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Test area of the SAGE survey

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Abstract Sky surveys represent one of the most important efforts to improve developments in astrophysics, especially when using new photometric bands. We are performing the Stellar Abundance and Galactic Evolution (SAGE) survey with a self-designed SAGE photometric system, which is composed of eight photometric bands. The project mainly aims to study the stellar atmospheric parameters of $\sim$0.5 billion stars in $\sim$12 000 deg^2 of the northern sky, which mainly focuses on Galactic astronomy, as well as some aspects of extragalactic astronomy. This work introduces the detailed data reduction process of the test field NGC 6791, including the data reduction of single-exposure images and stacked multi-exposure images, and properties of the final catalog.

Key words: methods: observational — techniques: photometric — surveys — astrometry — catalogs

1 INTRODUCTION

Stellar atmospheric parameters can be obtained through well-defined photometric systems, e.g., the Strömgren-Crawford (SC) photometric system. But until now, there have been a few sky surveys or catalogs, e.g., the Geneva-Copenhagen Survey (GCS, Nordstöm 2004) and Hauck & Mermilliod Catalog (HM, Hauck & Mermilliod 1998), but they have shallow limiting magnitudes, which are only around $V = 8$. Another recent southern-sky survey, SkyMapper which is lead by Australian National University (ANU), is also based on their own photometric system. In the northern sky, we still lack deeper sky surveys ($V \sim 15$), dedicated to deriving the stellar atmospheric parameters of a large sample.

Therefore, we are performing the deep Stellar Abundance and Galactic Evolution (SAGE) photometric survey ($V = 15$ with signal to noise ratio (S/N) of 100σ) of the northern sky. This paper introduces a test area chosen from the survey on which we merged single-epoch catalogs produced by the science data pipeline (SDP) into a master catalog, and analyzed the data. The procedures that are part of the SDP include image correction, astrometric calibration, photometry and flux calibration.

In order to obtain the stellar atmospheric parameters more accurately and more efficiently, we designed a new photometric system: the SAGE system, by combining our new self-designed filters with some existing photometric bands. This system consists of eight filters: Strömgren-u, SAGE-v, SDSS g, r, i, H$\alpha_{\rm wide}$, H$\alpha_{\rm narrow}$ and DDO-51 (The brief names for the eight filters are: $u_{\rm SC}$, $v_{\rm SAGE}$, g, r, i, H$\alpha_{\rm w}$, H$\alpha_{\rm n}$ and DDO51 respectively) The SAGE system will not only help to provide stellar atmospheric parameters, e.g., effective temperature, surface gravity and metal abundance, but also to study Galactic structure and evolution. Fan et al. (2018) introduces the SAGE photometric system, the survey strategy and the related scientific goals in detail.

The SAGE survey is a northern sky survey with the SAGE photometric system, with its 5σ depths expected to be $\sim$21.5 mag in $u_{\rm SC}$-band, $\sim$21.0 mag in $v_{\rm SAGE}$-band, and $\sim$19.5 mag in g-, r- and i-bands. In the SAGE survey, the observations started in 2015 and we plan to finish the whole project, including observations, photometry, flux calibrations and astrometric calibrations in four or five years. A photometric catalog with uniform depth will be produced by the SAGE survey, which will help in scientific research on the Milky Way and even external galaxies.

2 SAGE PHOTOMETRIC SURVEY AND OBSERVATIONS

The SAGE survey will cover an area of $\sim 12\,000$ deg^2 in the northern sky with Decl. $\delta > -5°$, excluding the bright Galactic disk ($|b| < 10°$), and the sky area of $12\,\text{h}<$ R.A. $<18\,\text{h}$. Details about coverage can be found in Zheng et al. (2018).

Three telescopes are used in the SAGE survey. The first is the 90-inch (2.3-meter) Bok telescope, operated by Steward Observatory of the University of Arizona (hereafter Bok), which is located at Kitt Peak National Observatory; the second is the Nanshan One-meter Wide-field Telescope at Nanshan Station of Xinjiang Astronomical Observatory, Chinese Academy of Sciences (NOWT); the third is the Zeiss-1000 Telescope at Maidanak Astronomical Observatory (MAO), Ulugh Beg Astronomical Institute, Uzbek Academy of Sciences (UBAI). Fan et al. (2018) and Zheng et al. (2018) introduced the telescopes and relevant observations that are part of the SAGE survey.

