGN pairs, AGN-starburst pairs or starburst nuclei in their centers [33]. When two AGN are found in a merger remnant, they can form a dual AGN (DAGN) if the nuclei are separated by < 10 Kpc. AGN pairs at separations of a few parsecs or << 1 Kpc are called binary AGN (BAGN). The number of DAGN identified till now is less than 50 [32] and the number of binary AGN identified is less than 5 [23].

There are several reasons why we need to find more DAGN or BAGN. The first reason is that they represent SMBHs coming closer together in galaxies. At distances of several Mpc and beyond the local universe, the only way to detect SMBHs is through the radiation emitted from AGN activity. The mass of the SMBH pairs affects the stellar and gas content of the nuclear regions of the galaxies, triggering disk instabilities and star formation. Secondly, although DAGN are rare in the universe, their study is important for understanding the growth of SMBHs as it is suggested that merger-triggered AGN may dominate SMBH growth [22]. Third, SMBH binaries represent black holes that will eventually merge and produce gravitational radiation [21]. Although the gravitational radiation will be emitted only when the SMBHs are at very close separations, a larger sample of DAGN will help us understand the evolutionary path for such systems. Fourth, AGN give out enormous amounts of radiation that can push gas out from the nuclear region and even beyond the galaxy. This is called AGN feedback and it can result in the growth the circumgalactic medium around galaxies [16]. The gas can also fall back onto the disks resulting in star formation. In the past decade it has become clear that AGN feedback is important for galaxy evolution, and if there is an AGN pair then the effect will be even more important not only because of two AGN in the galaxy center, but also because the AGN winds can overlap and produce additional feedback effects. Hence, large samples of DAGN are essential for fully understanding the role of mergers in galaxy evolution.

The earlier DAGNs have been serendipitously discovered [9, 24, 35, 37], mainly during galaxy surveys of emission line galaxies and merger remnants. Later studies used samples of double peaked AGN emission line galaxies (DPAGN) to search for DAGN [44]. However, DPAGN can also be due to AGN outflows or rotating disks. So one of the best ways in which to detect DAGN is by identifying individual nuclei in a dual nuclei galaxy [34]. The existing surveys of galaxy pairs are either too small [20] or the galaxy separations are too large to include merger remnants [30]. Thus a deeper and larger catalog is necessary in order to do statistical studies of dual nuclei galaxies and identify DAGN. The detection of previously undiscovered samples is essential for understanding the final stages of the galaxy merging process. Hence, there is a need of a pipeline to sift through a large catalog of galaxies and steadily increase the pool of candidate DAGNs. The aim of this paper is to develop an algorithm that extracts images from the Sloan Digital Sky Survey (SDSS) survey and identifies a pool of dual nuclei systems that we will use later for identifying a large sample of DAGN.

2 Previous Studies, Test Sample and Input Catalog

As mentioned in the previous section, galaxies with two nuclei separated by kiloparsec scales are known as DAGN, whereas, the ones in which the separation is of the order of parsecs are called binary AGN. The hierarchical model of structure formation predicts the formation of such gravitationally bound binary SMBHs. The accretion of mass onto the nuclei transforms the nuclei into AGN and is an important part of SMBH growth and galaxy evolution. Moreover, these galaxy merger events could ultimately give rise to black-hole merger events which are crucial for gravitational wave detection [3]. There have been several studies of double nuclei galaxies at different wavelengths. In this section we discuss these previous studies and describe the test sample which we finally use for testing our algorithm.

