A Catalog of Automatically Detected Ring Galaxy Candidates in PanSTARSS

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Abstract

We developed and applied a computer analysis method to detect ring galaxy candidates in the first data release of the Panoramic Survey Telescope and Rapid Response System (PanSTARRS). The method works by applying a low-pass filter, followed by dynamic global thresholding, to search for closed regions in the binary mask of each galaxy image. Applying the method to $\sim 3 \times 10^6$ PanSTARRS galaxy images produced a catalog of 185 ring galaxy candidates based on their visual appearance.

Key words: catalogs – galaxies: peculiar – methods: data analysis – techniques: image processing

1. Introduction

Ring galaxies are rare irregular galaxies that are not on the Hubble classification scheme. Thérys & Spiegel (1976) proposed a separate classification scheme for ring galaxies that includes three sub-classes based on their visual appearance: empty ring galaxies (REs), ring galaxies with off-center nucleoluses (RNs), and ring galaxies with knots or condensations (RKs). They also identified that most, although not all, ring galaxies have a companion (Thérys & Spiegel 1977). Few & Madore (1986) separated ring galaxies into two sub-classes: “P-type” rings, which have a knotty structure or an off-center nucleolus, and “O-rings,” characterized by a smooth ring structure and a centered nucleolus.

Ring galaxies can be identified as polar rings (Whitmore et al. 1990; Reshetnikov & Sotnikova 1997; Macciò et al. 2005; Finkelman et al. 2012; Reshetnikov & Combes 2015), collisional rings (Appleton & Struck-Marcell 1996), bar-driven or tidally driven resonance rings (Buta 2000), ringed barred spiral galaxies (Buta et al. 2001), and Hoag-type objects (Longo et al. 2012). The “Hoag’s Object” (Hoag 1950; Brosch 1985; Schweizer et al. 1987) was discovered in 1950, and its discovery was followed by the identification of other ring galaxies.

Catalogs of ring galaxies were created in the past by manual observation. The early Arp (1966) catalog of peculiar galaxies contains two galaxies with the visual appearance of an empty ring. The catalog of southern peculiar galaxies (Arp & Madore 1988) includes 69 systems identified as rings. Whitmore et al. (1990) compiled a list of 157 polar ring galaxy candidates, and about half a dozen of these objects were confirmed as polar ring galaxies by kinematic follow-up observations (Finkelman et al. 2012). Madore et al. (2009) prepared an atlas of collisional ring galaxies. Garcia-Ribera et al. (2015) discovered 16 polar ring galaxy candidates. Buta (1995) created a catalog of Southern ring galaxies. Moiseev et al. (2011) used crowdsourcing and non-scientist volunteers to prepare a catalog of ring galaxy candidates through the Galaxy Zoo citizen science campaign.

While manual analysis performed by expert or citizen scientists has provided useful catalogs of ring galaxies, the rapidly increasing data acquisition power of digital sky surveys such as the Large Synoptic Survey Telescope (LSST) can potentially allow the identification of a very large number of ring galaxies among billions of astronomical objects. Due to the large sizes of these databases, effective identification of these objects requires automation, leading to the development of automatic methods of identifying peculiar objects in large databases of galaxy images (Shamir 2012, 2016; Shamir & Wallin 2014). Here we describe an automatic image analysis method that can identify ring galaxies and apply the method to mine through $\sim 3 \times 10^6$ galaxies imaged by the Panoramic Survey Telescope and Rapid Response System (Hodapp et al. 2004; Chambers et al. 2016; Flewelling et al. 2016) to compile a catalog of ring galaxy candidates.

2. Methods

2.1. Data

The data set was obtained from the Panoramic Survey Telescope and Rapid Response System (PanSTARRS) first data release (Hodapp et al. 2004; Flewelling et al. 2016; Chambers et al. 2016). The initial data set includes 3,053,831 objects with $r$ magnitudes of less than 19. To avoid stars, the data set included 2,394,452 objects identified as extended sources in all bands, and 659,379 additional objects that were not identified as extended objects in all bands, but their PSF $i$ magnitudes, subtracted from their Kron $i$ magnitudes, were larger than 0.05, and their $r$ Petrosian radii were larger than 5.75. Objects that were identified as artifacts, objects that had a brighter neighbor, a defect, a double PSF, or a blend in any of the bands were excluded from the data set, as such objects require time to download and process while also significantly increasing the false positive rate.

