Creating updated, scientifically-calibrated mosaics for the RC3 Catalogue

Abstract

The Third Reference Catalogue of Bright Galaxies (RC3) is a reasonably complete listing of 23,010 large, bright galaxies. Using the latest Sloan Digital Sky Survey's Data Release 10 (SDSS DR10) data, we provide color composite images and scientifically-calibrated FITS mosaics in all SDSS imaging bands, for all the RC3 galaxies that lie within the survey's footprint. To get a larger sky coverage, we then conduct the procedures on photographic plates taken by the Digitized Palomar Observatory Sky Survey (DPOSS) for the B, R, IR bands. Due to the positional inaccuracy inherent in the RC3 catalog, the mosaicking program uses a recursive algorithm for positional update first, then conduct the mosaicking procedure using IPAC's Montage.The program is generalized into a pipeline, which can be easily extended to future survey data or other source catalogs.

1. Introduction

Astronomical catalogs such as the famous Messier Catalog and New General Catalog (NGC) has its historical usage in helping astronomers who are studying objects that shares some common property. This was particularly important in the days when all-sky information was not available, so data was taken by pointing the telescope at some particular location. Wide sky surveys such as the Sloan Digital Sky Survey(SDSS), Digitized Sky Survey (DSS), and Two Micron Sky Survey (2MASS) not only provide improved astrometry for finding these objects, but also photometry and systematics that could affect the imaging of the detected sources, such as information generated through SDSS's `photo` pipeline (Lupton et al. [10]). With large sky surveys such as the SDSS, the job of target-based imaging is a lot easier since the position values of objects of interest are readily accessible via NED/ SIMBAD. The role of the astronomical catalogue has evolved into samples for statistical studies for some particular type of object (QSO, pulsars, x-ray sources) or used in cosmology studies.

There has been existing literature on making mosaics for RC3 galaxies using data from the Sloan Digital Sky Survey(SDSS). Hogg and Blanton made g,r,i colored images of selected RC3 galaxies by using data from the SDSS DR6.[1] The EFIGI catalog (Baillard et al. [2]), dedicated to studying morphology of galaxies, also obtained a subset of 4458 RC3 FITS and color images using SDSS DR4 data and discarded artifacted or missing data via visual inspection. We perform the mosaicking procedures on the whole RC3 catalog using an automated positional update algorithm on the most recent SDSS DR10 imaging data. In addition, we designed a mosaicking pipeline that creates scientifically-calibrated mosaics, color-band images, as well as a set of updated positions, which can be easily adapted for existing surveys such as Two Micron All Sky Survey (2MASS),The Palomar Digital Sky Survey (DPOSS), or future imaging data release from Dark Energy Survey (DES) and Large Synoptic Survey Telescope (LSST) for larger sky coverage and multiband images.

2. The RC3 Catalog and Survey Data

The attempts to select catalog object based on brightness selection limit to traces back to original Harvard Survey of the External Galaxies (H. Shapley and A. Ames 1932) which contained 1249 objects (mostly galaxies) brighter than the 13th magnitude. Many of these were included in the University of Texas monographs in astronomy, predecessors to the Third Reference Catalog of Bright Galaxies (RC3) catalog .The RC3 Catalog is an update of the Original and Second Reference Catalog of Bright Galaxies, which collected from 150 different sources, each telescope has different accuracy, precision, and coverage. The RC3 compiled by de Vaucouleurs et al. [5], contains a complete listing of 23,010 galaxies with D_25 apparent major isophotal diameter greater than 1 arcminute and with a total B-band magnitude greater than 15.5 nanomaggies. After the RC3 catalogue was published was incrementally updated from any available data and maintained by Harold G. Corwin.[2] Since imaging data used to update these sources came from various different imaging program (telescopes), there is a non-uniform of gaalxies that were updated. In this project, we used the catalogue information available through the VizieR Service which contained the original RC3 data published in 1991.There is also a 1994 version updated by Corwin available on VizieR.

Since the RC3 catalog is a reasonably complete representation of large, bright nearby galaxies in the extra-

[1] `http://cosmo.nyu.edu/hogg/rc3/`

[2] http://haroldcorwin.net/rc3/bugs.rc3

galactic sky, its usage is still evident in literature. Selected galaxies or complete subsets are used in astrophysical studies of quasars and X-ray sources(Walton et al. [14]) or galaxy morphology and properties. The RC3 catalog is also used in statistical studies for cosmology studies such as the New York University-Value Added Galaxy Catalog (NYU-VAGC).

