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TITLE

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ABSTRACT

Subject headings: infrared: galaxies — submillimeter: galaxies — galaxies: starburst — methods: data analysis

1. INTRODUCTION

1.1. *Lilly-Madau formalism*

1.2. *SED fitting as a standard technique of mass and redshift estimation*

SED fitting is now a standard technique of deriving stellar mass and photometric redshifts for a large set of galaxies. In this method multi-band photometry for a given galaxy is fitted to a series of a templates predicted by a certain stellar population synthesis (SPS) model. The best-fit template gives the parameters of the galaxy, including its redshift and mass. Historically, SPS models were using restframe optical photometry. One caveat is the degeneracy between the dust extinction and age of the stellar population, as both make the color of galaxy red, i.e. galaxy can be red because it is intrinsically red with no young massive star and ongoing star-formation, or it can be very dusty, or it can be metal-rich and metals effectively absorb light in the bluer bands. Solution to this is to implement restframe near-IR where light suffers much less extinction (comparing to restframe UV and optical) and thus the degeneracy can be broken. We aim to build the largest sample of galaxies with optical and near-IR photometry over a large sky area. The natural choice for us then is to use optical Sloan Digital Sky Survey (SDSS) and IR all-sky data from Wide-Field Infrared Survey Explorer (WISE).

1.3. *problems associated with construction of the catalog*

Blending, poor spatial resolution in IR our method template fitting

1.4. *Goal of this paper*

In this paper we present our technique for construction a catalog of galaxies with reliable SED data in optical and near-IR in Stripe 82 field. We discuss data selection, sources identification in different bands and problems associated with it.

2. DATA DESCRIPTION

2.1. *SDSS and Stripe 82*

The imaging component of the SDSS, which was done in five broad bands ($u'g'r'i'z'$), has covered 14,555 deg^2. In most area, the SDSS only scanned for one pass at an exposure time of 53.9 seconds per band, and thus is rather shallow (for example, the r'-band 5 σ limiting magnitude is 22.2 mag). For this reason, in most cases the SDSS can only probe the normal galaxy population up to $z \approx 0.4$. However, the Stripe 82 region, which is a long stripe along the equator that spans $20^h < RA < 4^h$ and $-1.26^o < Dec < 1.26^o$, is the exception. It was repeatedly scanned ($\sim$ 70-90 times, depending on RA) for calibration purpose during the survey (Adelman-McCarthy et al. 2007), and thus the combined scans can reach much better sensitivities.

A number of teams have created deep Stripe 82 stacks and made them available to public. The first such stacks were produced by Annis et al. (2014) based on the data obtained up to December 2005 (20-35 runs), which achieved 1-2 magnitude deeper limits than the single-pass SDSS images. Several other teams (e.g., Jiang et al. 2009; Huff et al. 2014) produced different stacks using different procedures to optimize the image qualities.

Jiang et al. (2014, hereafter J14) released a new version of stacks using only the images that were taken under the best weather conditions. These stacks are $\sim$ 0.2 mag deeper than those produced by Annis et al. (2014), reaching 5 σ limits of 23.9, 25.1, 24.6, 24.1, 22.8 mag in $u'g'r'i'z'$, respectively, and also have better PSF characteristics. We adopt these stacks in our work.

2.2. *Structure of SDSS Stripe 82 files*

We use description from J14 to present the structure of optical data. An SDSS run (strip) consists of six parallel scanlines, identified by camera columns (Figure **??**). The scanlines are 13.5 arcmin wide, with gaps of roughly the same width, so two interleaving strips make a stripe that consists of total 12 scanlines (columns). Their names in the direction of increasing declination are: $col01 \rightarrow col07 \rightarrow col02 \rightarrow col08 \rightarrow col03 \rightarrow col09 \rightarrow col04 \rightarrow col10 \rightarrow col05 \rightarrow col11 \rightarrow col06 \rightarrow col12$.

The size of each co-added SDSS image is 2854 x 2048 pixels, or roughly 18.8' x 13.5' (RA x Dec), with a pixel size of $0.396''$ and an average full width at half maximum (FWHM) of $\sim 1.5''$ in u-band, $\sim 1.3''$ in g-band, and $\sim 1''$ in r-, i-, and z-bands. In total there are 401 SDSS images in each column and overall $12 \cdot 401 \cdot 5 = 24,060$ SDSS images in all 5 bands. Each SDSS image has a corresponding weight.fits image, that records relative weights at individual pixels.

2.3. *WISE and unWISE*

WISE (Wright et al. 2010) is a near-to-mid IR space telescope launched in 2009 and has performed an all-sky

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imaging survey in four bands at 3.4, 4.6, 12, and 22 μm (denoted as W1, W2, W3, and W4, respectively).