The images were then downloaded via the PanSTARRS cutout service as $120 \times 120$ JPG images, in a process similar to the image download done in Kuminski & Shamir (2016). The JPG images that were downloaded and analyzed were the $g$ band images, as the $y/i/g$ color images were in many cases noisy, and did not allow effective automatic analysis. To avoid pressure on the PanSTARRS web server, one image was downloaded at a time, therefore the processes required 62 days to complete.

The initial scale was set to $0.025$ per pixel. As done in Kuminski & Shamir (2016), after each image was downloaded, all pixels located on the edge of the frame with grayscale values higher than 125 were counted. If the number of pixels was 25% or more of the total number of pixels on the edge, the scale was increased by $0.005$, and the image was downloaded again. This was repeated until the number of foreground pixels on the edge
was lower than 25% of the total edge pixels. The change in scale helped us to analyze objects that were initially too large to fit in a $120 \times 120$ image using the initial $0.25$ per pixel scale.

Images that contain substantial noise or artifacts are difficult to analyze correctly and can trigger false positives, as will be explained in Section 2.2. Due to the large scale of the initial data set, even a low rate of false detections can lead to an unmanageable data set. Because compression algorithms are more efficient when the signal is smooth, clean images of real galaxies tend to have a smaller compressed file size, therefore artifacts and noisy images can be rejected by their compressed file sizes (Kuminski & Shamir 2016). Table 1 shows examples of galaxy images and their file sizes. Based on empirical observations, a threshold was set so that only images with file sizes of less than 5.5 KB were analyzed and larger files were rejected.

### 2.2. Galaxy Image Analysis

Each image is smoothed utilizing a median filter with a window size of $5 \times 5$ to facilitate noise reduction and is converted to grayscale. The image is then converted into its binary mask using a dynamic threshold. The dynamic threshold starts with a minimum of 30, and is incremented iteratively until it reaches the gray-level of 200. The conversion of the original ring galaxy into a binary map is displayed by Figure 1.

For each threshold level the binary mask is computed, and a search for a ring inside the foreground is performed using a flood fill algorithm (Asundi & Wensen 1998). Figure 2 shows the binary maps of a ring galaxy at different gray-level thresholds. Flood fill is an algorithm typically associated with the “bucket fill” tool in painting programs. Here, we used a stack-based 4-connected version of the flood fill algorithm, which is a non-recursive process that starts with an initial pixel and then analyzes the four pixels surrounding it. Each of these four pixels is flagged, and then their neighbors are also added. That continues until all pixels are flagged, or no neighbors with values of 0 remain. In that case it is determined that no paths of pixels with values of 0 to the edge exist, therefore the image is suspected to be a ring galaxy. However, if a pixel that is on the edge of the image is flagged, the algorithm stops and it is determined that no ring exists in that gray-level threshold.

The flood fill algorithm is applied for each pixel in the binary mask. If the flood fill algorithm finishes without reaching a pixel that is on the edge of the frame, the number of pixels in the closed area is counted, and divided by the number of foreground pixels. If the number of pixels in the closed area is less than 10% of the number of foreground pixels, it is assumed that the closed area is too small to be considered a ring galaxy. Figure 3 shows an example of closed areas in the binary mask that can be considered candidate rings (left), and small areas in the binary mask of the same image that are merely local grayscale variations (right).

| PanSTARRS object ID | File size (KB) | Image |
|---------------------|---------------|-------|
| 102230806134866752   | 9.40          |       |
| 103480451533225122   | 9.58          |       |
| 103570759842751155   | 9.43          |       |
| 100840464055080903   | 3.17          |       |
| 104720155726185389   | 3.10          |       |
| 10494142843081464    | 3.88          |       |

**Table 1.** Examples of Clean Galaxy Images and Artifacts or Noisy Images in PanSTARRS.

**Note.** The file size provides a simple mechanism to reject noisy images.
Processing a small 120 × 120 galaxy image using a single core of an Intel Xeon E5-1650 requires ~2.1 s to complete.

2.3. False Detections

When mining through a very large number of galaxies, even a small rate of false detections can lead to an unmanageable database. Of over three million images that were tested, the algorithm detected 2490 galaxies in which manual inspection showed no ring. These galaxies included artifacts, saturated objects, and regular galaxies. Figure 4 shows examples of false detections of galaxies as rings. However, these objects are fairly rare, and the false detection rate is less than 0.1% of the initial set of galaxies.

Another aspect related to false detection is confusion between ring galaxies and ringed disk galaxies (Buta 2013). That difference, however, is more difficult to identify automatically, as ringed disk galaxies normally feature ring-like structures as nuclear, inner, or outer rings.