The main catalog that we used for testing the algorithm developed in this paper is from Gimeno et. al. [20]. The relevance of galaxy interactions and minor mergers in the formation of double-nuclei galaxies, the correlation between geometric and photometric parameters of the nuclei and their host galaxies, have been investigated in this study. It also discusses the differences or similarities between the component nuclei and their location in the host system. The galaxies selected had systematic velocities $cz$, and redshifts $z$ in the range $cz < 15000$ km/s, $z < 0.05$, $m_B < 18$. Mezcua et. al. [28] did further studies of this sample using observations. In their study, the luminosity of the nuclei and their relative separations were derived from the multi-component photometric fits to the galaxies in the $r$-band SDSS optical images. A majority of the sources have projected separations $\leq 4kpc$. The ratio of nuclear luminosities indicated that most of the systems were in the final stages merging. This was supported by the existence of a single galaxy disk in 65% of the systems studied and the significant correlation between nuclear luminosity and host luminosity for the
single-disk systems. The sources fitted with a single disk are in a more evolved stage of the merging process and present an enhancement of the nuclear luminosity compared to the double-disk systems.

Koss et al. [26] have mentioned the difficulty of resolving each AGN in optical and X-ray observations. The *Swift Burst Alert Telescope* survey was used to create a catalog of 167 AGN out of which 81 have a close companion within a 100 kpc radius. MRK 739 (also listed as NGC 3758 in Gimeno et al. [20]) has been well known since 1986 due to the paper by Netzer et al. [29]. In another work by Koss et al. [27], SDSS optical imaging and observations from the *Chandra X-ray Observatory* were utilized to rule out the possibility of MRK 739W (the nuclei on the western side) being a starburst region, which was suggested by its optical spectra. MRK 739E was already known to be an AGN due to Netzer [29]. It is interesting to note that the optical spectra of MRK 739E and MRK 739W both have a peak around 6750 Angstrom that falls under the R-band of the SDSS filters.

The detection of double-nuclei galaxies is important from the point of view of Cosmology and Structure Formation. Davis [17] and Springel [39] have suggested that galaxy interactions play an important role in the growth of their central SMBH. It has been suggested theoretically that DAGN must be found in relative abundance in our universe [25]. However, such objects are rarely found as most of them are radio-quiet and are difficult to resolve in the optical. Previously, double-peaked narrow emission lines were used as the criteria for a galaxy to be a candidate DAGN. However, such a criteria has received criticism as similar observations can be drawn from other phenomenon in single active nuclei galaxies itself (Xu & Komossa [42]). This suggests that alternative methods must be devised to procure candidates for DAGN galaxies. For example radio observations have used the Very Large Baseline Array (VLBA) to identify DAGN candidates [19]. There have been efforts towards studying individual DAGNs such as MRK 739 by Koss et al. [27], MRK 463 by Bianchi [6] and ARP 299 by Ballo et al. [4]. Rubinur et al. [33] have conducted radio-studies on a sample of DPAGN. Hence, it is an important task to increase the pool of DAGN candidates for robust statistical studies. In this paper, we have focused on detecting the presence of dual nuclei given a 40′′ × 40′′ r-band image of a galaxy from the SDSS images of galaxies. This sample will form the basic sample for a followup study aimed at deriving a large sample DAGN in SDSS.

### 2.1 Selected Samples from Pre-Existing Catalogs

Mezcua et al. [28] have reported that out of the 107 galaxies in the Gimeno catalog, only 60 have imaging data in SDSS DR8. Two galaxies, NGC-3758 and MRK-212 are shown as representatives in figure (1). The former has gained some attention outside the astronomy community due to its symmetric morphology [40, 43], and the latter has been extensively studied in multiple wavelengths [32]. The algorithm is domain-specific and hence a pre-existing sample was necessary for its development and testing. We have chosen the Gimeno catalog [20] as our test sample, and GOTHIC has achieved 100% accuracy on this dataset. The images have been selected from SDSS.