The WISE team made the AllWISE Data Release 1 in 2013 November. The image products included in this release, known as the "Atlas Images", are the stacks of the images taken in the three mission phases, namely WISE Cryogenic Survey, WISE 3-band Survey and NEOWISE Post-Cryo Survey, reaching the nominal 5 σ limits in four bands are 0.054, 0.071, 0.73, and 5.0 mJy, respectively (see Cutri et al. 2013, for details). To optimize the detection of isolated sources, the individual images were convolved with the point spread function (PSF) during the stacking process. However, this operation has the drawback that it reduces the spatial resolution of the final stacks,, which is not desirable in many applications. To deal with this problem, Lang (2014, hereafter L14) reprocessed all the WISE images independently without the PSF convolutions, and produced the stacks that preserve the original WISE spatial resolutions. These image products of L14, dubbed as the "unWISE" images, have the PSF full-width at half maximum (FWHM) values of $6''$ in W1, W2 and W3 and $12''$ in W4. We use these unWISE images for this work.

2.4. *Structure of unWISE files - once again maybe I need to omit it in the paper*

The unWISE coadds are on the same tile centers as the WISE tiles with 18,240 images per band, 1.56 x 1.56 degrees each. The tiles are named by their RA, Dec center: tile "0591p530" is at RA = 59.1, Dec = +53.0 degrees; i.e., the first four digits of the tile name is $int(RA \cdot 10)$, then "p" for +Dec and "m" for -Dec, then three digits of $int(abs(Dec) \cdot 10)$. For each tile and band w1-w4, several images are produced, we shall list only the ones that we make use of:

– unwise-0000p000-w1-img-m.fits - "Masked" image, 2048 x 2048 pixels, TAN projected at 2.75"/pixel. Background-subtracted, in units of "Vega nanomaggies" per pixel: $mag = -2.5 \cdot (log_{10}(flux) - 9)$. This is the science image, the word "masked" means that some pixels have no unmasked pixels and no measurement at all: pixel value 0 and infinite uncertainty.

– unwise-0000p000-w1-std-m.fits - Sample standard deviation (scatter) of the individual-exposure pixels contributing to this coadd pixel.

Three unWISE images centered at the same RA cover the whole width of Stripe 82 in Dec (-1.26 δ ¡ +1.26). We shall call three such unWISE images a frame. There may be up to 72 SDSS images within one frame.

3. OVERVIEW OF METHODS FOR ANALYSIS

The most critical factor in SED fitting is consistent photometry in the involved bands, i.e., the photometry should include the same fraction of light across all bands so that the colors are defined in a consistent manner. This is challenging in our case because the spatial resolutions of WISE are at least 6× worse than that of the SDSS. For this reason, the objects detected in WISE often suffer blending. Even for relatively isolated WISE sources, the photometric apertures appropriate for the (low resolution) WISE images cannot guarantee the same fraction of light being included as what is done in the (high resolution) SDSS images. Such a systematic offset, which is different for every galaxy, severely skews the SED fitting.

To best address this problem, we opt to use the TPHOT software, which recently emerged as a robust and flexible tool to perform "template fitting". The basic idea is to use a high-resolution image (here an image from the SDSS) as the prior to build the morphological template of the source under question, convolve this template with the PSF of the low-resolution image (here the corresponding image from the unWISE), and fit this degraded template to the low-resolution image to obtain the total flux that is within the aperture as defined by the high-resolution image. In this way, we get reliable color information (i.e., flux ratio) in the most consistent manner.

While TPHOT is much more user-friendly as compared to its predecessors, running this software is still non-trivial. It not only requires careful tuning of parameters but also several tedious preparatory steps with both the high- and the low-resolution images. Here we detail our procedures.

3.1. *matching optical catalogs*

TPHOT input files must satisfy certain requirements: the low-resolution background-subtracted image must have the same orientation as the high-resolution image (i.e. no rotation allowed), and the origin of one pixel must coincide. Reference pixels (CRPIX) in all SDSS images within one unWISE footprint were changed using SWARP (Bertin et al. 2002) to match the world coordinate values (CRVAL) for a given unWISE image. ≈ 15% of the SDSS images have more than one unWISE image within its footprint. Such images were duplicated and assigned with different reference pixels, thus increasing the number of SDSS files from 4812 to 5556 images per band.