3. Ring Galaxy Candidates

The ring galaxy candidates that were detected with their R.A. and decl. coordinates are shown in Table 2, ordered by right ascension.

PanSTARRS images of the galaxies are displayed in Figures 5–8.

3.1. Comparison to Madore Collisional Ring Atlas

To assess the completeness of the catalog, the detected galaxies were compared to the Madore et al. (2009) catalog of collisional ring galaxies. The objects listed in Table 3 are objects from that catalog that are inside the footprint of PanSTARRS Data Release 1. The table shows the corresponding PanSTARRS object ID and the Kron magnitude measured on the r band, which is used as a criterion for...
### Table 2 (Continued)

| No. | Object ID          | R.A. (°) | Decl. (°)      |
|-----|--------------------|----------|---------------|
| 121 | 1435743384637652   | 19.1729  | 13.0836       |
| 122 | 1302843753075032   | 18.5284  | 12.7563       |
| 123 | 1487853874689022   | 18.9136  | 12.7563       |
| 124 | 1671023653475512   | 19.2834  | 12.7563       |
| 125 | 1843732244092001   | 19.6482  | 12.7563       |

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Table 2 (Continued)

| No. | Object ID          | R.A. (°) | Decl. (°)      |
|-----|--------------------|----------|---------------|
| 126 | 1302843753075032   | 18.5284  | 12.7563       |
| 127 | 1487853874689022   | 18.9136  | 12.7563       |
| 128 | 1671023653475512   | 19.2834  | 12.7563       |
| 129 | 1843732244092001   | 19.6482  | 12.7563       |

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### Table 2 (Continued)

| No. | Object ID          | R.A. (°) | Decl. (°)      |
|-----|--------------------|----------|---------------|
| 130 | 131190967335703   | 19.1729  | 13.0836       |
| 131 | 1435743384637652   | 19.1729  | 13.0836       |
| 132 | 1671023653475512   | 19.2834  | 13.0836       |
| 133 | 1843732244092001   | 19.6482  | 13.0836       |

| inclusion of objects in the initial data set, as described in Section 2. When multiple object IDs are associated with the same extended source, the selected object ID is the object whose photometric information is the closest to the photometry...
threshold for selecting the objects as described in Section 2.1. The PSF \( i \) magnitude subtracted from the Kron \( i \) magnitude was also used as a method for filtering objects that are not galaxies, as well as for the identification of the objects as extended sources in the \( g, r, i, \) and \( z \) bands. When \( i \)PSFMag-\( i \)KronMag is larger than 1000 it means that one of the \( i \)KronMag readings was bad, leading to a \(-999\) value. The table also shows what objects were detected as rings by the algorithm by downloading the image directly from the PanSTARRS server and running the algorithm.

With the exception of NGC 4774, the objects are not included in Table 2. The reason for the exclusion of these objects from the catalog could be the inability of the algorithm to detect them, as in the case of Arp 145, Arp 146, NGC 985, and Arp 150. Arp 145 is a relatively dim ring, and in the cases of Arp 150 and Arp 146, the ring is not full, therefore the method failed to detect it.

Figure 5. PanSTARRS images of resonance rings in ordinary galaxies.
due to an opening in the ring that allows the flood fill to “escape” from the ring and reach the edge of the frame. These systems were included in the initial list of galaxies, but were not detected due to the inability of the method to detect them.

An interesting case is the object VII Zw 466, which was used as the object for demonstrating the algorithm in Section 2.2, but was not detected when applying the algorithm to the PanSTARRS images. The reason is that the PanSTARRS photometric object associated with it, which was in the initial list, is not the center of the ring, as shown by Figure 9. Because the object was not centered, the full ring was outside of the frame, and due to the few bright pixels on the frame the object was not identified as too large, and was therefore not rescaled as described in Section 2.1.