![Figure 1: Double-Nuclei Galaxies Sample](image)

### 2.2 Input Catalog

Our input dataset is located in this public folder. It contains the entire SDSS and Gaia catalog in the Stripe-82 region, which was used for crossmatching (section 5.2), in the files SDSS_Stripe82_All.csv and Gaia_Stripe82_All.csv, respectively.
3 The GOTHIC Algorithm

The FITS data of the given source, in all the SDSS bands (ugriz) were downloaded and subsequently a cutout of 40″ centred around the source was performed. The algorithm works individually for each band. The sequence of steps can be described as follows -

1. Scaling/Smoothing of the image for ease of visualisation
2. Edge detection with Canny to approximate galaxy envelope
3. Sersic profile fitting to infer noise/signal levels
4. Peak detection by Iterated Hill Climbing
5. Identification of the galaxy as single/double-nuclei or neither, based on graph searching

Given below is the formal pseudocode for the algorithm, the details of which have been explained in Appendix A. The result of running GOTHIC is shown in figure (2)

GOTHIC(cood, frame)
1   cood - Celestial coordinates of an object
2   frame - FITS frame containing the object
3   img ← CUTOUT (frame, cood, 40″) ▷ Returns a 40″ cutout image
4   img ← LOG-NORMALIZE (img) ▷ Step 1
5   img ← GAUSSIAN-KERNEL (img, 5, 5) ▷ Step 1
6   edges ← CANNY (img) ▷ Step 2
7   hull, reg ← CONVEX-HULL (edges) ▷ Step 2
8   noise, signal ← SERSIC-FIT (img, reg) ▷ Step 3
9   sreg ← SEARCH-REGION (img, reg, noise) ▷ Step 4
10  peak_list ← ITERATED-HILL-CLIMB (sreg, img, 500) ▷ Step 4
11  verdict ← CLASSIFY (peak_list, sreg, img, signal) ▷ Step 5
12  return verdict

Figure 2: Detected peaks from GOTHIC

4 Mathematical Basis for Classification and Related Procedures

In this section, we detail lines 10 and 11 of GOTHIC. The procedure SEARCH-REGION extracts the region inside the blue border, as shown in figure (2). Drawing of the border, in which the galaxy of interest lies in the cutout image, is required by the classification procedure. Moreover, it is also dependent on the Sersic [36] light-profile parameters of the galaxy. Parameter fitting has been performed explicitly using scipy, instead of depending on derived parameters of the SDSS catalog. These steps have been detailed in Appendix A.
4.1 Iterated Hill Climbing

To identify the intensity peaks in the image, it is tempting to sort the pixels in descending order of pixel value and extract the top few pixels. This, however, does not give sufficient information to classify the object as a single-nuclei or double-nuclei galaxy. The top two pixels extracted are likely to be pixel neighbors near the brightest peak. Due to the high chance of foreground stars, which are brighter than the central galaxy, appearing in the field of view, it might lead to erroneous detections. The robust definition of a peak is a pixel whose value is greater than all of its neighbors. Finding a peak is achieved by a discrete hill-climbing algorithm, operating on a 2-D image. We have allowed for an angular resolution of 1”, which translates to a separation of 3 pixels in the cutout image. Hence, the neighbor of a pixel is defined to be the $7 \times 7$ square grid centred on it.

\[\text{HILL-CLIMB}(pt, \text{reg}, \text{img})\]

1. \(\triangleright\) pt - starting point
2. \(\triangleright\) reg - search region
3. \(\triangleright\) img - underlying image
4. newpt $\leftarrow$ NULL
5. while \(pt \neq \text{newpt}\)
6. \hspace{1em} do neighs $\leftarrow$ NEIGHS-IN-REG(pt, reg) \(\triangleright\) Returns the $7 \times 7$ grid neighbors centred at \(pt\)
7. \hspace{2em} newpt $\leftarrow$ pt
8. \hspace{2em} for \(n\) in neighs
9. \hspace{3em} do if \(\text{img}[n] > \text{img}[\text{newpt}]\)
10. \hspace{4em} then newpt $\leftarrow n$
11. \hspace{1em} \(pt \leftarrow \text{newpt}\)
12. return newpt