2.1. Positional Inaccuracy in RC3 Catalog

The principle motivation behind the automation algorithm is to resolve the problem of centering galaxies and finding RC3 galaxy in a given field of view. Initially, using the standard mosaicking steps in Montage, we obtained many images with off-centered or missing galaxies due to the inherent inaccuracy of the positions in the catalog. There is an non-uniform update of the catalog after the catalog was publish, more accurate position was collected from whatever sources/data they had access to. The B2000 coordinates (FK4 frame) in the RC3 catalog are denoted with two different levels of accuracy: HH MM SS.s, DD MM SS for the positions that has been updated (with accuracy of about 5-8 arcsec) and HH MM.m, DD MM for galaxies whose positional accuracy remain 1-2 arcminutes in the original catalog. In the latest version of the catalog (de Vaucouleurs et al. [6]), there remains 5492 RC3 galaxies that fall in the latter group.

2.2. Data

Figure 1: PGC120 mosaic using SDSS, DSS, 2MASS data

2.2.1. SDSS

SDSS is a optical 2.5m telescope at the Apache Point Observatory in New Mexico. We use the imaging data from Data release 10 which is part of the SDSS-III. SDSS-III is dedicated to studying galaxy clustering by looking at signatures of Baryon Acoustic Oscillation,structure and history of the galaxy , and the population of exo-planets. Feeding the SDSS data into the mosaicking pipeline has several advantages over data from other surveys, 1) It is one of the newest all-sky survey so has improved instrumentation and telescope compared to DPOSS. 2) (Not actually sure about this??) On a related note, the resolution of SDSS is better than 2MASS and DPOSS. 2MASS has a "tile" size, each tile is larger than a field in DPOSS ,smaller than Photographic plates in , so each pixel represents — -degree, which is much larger than SDSS's pixel size of —-.

(TALK ABOUT HOW SDSS IMAGING DATA IS PROCESSED; SEE PHOTOLITE PAPER LUTPON) The SDSS data is pass through `photo` pipeline, deblending, source , The data is queried using SkyServer through a SDSS Command Line Query Tool. Then the the calibrated, sky-subtracted corrected frame with the calibration meta-data (`fpC`) is retrieved in bulk from the Science Archive Server (SAS).

2.2.2. 2MASS

The Two Micron All Sky Survey (2MASS; Skrutskie et al. [12]) is a infared survey in the J(1.25 μm), H(1.67 μm), and K(2.17 μm) bands. Data taken from two 1.3m telescope covered 99.998% of the sky where each overlapping"survey tile" is 6 degree long by 8.5 arcminute strip for telescope schedulling purposes. The raw data processed through the 2MASS Production Pipeline System produces astrometrucally and photometrically calibrated , and source extracted atlas images that we use as inputs for our mosaicing porgram. Since the RC3 catalog contains large galaxies, we narrowed down our imaging data search to 2MASS's Extended Source Catalogs which contained only 1.6 million objects that are extended with respect to their instantaneous PSF. Some of the RC3 galaxies (larger than 120") is contained in the 2MASS Large Galaxy Atalas, a subset of the Extended Source Catalog. (Does 2MASS have more advantage in better seeing "cooler" object that give off thermal radiation?) The motivation in using 2MASS data is its large all-sky cover, however since each "survey tile" is large, the imaging resolution is lower. 3) Also, multiband recombined color image for 2MASS is less of a "true color" compared to SDSS. When mapping 2MASS's J,H,K band, the relative values show up (which is longest wavelength and shortest), so the contrast in feature is shown. But it is not true color.Since SDSS is an optical survey, it obviously "looks" much better than 2MASS's infrared data since mapping g,r,i band to R,G,B is approximately accurate in value.

- The benefit of smoother larger pixels (why?)

2.2.3. POSS-II

The Second Palomar Observatory Sky Survey (POSS-II) was a photographic survey that covered most of the northern nightsky in the B, R, IR bands. It is a update to POSS-I which was was one of the first major all-sky photographic survey. We also serve FITS mosaics from POSS-I which contains only the B and R band data taken in the 1950s to serve as comparison. This data can also be joined with another single band survey for RGB mapping (CITE: Make pretty color images, see email attachment for paper) and create colored mosaics.