The other objects were not included in the initial list of objects described in Section 2.1. For instance, Arp 318 is a group of “faint, diffuse streamers, peculiar galaxies” (Arp 1966), and as such is outside the scope of objects that can be identified by the algorithm described in Section 2. It also has a bad rKronMag measurement and was not detected as an extended source in any of the bands. Arp 10 also has a bad rKronMag measurement, and Arp 273 has a bad iKronMag measurement as well and was identified as an extended source.

| Catalog Name | PanSTARRS Object ID | R.A. | Decl. | Included in Table 2 | r Kron Magnitude | iKronMag-ipsfMag | Extended Source Bands | Ring Detected by the Algorithm |
|--------------|----------------------|------|-------|---------------------|------------------|-------------------|------------------------|-------------------------------|
| Arp 146      | 100030016843707022   | 1.6841 | −6.635 | No                  | 15.97            | 3.34               | r, i, z                | No                           |
| Arp 318      | 95800323797258621    | 32.379 | −10.159 | No                  | 22.492           | 1022.611           |                        |                              |
| Arp 10       | 114770346040298405   | 34.609 | 5.653  | No                 | −999             | 1020.9             |                        | No                           |
| Arp 273      | 155240353777382539   | 35.377 | 39.366 | No                 | 15.42            | 1021.098           | g, r                   | No                           |
| Arp 145      | 157650357813012712   | 35.785 | 41.372 | No                 | 16.59            | 4.68               | g, r, i, z             | No                           |
| NGC 985      | 97450365522587254    | 38.657 | −8.787 | No                 | 15.7             | 4.12               | g, r, i, z             | No                           |
| Arp 118      | 107770437986659641   | 43.795 | −0.181 | No                 | 13.2             | 5.22               | r, i, z                | Yes                          |
| Arp 147      | 109570478265116474   | 47.829 | 1.315  | No                 | 16.89            | 0.86               | r, i, z                | No                           |
| Arp 219      | 105450549711618738   | 54.975 | −2.118 | No                 | 17.14            | 3.8                | r, i, z                | Yes                          |
| Arp 141      | 196161085846518933   | 108.585 | 73.477 | No                 | −999             | 1020.056           | g                       | No                           |
| Arp 143      | 144021167270940513   | 116.723 | 30.019 | No                 | 20.18            | 0.98               | g, r, i, z             | No                           |
| NGC 2793     | 14931139115893056    | 159.197 | 34.430 | No                 | −999             | 0                  | z                       | No                           |
| Arp 107      | 144071630704802930   | 163.069 | 30.065 | No                 | 16.87            | 3.8                | r, i                    | No                           |
| Arp 148      | 157011659698568092   | 165.972 | 40.849 | No                 | 17.14            | 0                  | g, r                    | Yes                          |
| VII Zw 466   | 187681880151285551   | 188.018 | 66.404 | No                 | 16.76            | 2.73               | g, r, i                 | Yes                          |
| NGC 4774     | 152191932750252225   | 193.275 | 36.823 | Yes                | 15.459           | 1.7                | g, r, i, z              | Yes                          |
| Arp 150      | 119403498802526691   | 349.880 | 9.505  | No                 | 15.18            | 4.85               | g, r, i, z              | No                           |

Figure 6. PanSTARRS images of collisional rings.

Figure 7. PanSTARRS images of ring galaxies with off-center nuclei.

Table 3

Collisional Ring Galaxies from (Madore et al. 2009) That Are Inside the Footprint of PanSTARRS DR1
Autonomous sky surveys have enabled the acquisition of very large databases of images and other data, substantially increasing the discovery power of ground-based and space-based telescopes. To utilize this discovery power and turn these data into scientific discoveries, it is necessary to apply computational methods that can mine these very large databases. Since a substantial part of these data are in the form of images, full analysis of the data requires image analysis methodology. Here, we use a simple and fast automatic image analysis method and apply it to the PanSTARRS first data release to detect ring galaxy candidates. Despite the simple nature of this image analysis method, it can find ring galaxies that are highly difficult to find without using automation, and it is sufficiently fast to be applied to much larger databases such as LSST.

This finding shows that it is reasonable to assume that many more objects with ring structures could exist in PanSTARRS DR1, and were not detected in this experiment. Identifying all objects in PanSTARRS will require the improvement of the algorithm so that it can better handle “edge” cases, but also analyses of a larger data set of PanSTARRS objects, as it is possible that many relevant objects did not meet the criteria for the initial data reduction. The PanSTARRS photometric pipeline can in some cases provide bad measurement values (e.g., “−999”) or fail to identify an extended source, leaving the object outside of the initial list of galaxies. The initial data reduction is required for reducing the very large PanSTARRS data set of over $3 \times 10^7$ objects to a “manageable” number of galaxies that can be downloaded and analyzed. Some objects, such as Arp 138, are too large or have morphologies that cannot be identified by the proposed algorithm. However, this study shows that applying a first step of automatic image analysis can identify objects that would require substantial labor to identify manually.

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4. Conclusion

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