The input point \(pt\) is initialised randomly within the search region \(\text{reg}\). The procedure is guaranteed to terminate as the pixel value of \(pt\) strictly increases in each iteration until no greater neighbor, centred about it, can be found. ITERATED-HILL-CLIMB iterates over HILL-CLIMB, by seeding random initial points in the search region, and returns a list of peaks thus obtained. It is also to be noted that a peak is accepted only if its signal to noise ratio $\geq 3$. Figure (3) shows the output for example double-nuclei galaxies.

\[\text{ITERATED-HILL-CLIMB}(\text{reg}, \text{img}, \text{iter})\]

1. \(\triangleright\) reg - search region
2. \(\triangleright\) img - underlying image
3. \(\triangleright\) iter - number of iteratons to perform
4. peak_list $\leftarrow$ [ ] \(\triangleright\) Empty list
5. \(i \leftarrow 0\)
6. repeat \(pt \leftarrow \text{CHOOSE-RANDOM}(\text{reg})\) \(\triangleright\) Returns a random point in the region \(\text{reg}\)
7. \hspace{1em} peak $\leftarrow$ HILL-CLIMB(pt, reg, img)
8. \hspace{2em} if peak not in peak_list and SNR(peak) $\geq 3$
9. \hspace{3em} then APPEND(peak, peak_list) \(\triangleright\) Adds peak to the list \(\text{peak\_list}\)
10. \hspace{1em} \(i \leftarrow i + 1\)
11. until \(i = \text{iter}\)
12. return peak_list

4.2 Graph-Searching and Classification

The peaks in \(\text{peak\_list}\) comprise local maxima, the global maxima, and the peak(s) corresponding to the central object in the image. It is the latter which is ascertained by graph-searching. This is exhibited by the sample cases in figure (3a), where ITERATED-HILL-CLIMBING detects a peak on an offset stray object, and figure (3b), where multiple peaks are detected in the object of interest. The procedure CLASSIFY processes the list of peaks and returns one of the three verdicts - NO_PEAK, SINGLE or DOUBLE.
Figure 3: Optima from Iterated-Hill-Climbing

**CLASSIFY**(peak_list, reg, img, signal)

1. \( \triangleright \) reg - search region
2. \( \triangleright \) peak_list - peak list
3. \( \triangleright \) img - underlying image
4. \( \text{comps} \leftarrow \text{CONNECTED-COMPONENTS} \ (\text{reg}) \) \( \triangleright \) Runs depth-first-search
5. \( \text{SORT-BY-DISTANCE} \ (\text{comps}) \)
6. \( \text{group} \leftarrow \text{FIRST-GROUP} \ (\text{comps}) \)
7. \( \text{lcmp} \leftarrow \text{LARGEST-COMPONENT} \ (\text{group}) \)
8. \( \text{pks} \leftarrow \text{FIND-PEAKS-IN} \ (\text{lcmp}, \text{peak_list}) \)
9. \( \text{pks} \leftarrow \text{FILTER-BY-INTENSITY} \ (\text{pks}, \text{img}, \text{signal}) \)
10. \( \text{len} \leftarrow \text{LENGTH} \ (\text{pks}) \)
11. \( \text{if} \ \text{len} \geq 2 \)
12. \( \text{then return} \) DOUBLE
13. \( \text{elseif} \ \text{len} = 1 \)
14. \( \text{then return} \) SINGLE
15. \( \text{else return} \) NO_PEAK

The cutout image is treated as a graph \( G(V, E) \) with pixel coordinates \((x, y)\) as vertices. \( \text{img}(x, y) \) is the function that maps pixel coordinates to intensity values. The edge relation is also defined as \( E \)-

\[
\text{img}(x, y) > \text{noise} \Rightarrow (x, y) \in V
\]

\[
x_2 = x_1 \pm s_x, y_2 = y_1 \pm s_y \Rightarrow ((x_1, y_1), (x_2, y_2)) \in E
\]

\[
s_x, s_y \in \{-1, 0, 1\}
\]

\[
s_x \neq s_y = 0
\]