The photographic plates used to create our data product was made accessible through STScI's effort in the Digital Sky Survey (DSS) project. The DSS data consists a set of photographic plate data from POSS-I,II and UK Schmidt Telescope Survey. For DSS, the data querying is done by through NASA/IPAC Infrared Science Archive's

(IRSA) Finder Program Interface. Each photographic plate is 6° by 6° of the sky. After lossy compression, each plate is 1.1 GB. A cropout of the plate can be retrieved to speed up computing time. Due to the large size of these plates, the program rarely has to stitch together multiple fields, only the positional update algorithm is executed.

Even though DSS has the advantage of a greater sky coverage than SDSS, objects near the boundary on photographic plates suffers from distortion, [# What is the name for this distortion effect?] which may result in inaccurate astrometry for those objects. Another disadvantage of photographic plates is that it is much less sensitive to photons($\approx$ 1% quantum efficiency) compared to CCD ($\approx$ 80%). However, this does not affect the mosaics as much because RC3 objects are bright.

3. Mosaic Pipeline and algorithms

3.1. Algorithm

To address the problem of inaccurate positions discussed in subsection 2.1, we develop an algorithm that first updates the position by finding the galaxy in the imaging data. An `RC3` object contains its The Catalogue of Principal Galaxies (PGC) number, updated and catalog ra,dec,radius for each galaxy in the RC3 catalog. Since every RC3 galaxy has a unique PGC number, we record its PGC number in order to identify the RC3 galaxy of interest for cases of source confusion. The method `source_info` updates the position of individual RC3 objects by first creating a single band mosaic with a field of view 6 times the radius of the galaxy, then SExtractor detects all sources in the mosaic and select only the ones with a radius greater than 5.94 arcseconds. If the mosaicking field is chosen correctly, then SExtractor's sky level estimation is fairly accurate. Nevertheless, this size cut is large enough such that it eliminates most of stellar point sources and mistaken background noises but retains the subset of RC2 galaxies inside the RC3 Catalog that are smaller than 1 arcminute as described in de Vaucouleurs et al. [7].

If there are multiple galaxies in the field of view that satisfy this criteria, then it is passed into the source confusion algorithm to verify which one is the galaxy of interest. Then we record the single source of interest and generate mosaic FITS file for all bands and color images. If no sources are detected, then we mosaic the single band FITS using a larger field of view. This is done recursively, while keeping track of the number of iterations in each recursive steps. The process is terminated at the 5th recursive step and generates a mosaic for each bands. Then we select mosaics from 3 imaging bands and recombine them to make two colored mosaic. One emphasizes on low surface structures so that the halos around the galaxy can be seen; the other image is a poster/publication image that uses higher cuts on the background to ensure a clean contrasting image. 3 band passes is necessary for generating a colored image it enables (relative??) R,G,B mapping, also it is the number of imaging bands chosen by many surveys since it is the minimum number of bands required to distinguish the effects of interstellar extinction and distinguish stellar and extra-galactic population (Skrutskie et al. [12]).

3.2. Source Confusion

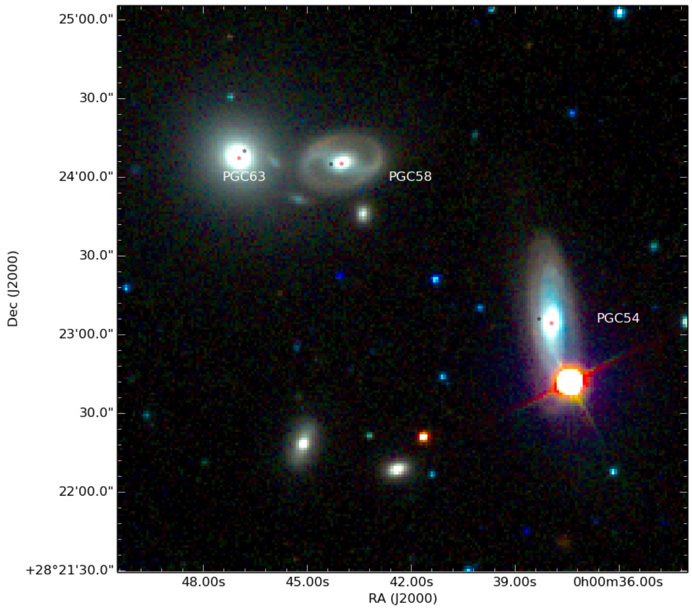

Figure 2: 3 source confused RC3 Galaxies; Green marker denotes coordinates denoted in the RC3 catalog, red marker denotes coordinates updated by the algorithm