SDSS bands have different sensitivity and FWHM, each field has different number of sources in different bands. R-band has a combination of a great depth, roughly 24.6 AB and ≈ $1''$ PSF FWHM and was chosen as a detection band for the catalog. Another issue is the flux measurement - reliable SED fitting requires consistent multiwavelength photometry while different photometric conditions and FWHM could result in not measuring the same fraction of the total flux and, as a result, non-consistent colors even in optical filters alone. For that reason $g'r'i'z'$ bands were convolved to the PSF of the one with the worst FWHM, i.e., u-band. In such a case the size variation in different bands will be attributed to the intrinsic difference in morphology at different wavelength. For the price of loosing some sources due to blending, more robust optical colors will be extracted. Matching is performed with `IRAF/psfmatch` task that requires supplying the image with the corresponding kernel - PSF matching function. Building a kernel requires knowledge of the PSFs of the input image and a matched image. Construction of 27, 780 PSFs in Stripe 82 (5, 556 per band) is the most time-consuming part of the project.

We run SExtractor on each SDSS image and only mark sources from the output catalog as a point-like, if their stellarity index (determined by a CLASS STAR parameter) is close to 1, sources are bright, but not saturated, they do not lay within 2· PSF radius to the edge of the FITS image, and have all their flux contained within some small aperture. The later was calculated as the difference MAG diff between MAG APER that returns all flux within some fixed aperture and MAG BEST that returns MAG AUTO value in the absence of contamination from the nearby sources and MAG ISOCOR otherwise. Exact parameters depend on the band and also were adjusted during test runs so that each SDSS image has no less than 20 PSF stars (stars were sorted by their magnitude, from bright to dim), with the maximum number of PSF stars limited to 160 (larger values significantly slow down IRAF).

* matching all 5 bands to the PSF of the u-band

When all PSF stars are selected PSF was constructed using standard IRAF/psf. Then we run IRAF/seepsf, a task that takes the input PSF computed by the IRAF/psf task, consisting of the parameters of a 2D analytic function stored in the image header, and computes 21x21 pixel output PSF FITS image consisting of the sum of the analytic function and the residuals. Visual inspection of all PSF images revealed a certain fraction of defect PSFs. The reason for it can be either a blended source within the PSF radius, high background values due to the nearby bright star (within up to several arcmin), or noticeable elongation of the source (may be due to inclusion of a galaxy in our sample or due to intrinsic problems with SDSS image). The fraction of such images varied in different bands but generally was $\approx 4\%$ and for such images we re-run IRAF/psf in interactive mode (manually selecting PSF stars from a preselected catalog). All PSF images were normalized to unity total counts using wcstools/sumpix [Mink, 1998] and IRAF/imarith tasks. Several PSFs for all 5 bands and 6 different columns centered at RA=21:56:46 are shown in Figure 3.2. We used IRAF/lucy, a task that uses algorithm developed independently by Lucy [Lucy, 1974] and Richardson [Richardson, 1972], to create kernels for pairs of images in x- and u-bands, where x- stands for g-, r-, i-, or z-band

With kernels in hand it is now possible to run IRAF/psfmatch that convolves input image with the kernel to produce a psf matched output image (Figure 3.3). From when u-band, g-band, r-band etc images mean "SDSS Stripe 82 images stacked by J14 with new CRVAL and new CRPIX values", while g matched u, etc. means images in the g-band matched to the PSF of the u-band image.

* catalog construction with SExtractor in dual mode, using r_matched_u band for detection SDSS co-adds from J14 already have associated catalogs on the whole Stripe 82 region. We decide not to use it and create our own for several reasons:

- J14 catalogs are not matched between the bands, resulting in different number of objects in different bands.
- SNR at which the source is rejected is too high and there are a lot of sources that are identified in several bands when we perform our own photometry that were not included in J14 catalog.
- Bright and saturated objects are detected as multiple sources, none of which is at the center of such object making correct SED fitting impossible.

On Figure ?? we show a comparison of the original catalog from J14 (sources within green regions) and our catalog (sources within red regions). In the next 2 subsections we show the strategy for catalog construction with consistent optical colors in all 5 SDSS bands.

To construct a consistent optical catalog we run SExtractor in the dual mode - the first image is used for detection and astrometry information, while the second is used solely for photometry. We take r mathced u image as detection image and supply consequently all 5 bands to extract photometry of the sources and reject sources with SNR ¡ 5 based on the r matched u flux. R matched u catalogs as well as corresponding segmentation maps also serve as an input to the TPHOT to derive consistent photometry on near-IR bands. Our parent catalog now consists of 26,585,000 sources. We notice that very few sources were rejected at this stage - objects that appear almost undetectable had FLUX AUTO / FLUXERR AUTO larger than 5 or even 7.