4.2.1 CONNECTED-COMPONENTS and SORT-BY-DISTANCE

The image graph is not necessarily fully connected. By running depth-first-search, the connected components are enlisted into \( \text{comps} \). Physically, each component represents an indivisible envelope of light intensity. \( \text{comps} \) is sorted by \( \text{SORT-BY-DISTANCE} \) according to the metric, \( m \), which takes a vertex subset, \( v \), as its input (\( v \in \text{comps} \) -

\[
m(v) = \sqrt{(\bar{x} - x_{img})^2 + (\bar{y} - y_{img})^2}
\]

\[
\bar{x} = \text{mean}(x), \bar{y} = \text{mean}(y) \ \forall \ (x, y) \in v
\]

The metric is essentially the radial pixel distance of the centre of a component, from the centre of the cutout image. This is necessary SDSS catalogs celestial coordinates of \( \text{objid} \)s with respect to an object’s centre, and any detected peaks should lie in the intensity envelope corresponding to the given \( \text{objid} \).
4.2.2 **FIRST-GROUP and LARGEST-COMPONENT**

\[
S_i = \{c_j\}, \quad i \in \mathbb{W} \\
i = \left\lfloor \frac{m(c_j)}{10} \right\rfloor \forall c_j \in S_i, \quad c_j \in \text{comps}
\]

The list \( \text{comps} = [c_1, c_2, ..., c_n] \), sorted by metric \( m(v) \), is aggregated into disjoint subsets by the above relation. This contrasts two opposing factors - closeness of an envelope of intensity from the centre of the image, and the relative size of such an envelope. From manual observation of the image samples, it is noted that the underlying image graph is usually disconnected (true of noisy images) and it would be remiss to simply choose the closest component to the centre. **FIRST-GROUP** returns the set \( S_m \) where \( m \) is the smallest number such that \( S_m \neq \phi \) and **LARGEST-COMPONENT** returns the largest component in \( S_m \) which is \( \max(|c_i|), \ c_i \in S_m \), which is then stored in \( lcmp \).

4.2.3 **FIND-Peaks-IN and Sort-by-Intensity**

The procedure **FIND-Peaks-IN** returns \( \text{peak\_list} \cap lcmp \) as they are both sets of the form \( \{(x, y)\} \). This is stored in \( pks \) and any \( \text{img}(x, y) < \text{signal} \) for \((x, y) \in pks\) is discarded by **Filter-by-Intensity**. Based on the length of the remaining list, the verdict of **SINGLE**, **DOUBLE** or **NO_Peak** is returned.

5 Preliminary Detections

![Figure 4: Detections from Blind-Search in Stripe-82](image)

With CasJobs, 100,000 galaxies were chosen at random from the Stripe-82 [2] region and classified by GOTHIC in 4 bands (ugri). The input file is `SDSS_Stripe82_100000.csv` (section 2.2). We present some positive detections that also have spectroscopic data available in SDSS. From their cutout images, it can be seen that their morphology is similar to that of NGC-3758 or MRK-212, from the Gimeno sampling. These are displayed in figure (4). Samples such as 4b, 4c, 4e have their double peaks in the same envelope of light. In all probability, these are true double-nuclei galaxies. The remaining 4a, 4d, 4f are two separate, interacting galaxies.

5.1 **Blind-Searching in Stripe-82**

1. 2,298 galaxies were classified as double-nuclei. These were checked manually for the presence of large foreground stars as SDSS cataloguing is not error free.

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2. 1,246 images were determined to not be dominated by a large foreground star. It was noted that the images from the z-band were extremely noisy/erratic.

3. 854 images had valid entries of photometric redshift at both the detected peaks. Of these 589 galaxies had their double peaks cataloged as unique objid in SDSS, and the remaining 206 had non-identical objid among the their two peaks.