Large galaxies tends to form gravitationally bound structure known as galaxy clusters . The source confusion algorithm works on the assumption that the only galaxies that are large enough to cause source confusion also lie in the RC3 catalog, since the catalog is reasonably complete for galaxies having apparent diameters larger than 1 arcmin. First, the program retrieves a list of n number of RC3 galaxies that may lie in the field of view of the generated mosaic. The `otherRC3` method in the `Server` class queries this information using the Vizier Catalog. If this information is provided by a survey's query service (such as the RC3 Table in SDSS's SkyServer), it can be overridden. The goal is to match the results returned by the server with the list of n largest sources detected by SExtractor.

(a) Before (b) After

Figure 3: Using source confusion algorithm to generate mosaic centered at PGC58

We need to cross-correlate the coordinate by matching together the relative differences between the sources, due to the unreliability of absolute coordinates inherent to the catalog as discussed in section 2.1. We assume that the positional inaccuracy is due to instrumentation and measurement error but retains the galaxies' relative locations. Therefore, we compute all the possible distances between any two RC3 galaxies that lies in our field. Then compare this with the set of differences generated by the SExtractor-generated list. We select n number of galaxies that has the closest values in both list, thereby matching together the galaxies from the catalog with the detected sources. Finally, we mosaic using that galaxy's coordinates as center. Our premises proves to be valid, as the algorithm executed with a success rate of 99.97% in the SDSS run, and is capable of correctly resolving up to 8 RC3 sources in one example.

3.3. Class Hierarchy

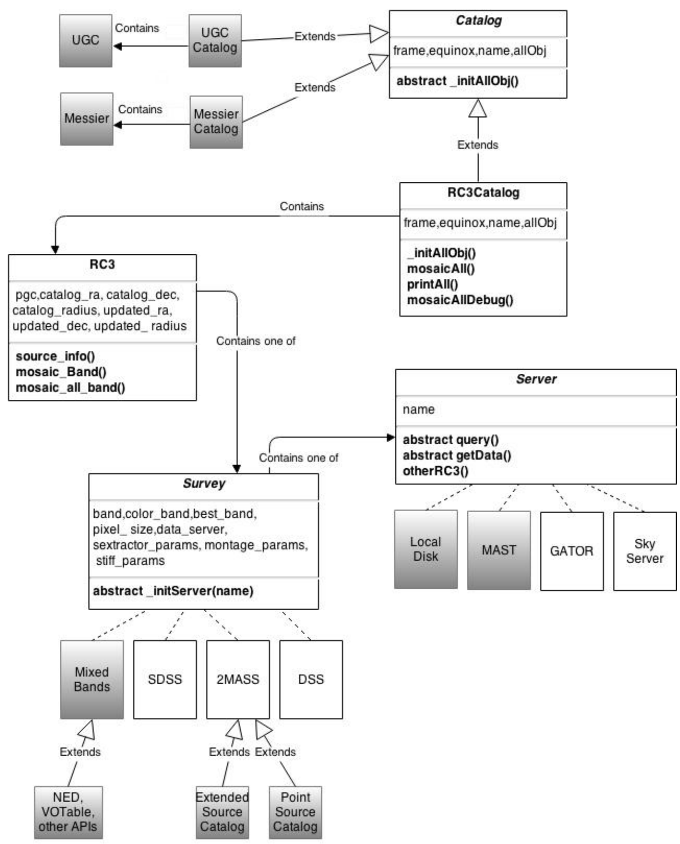

Figure 4: UML Class diagram for mosacking pipeline. Greyed out boxes are possible extensions of this pipeline

The motivation behind building a class hierarchy is to establish a mosaicking pipeline for any given catalog and survey data. We identify the essential components required for mosaicking program to work. The relationship between these essential steps are reflected in our design of the abstract `Survey`,`Catalog`, and `Server` classes.