* correction of the error magnitudes in g ,r ,i and z matched u bands

Photometry comparison between original x-band and x matched u-band catalogs shows a systematic underestimation of the errors associated with the source's flux (Figure 3.4). We believe that the reason for this was that we supplied to SExtractor science images matched to the u-band while the weight images were not matched to the u-band. This was the reason for high SNR ratios and low rejection rate for the faint sources. To correct for that we use STILTS code [Taylor, 2006] to match x-band and x matched u catalogs in 5 bands and for each separate image we calculate the mean ratio of the flux error before and after PSF matching. All magnitude errors in a given image are then multiplied by this coefficient. Figure 3.5 shows coefficients for all 5556 images for 4 bands matched to the u-band. We did not apply IRAF/psfmatch task to the u-band, but still calculated that correcting coefficient because r matched u FITS file was used as detection image in SExtractor. All coefficients for this band are less than 1. (CHECK THIS!)

We anticipate that while corrected values account for statistical error, there should also be a systematic error in magnitude that needs to be taken care of. We performed a series of tests where different constant errors were added in quadrature to the reported magnitude error and then the goodness of fit on the graph z spec vs z phot was checked. We found that correlation is the tightest when 0.04 magnitude error is added in quadrature (so final error cannot be smaller than 0.04). Each source in each band was assigned by a error in magnitude that was calculated using the following equation:

$$magerr\_corrected = \sqrt{0.04^2 + (\frac{1.0857}{SNR} \cdot correction\_coefficient$$

** masking area around bright stars
** removing double objects
** star-galaxy separation

3.2. *preparatory work with input files to TPHOT*

* SWARPing of unWISE files

We use SWarp to change the pixel scale of all unWISE images from original 2.75 to 2.772 to match the integer pixel scale ratio with SDSS images = 7. Now we construct unWISE PSF functions that is to be convolved

with SDSS PSF to produce kernels - one of the most important set of the input files to TPHOT. There are 240 unWISE images within Stripe 82 footprint per band. Bands w3 and w4 are too shallow and no reasonable flux can be extracted for the vast majority of optical sources in these bands, so for the purpose of this project we only use w1 and w2 bands. We followed the strategy from the previous section (i.e., running SExtractor, selecting potential PSF stars using STILTS) to construct PSF for all 480 images with two major differences in the procedure: 1) Center pixels of saturated sources in unWISE standard deviation images (unwise- 0000p000-w1-std-m.fits) always have zero value and that is an invalid input for TPHOT. We use IRAF/imcalc to detect such pixels and change its value to 9999. 2) We construct each PSF function using IRAF/psf interactive mode. This was done to perform more robust selection of stars as 3 PSFs from one unWISE frame are convolved with up to 72 SDSS PSFs and thus its quality is crucial - incorrect PSF profile leads to wrong flux estimation associated with such sources and also characteristic positive and negative ring-shaped patterns in the residuals.
After running the IRAF/seepsf task we get PSF FITS images, 19x19 pixels each. All unWISE PSFs are then normalized to unity total counts using IRAF/imarith and sub-sampled in size by the factor of 7 using IRAF/imlintran (to 133x133 pixels) to match the pixel scale ratio between unWISE and SDSS images. Result is presented on Figure 3.6 * kernel construction We use r matched u band as a detection band for the optical sources and also as a high-resolution image for the template fitting. We run the same algorithm to create 5556 r matched u PSFs (not to be mixed up with the r matched u PSF that we use to change FWHM of the original r-band). IRAF/lucy is used to convolve normalized r matched u PSF with normalized and sub-sampled unWISE PSF to create kernels. These kernels serve as one of the inputs for TPHOT.

* naming convention
Both final and intermediate results are a combination of SDSS and unWISE data and we introduce our new naming convention that is used throughout the project. E.g. file kernel.w1.0000p015 12r u 111.fits is a kernel made by convolution of the PSF function of the file unwise-0000p015-w1-img-m.fits and PSF function of the file S82 12r 111.fits in r-band, that has been previously matched to the PSF of the u-band.

4. REDSHIFT AND MASS ESTIMATION

The availability of near-IR filters helps improving the z phot accuracy beyond z 1.3, where the 4000 break goes out of the z 0 filter and the Lyman break is not yet detectable in the u band. (from 1809.03373.pdf)

4.1. *TPHOT*

parameters, limitations, computation on the cluster

4.2. *Final catalog with photometric redshifts*

matching by the source number comparison output fluxes from TPHOT to the unWISE catalogs

4.3. *EAZY*

redshift determination, matching to the spectroscopic redshifts comparison of the redshift with and without unWISE data (similar results) star-galaxy separation final cleaning of the catalog removing of bright stars and duplicated sources

5. RESULTS

6. DISCUSSION

7. SUMMARY

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APPENDIX

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APPENDIX

A. PROSPECTIVE AUTOMATION OF THE DECOMPOSITION PROCESS