4. 104 of the 854 had spectral information available.

The results from the blind-search are available in SDSS_Stripe82_Results.csv (section 2.2). The distributions of the photometric redshifts and the color diagram of the detected double-nuclei galaxies is given in figure (6). The peak is at $z = 0.356$ with a standard deviation of $\sigma_z = 0.197$, and the Kolmogorov-Smirnov goodness-of-fit test gives a statistic of $\approx 0.05$ and $p$-value of $\approx 0.012$. The distribution of the photometric magnitudes in each of the bands is also given in figure (5).

**5.1.1 Band Statistics**

The maximum simultaneous detection of a double-peaked galaxy was in 4 bands. The maximum detections occured in the i-band with 519 detections. Detection counts and correlations are summarised in table (1) and (2), respectively.

**5.1.2 Detection Accuracy**

The false-positive rate is $\frac{2298 - 854}{2298} \times 100 \approx 62.8\%$. The false negative rate is expected to be minimal as GOTHIC was tested to have 100% accuracy on the Gimeno [20] sample. The high false-positive rate is due to the obstruction of the
field of view by large foreground stars in SDSS images, and also due to the fact that SDSS labels of Star/Galaxy are faulty.

![Redshift Distribution](image1)

![Color Diagram](image2)

Figure 6: Distributions from Blind-Search in Stripe-82

| Bands | u | g | r | i |
|-------|---|---|---|---|
| Total Detections | 90 | 94 | 284 | 519 |
| Exclusive Detections | 76 | 37 | 140 | 390 |
| Maximally Correlating Band | i | g | i | r |
| Detactions with above | 10 | 53 | 123 | 123 |

Table 1: Detection information from Blind-Search

| Bands | u | g | r | i |
|-------|---|---|---|---|
| u | 8 | 8 | 10 |
| g | 8 | 53 | 35 |
| r | 8 | 53 | 132 |
| i | 10 | 35 | 132 |

Table 2: Band Correlation in Blind-Search

5.2 Cross-Matching SDSS with Gaia

In an effort to reduce the false-positive rate, it was decided to crossmatch the SDSS catalog with Gaia in the Stripe-82 regions. By this method, we have sampled another 100,415 galaxies that are devoid of any stars up to 70″. To illustrate how interspersed Gaia stars are among the SDSS galaxies, each galaxy in from SDSS is crossmatched to its nearest star in Gaia. Subsequently, the galaxies are binned, according to the angular distance of the nearest crossmatch, in intervals of 10 arcseconds. The resulting plot for the Stripe-82 region is as shown in figure (7). It was done by the KD-Tree crossmatching utility in astropy. The input file is `SDSSxGaia_Stripe82_100434.csv` (section 2.2)

1. 4,215 galaxies were classified as double-nuclei by GOTHIC
2. 3,573 images were determined to not be dominated by a large foreground star.
3. 3,431 images had valid entries of photometric redshift at both the detected peaks. 3,185 had unique objid in SDSS, and 246 were non-identical.
4. 230 had spectral information available
5.2.1 Plots and Distributions

The results from the crossmatched search are available in SDSSxGaia_Stripe82_Results.csv (section 2.2). The photoZ distribution has nearly the same features as that of the random-search example - a normal distribution with mean at $z = 0.38$ and $\sigma_z = 0.184$. Due to a higher number of galaxies with spectral information available, we have shown the distribution of the schlegel[8] redshift and the color-diagram for the 230 samples in figure (8). The redshift distribution does not have a clear peak, as in the previous case, and the data points in the color-diagram are not as diverse. Double-Nuclei galaxies with spectroscopic data would be necessary to conduct astrophysical studies, and this has been discussed in section (6).