Server. Data acquisition is composed of two main tasks: querying imaging data and retrieving data from server. Most surveys have an API that enables data access by SQL or customized query. To make the `Server` class work, we need to figure out how to convert positional values to record-keeping parameters dependent on the survey's telescope. For example, SDSS image frames are uniquely identified by a particular combination of run, camcol, and field and 2MASS refers to this with its sexagesimal, equatorial position-based source name. In the case where the survey has no special name referring to the imaging frame, such as in the case of DSS , the user can invent their own naming scheme as placeholders for naming the raw imaging data. This step can usually be done using the SQL search. In addition to these two essential functions, each `Server` class should also implement the query builder methods that are used inside the main mosaicking program. Our choice of using a server instead of a data object enables code reusability across various surveys that uses common server tools , such as IPAC's GATOR query service (Alexov et al. [1]) or Astroquery.

Catalog Objects. For the purpose of mosaicking RC3 galaxies, we did not create a `CatalogObject` class, although it would be helpful to have a generic class similar to the functions in `RC3Objects` as an extension to the pipeline. They contain basic information about the particular object and are survey-independent. They perform the essential mosaicking features on a per-object basis so that they not only can be further used in the `Catalog` class but they could also be easily used for comparing resulting mosaics from multiple surveys. The final step in the mosaic procedure generates 2 TIFF color images as described in Section 3.1. When extending the pipeline to other surveys, investigators can adjust the STIFF parameters to better suit the telescope-specific imaging details following the guidelines in Bertin [3].

Catalog. The `Catalog` class contains a list of objects that lies inside the catalog. Although the use of the Catalog container class seem unnecessary, it enables a clear separation between basic mosaicking functionality for individual galaxies and for the entire catalog. This can be used to study some particular object, executed on all objects in a `Catalog`, or simply used for debugging purposes. This abstraction barrier ensures minimal changes to the code in both classes when an investigator decides to input data from a new survey in the future.

4. Results

4.1. Result from SDSS/DPOSS run

There are a total of 12512 RC3 galaxies within the SDSS footprint. The automated mosaicking pipeline was successful for 90.22% of the galaxies. 2446 RC3 galaxies is mosaiced using an updated position that was more than 1 arcminute off the values recorded in the RC3 catalog. On (

bigdog specs) machine, the program processes on average about 80 RC3 objects per hour using SDSS data. The finished data product occupies 39 GB of diskspace.

(# More stats on this after DSS finishes its run)

For the DPOSS Run, there are a total of [*] galaxies within the POSS-II footprint. The automated mosaicking pipeline was successful for[*] % of the galaxies. 2446 RC3 galaxies is mosaiced using an updated position that was more than 1 arcminute off the values recorded in the RC3 catalog. The program processes on average about 18.6 galaxies per hour using SDSS data. The finished data product occupies [*]GB of diskspace.

4.2. Performance

We accelerate the mosaicking process by performing the recursive algorithm on only a single band FITS file designated as `best_band`, then mosacking all bands only once per object. For SDSS, we use the image obtained by the r band filter since transmission curve in Stoughton and Bernardi [13] shows that r band has the highest quantum efficiency. For 2MASS, The K_s band was chosen to be the `best_band` since it has the highest transmission as shown in Figure 2 of Skrutskie et al. [12].

Most of the computation time is spent on downloading the raw FITS files from the survey's specific server. Therefore, even though Montage's modular design enables its performance to scale with number of processor (Jacob et al. [8]), the process would not be significantly sped up by the use of Message Passing Interface (MPI). Therefore, the speed depends more on the bandwidth (downloading rate) rather than the number of cores in the machine. This average runtime would also depend on the sky coverage of the particular survey and the speed of query.

This process can be significantly sped up if the investigator already has imaging data stored locally on a disk or have access to running the mosaic program alongside the survey's datacenter. We have designed our class hierarchy such that this can be written as a subclass of `Server` with user-defined details of where the images are stored.

4.3. Technical Details

Due to the recent surge in popularity of Python in astronomy, we wrote the program in Python 2.7.6 so that the program's dependencies are more widely supported for extending its usage on future datasets. Most of the mosaic steps are done using IPAC's Montage [8] mosaic engine along with the AstroPy Montage wrapper[3] and the final colored image is created using Astromatic's STIFF v.2.4 [3]. Our choice of the two program makes use of the best features from both programs. Montage creates scientifically-calibrated images by retaining the astrometry and photometry of input sources during image reprojection step. STIFF provides the flexibility of adjusting many variables for the final colored image, as well as automatically estimating upper and lower cuts on the dynamic range using statistics derived from a pixel histogram. The source extraction is done using SExtractor v.2.19.5 [4]. The resulting web search database was created using the Python sqlite3 module and the web search interface was written with PHP.

[3] `http://www.astropy.org/montage-wrapper/`

4.4. Known Errors

Even though a series of exception handling and error prevention mechanisms were put in place, there are still errors in the data product that we produced. Error flags were put inside the web search database denoting the errors described below.

```
Error Information
0 = no error
1 = mosaicAll error
2 = stiff error
3 = strange error
4 = Montage image reprojection failure
5= mSubImage failure
```

1. mosaicAll error is a general error that is raised when the program breaks when mosaicing all bands.
2. STIFF enforces that the mosaic FITS used for RGB mapping but must be exactly the same dimensions in order to generate a colored image. Sometimes no resulting color images produced because 3 colored band not the same size. This happens particularly more often in SDSS's g band and in DPOSS (Not sure what this happens more in the g band specifically??). This also happens more often in DPOSS data since the photographic plates are non uniform in size.
3. In the source confusion algorithm, we store the galaxies that pass the size cut inside a radius with PGC as key and position as values. This error flag is raised when sql region search does not included the galaxy itself.
4. `mProjectExec` is the Montage procedure that creates the reprojected image from the raw FITS files. Sometimes reprojected images are not created even when Montages' debug statement clearly shows that the reprojection was successful and table and header files are corrupted. This results in an error in later mosaicking steps. We have implemented error prevention mechanism to ensure that mosaic procedures terminates correctly in such cases and wrote the problematic galaxy into failed_projection, which can be examined later.
5. `mSubImage` crops a finished mosaic to the specified box frame. Only a box length of , usually two times the radius. If it doesn't work, another attempt for 1 Montage throws an error when the program tries to crop the image with specified boundary lying outside the image field.

4.4.1. Other Errors

Montage's background rectification module is not used in creating the FITS mosaics . Attempts were made in implementing these procedure, however it is sometimes stuck in the step where the background model is applied to the projected images and produces huge difference images files (≈50GB) for reason that we have not figured out yet. This should not affect the astrometric quality of the data product. Sometimes scanlines may be seen as brightness differences in the SDSS mosaics, but the effect is much more severe and clear visible difference is mostly observed in the color images for 2MASS which manifests as completely different boundaries, this will likely affect the photometric quality of the resulting 2MASS mosaics.(?)

5. Conclusion

Wide-area sky surveys are used to answer fundamental questions regarding large-scale structure and the cosmological history of the universe. The mosaicking procedures described in this paper provides a convenient way to generate mosaics for sky survey imaging data for a given catalog, or on a per-image basis. This can be easily adapted for future data to create the scientifically-calibrated FITS mosaics as well as colored images.

Feeding in the new data enables a greater sky coverage and higher resolution images of objects inside the catalog. The scientifically calibrated FITS images can be used as for individual studies, as well as used for improved astrometry in updating the catalog. It can also be combined with the calibrated mosaics of different wavelengths into multi-band color images with mosaics from single/double band surveys such as POSS-I and GALEX.

The data product may also be useful during the target selection/commissioning stage of new surveying telescope such as the LSST and DECam. With the trend of future telescope having larger aperture(focal plane?), large nearby galaxies covered in the RC3 catalog needs to be properly masked to prevent the loss of imaging details from saturated CCDs. The updated RC3 coordinates tells us which regions of the sky may be affected by these large galaxies, and the FITS files can be used to model-fit the galaxy's shape and light distribution. The FITS images can be used along with existing tools for scientific analysis, such as Astrometry.net(Lang et al. [9]) , SExtractor, APLpy(Robitaille and Bressert [11]). The program is designed such that other APIs such as HEASARC's SkyView, Aladin, and NED can easily be latched on. This can also be extended for other astronomical catalog such as the Messier Catalog or NGC, as well as catalogs with user-defined selection limit.

We have provided documentation on GitHub that guides investigators through the steps to adapting the pipeline for future imaging data.The source code and documentation for the pipeline described in this paper can be found in the project repository: `https://github.com/ProfessorBrunner/rc3-sdss`. The data product from the SDSS and DPOSS run is available via a search form at `http://lcdm.astro.illinois.edu/search.html`.

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