5.2.2 Band Statistics

The maximum simultaneous detection of a double-peaked galaxy was in 3 bands. The maximum detections occurred in the r-band with 1535 detections. Detection counts and correlations are summarised in table (3) and (4), respectively.
### 5.2.3 Detection Accuracy

The results from random-search and crossmatching with Gaia is summarised in table (5). NDFS is the number of detections that are not dominated by a large foreground star, which is significantly higher in the case of crossmatching. The false positive rate is reduced by 82% and the filtered detection rate (double peaks that correspond to a valid objid in SDSS) is increased by 320%.

| Input Size          | Random-Search | Gaia-Crossmatch |
|---------------------|---------------|-----------------|
| GOTHIC Detections   | 2298          | 4214            |
| NDFS                | 854           | 3753            |
| False-Positive Rate | 63%           | 11%             |
| Filtered Detection Rate | $7.95 \times 10^{-3}$ | $3.34 \times 10^{-2}$ |

Table 5: Comparison of Blind and Crossmatched Searches

(NDFS - Not Dominated by Foreground Star)

### 6 Future Scope of Work

The photoZ attribute in SDSS is itself constructed from predictive techniques\cite{14, 12} and does not provide a strong basis for the astrophysical study of any sample of double-nuclei galaxies obtained via the pipeline. Galaxies with available spectroscopic data would be crucial to further studies and new techniques need to be developed to obtain such sample quickly, as only a tiny fraction of galaxies in SDSS have spectral data available. It would also be useful to develop a technique to differentiate between truly double-nuclei galaxies and interacting galaxies, as demonstrated in figure (4).

### 7 Conclusion and Summary

A novel detection pipeline GOTHIC, has been proposed, that given an image of a galaxy from SDSS, determines whether it is possibly a double-nuclei galaxy. It enjoys 100% accuracy in the Gimeno\cite{20} sample of double-nuclei galaxies. Focusing on the Stripe-82 region in SDSS, we have sampled 100,000 galaxies at random and run it through the pipeline. Due to a high false-positive rate by the obstruction of foreground stars in the field of view, an alternative cross-matching technique has been used to intelligently sample the input sources, and its superiority has been demonstrated by its higher detection and lower false-positive rate.

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A Details of GOTHIC

A.1 Scaling/Smoothening

FITS files deliver pixel intensity in units of nanomaggies. Due to shot noise, and possible numerical errors in the SDSS pipeline, some of the pixels have negative values for intensity. This is unphysical and such pixels need to be modified before the smoothening process. If this is not done, the log-normalisation produces a heavily skewed color-scaling, which is unfit for further processing. A $40''$ cutout centred around the object is taken. Then the maximum negative pixel value is found out in the cutout, which is subsequently added to all the pixels. To perform the log-normalisation, a lower and upper limit needs to be supplied, within which the normalisation would be conducted, subsequently followed by convolution with a $5 \times 5$ gaussian kernel -

\[
\text{lower} \leftarrow \max(0.1, \frac{\text{median}(\text{cutout})}{2}) \\
\text{upper} \leftarrow \max(\text{cutout})
\]

![Cutout Image](image1.png)

(a) Before smoothening (b) Gaussian kernel convolved

Figure 9: Smoothening Cutout Image

A.2 Edge Detection

Canny [10] has been used as the standard edge-detector. The edges detected do not necessarily correspond to the physical boundary of the object, since Canny utilizes the Sobel [41] operator which computes a first-order spatial derivative of the image. Using two kernels, the Sobel operator approximates $\frac{\partial}{\partial x}$ and $\frac{\partial}{\partial y}$ at every pixel which is subsequently replaced by $\sqrt{\left( \frac{\partial}{\partial x} \right)^2 + \left( \frac{\partial}{\partial y} \right)^2}$, that constitutes the magnitude of the edge.

Apart from the edges detected at the border of the galaxy envelope, it is possible that some edges of high magnitude are detected within it. Moreover, the edges at the envelope border don’t necessarily form a closed figure. Hence, the convex hull [38] of the edges is used to bound the light envelope of the galaxy in a closed polygon. The statement of the convex hull problem is as follows - Given a set of points $S = \{(x_i, y_i)\}$, find the smallest convex subset $H$ of $S$ such that every member of $S$ lies within the polygon defined by $H$. The definition of a convex subset $H$ is as follows -

\[
(x, y) \in \text{interior}(H) \\
\forall (x, y) \in L \\
\forall (x_1, y_1), (x_2, y_2) \in \text{interior}(H)
\]

where $L$ is the line-segment between $(x_1, y_1)$ and $(x_2, y_2)$, and $\text{interior}(H)$ being the region contained by $H$. In other words, all points in any line segment within the interior of the hull, lie within the hull. Figure (A.10) shows this operation. The procedure accurately bounds the central galaxy within the cutout, however, it’s possible it also includes stray foreground objects within the field of view. This is handled by the techniques discussed in (4.2)
A.3 Intensity Distribution Fitting

The convex hull method, as demonstrated above, usually encloses more than the galaxy envelope. Frequently, stray objects are enclosed within it. For bands with weak signals, the hull might enclose a large region without any appreciable signal. Thus, it is important to identify the pixel value which separates noise and signal. The Sersic [36] profile is widely used to fit the intensity distribution of galaxies. Intensity of light of a galaxy is taken to be a function of the radial distance from its centre. It is typically expressed in terms of the log of the intensity function. This form of is convenient as the original intensity data has been log-normalised. Hence, except by a constant factor, the sersic profile is applicable for intensity fitting -

$$\log I(R) = \log I_0 - k R^{\frac{1}{n}}$$

The parameter $n$ is known as the sersic index, which characterises the shape of the plot. It has been stated in [11] that $1 \leq n \leq 15$ can fit most galaxies. However, we have found that $0.25 \leq n \leq 15$ gives a better fit for our purposes as we are observing the galaxies in 4 different bands.

A.3.1 Translating Frequency to Radius

It is a simple matter to compute the histogram of the pixel intensity values. However, the sersic profile requires intensity values to be fit against radius from the centre of the galaxy, and not its respective frequency count. Thus, it’s necessary to translate the frequency of pixel values to their distance from the centre of a galaxy. This is achieved by finding the number of solutions for (given $R$) -

$$x + y = R$$

$$x, y \in \mathbb{Z}$$
Let the number of solutions be $S_R$. It can be seen that the enclosing rectangle for $S_4$ can be shifted one step outward, except the four vertices, to partially cover the edges of $S_5$, after which 8 points would be remaining. Thus, the recurrence is -

$$S_{R+1} = (S_R - 4) + 8 = S_R + 4$$

The base case is $S_1 = 4$, which gives $S_R = 4R$. In another words, if the number of solutions is taken to be the frequency of a particular pixel value, then $f = 4R$

### A.3.2 Setting the fit function

The maximum pixel value enclosed in the hull region, $P_{\text{max}}$, translates to $\log I_0$ as the cutout has been log-normalised. With $P(f)$ as the inverse of the pixel value-frequency histogram $f(P)$, the function to be fit for the parameters $k, n$ is

$$P(f) = P_{\text{max}} - k \left( \frac{f}{4} \right)^{\frac{1}{n}}$$

![Figure 12: Fitting the Sersic Profile](image)

### A.3.3 Inferring the noise and signal levels

From the fit, the noise and signal levels are inferred which aid in searching the intensity peaks in the image. Peak searching is only performed in those regions that lie above the noise level (noise). This step is necessary as the residual coarseness of the image results in erroneous peaks. We infer the noise level from the radius at which the Sersic fit gives 95% of the integrated light. The signal level is also determined by the same process, but at 50% of the integrated light, and referred to as (signal). The regions of the image above the noise level are marked in turquoise in figure (13b).

![Figure 13](image)