The SAGE survey started observations in the autumn of 2015. By the end of Jan. 2018, observations of g, r and i bands with NOWT were completed. Meanwhile, the observations of u_{SC}- and v_{SAGE}-bands on Bok are $\sim 2/3$ completed and observations of the two bands are expected to be completed at the end of 2019. Observations with the MAO 1-m telescope are scheduled to start in the autumn of 2018. The up-to-date status of the observation progress can be checked on our website[1].

3 TEST AREA

In this paper, we discuss a test area that is used as a sample: NGC 6791, an open cluster. We performed a series of dithered observations on it with Bok in the u_{SC}- and v_{SAGE}-bands. The pointing and coverage of multiple exposures are shown in Figure 1. The blue box indicates the outline of this test area; the 16 black crosses are the centers of each exposure while the black dotted box is the coverage of one exposure corresponding to $1.08° \times 1.03°$. The red circle at the center is the approximate position and size of NGC 6791.

4 SCIENCE DATA PIPELINE

The science images are processed through our semi-automatic SDP. We stacked the bias images and flat-fielding images for each night, and use them to correct the
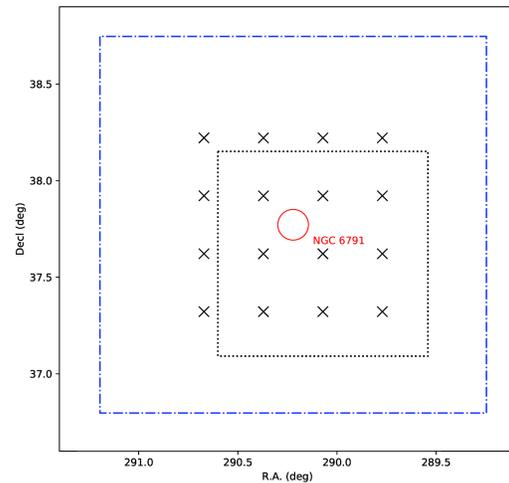
Fig. 1 The *blue box* shows the outline of this test area; the 16 *black crosses* are the centers of each exposure while the *black dotted box* is the coverage of one exposure corresponding to $1.08° \times 1.03°$. The *red circle* at the center is the approximate position and size of NGC 6791.

science images. Then we extract objects and calibrate their flux.

The Software for Calibrating AstroMetry and Photometry (SCAMP, Bertin 2006) is used for deriving the astrometric solution, then we compute the distortion solution which is expressed by the Simple Image Polynomial (SIP, Shupe et al. 2005). The astronomical reference catalog adopted in our work is the Position and Proper Motion Extended (PPMX, Röser et al. 2008) catalog and the more accurate version, the Catalog of Positions and Proper Motions on the ICRS (PPMXL, Roeser et al. 2010) will be adopted in the future work.

We apply the Source Extractor (SExtractor, Bertin & Arnouts 1996) to extract all the sources from images and evaluate their flux, i.e. photometry. We use the Kron-like elliptical aperture photometry (MAG_AUTO) and the corresponding uncertainties (MAGERR_AUTO) as our main output photometry. We also perform aperture-correction for photometry of all the detected sources.

For the flux calibration, we convolve the flux calibrated spectrum library Hubble Space Telescope CALSPEC Flux Standards (CALSPEC, Bohlin 2014) and the Next Generation Spectral Library (NGSL, Heap & Lindler 2010) with the filter transmissions of the SAGE system to derive the u_{SC} and v_{SAGE} magnitudes of standard stars. We have chosen 21 standard stars from the libraries with all the spectral types with suitable brightness for our observations. In a photometric night, we observe the standard stars in a large airmass range dozens of times to fit the atmospheric extinction curve and the extinction

coefficients, which are then applied to calibrate the flux of secondary stars that we observed. The typical uncertainty of flux calibration is ∼0.01 mag.

For the $u_{\rm SC}$ and $v_{\rm SAGE}$ bands, the flux calibrations are more complicated. For the previous version, we predicted the magnitudes from the AAVSO Photometric All-sky Survey, Data Release 9 (APASS DS9, Henden et al. 2015), which provides the g, r and i band photometry, by using a polynomial color-color relationship. The colors are derived with photometry from the MILES stellar library (Falcón-Barroso et al. 2011). For the current version, we applied the more accurate catalog (PS1) from the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS, Chambers et al. 2016) to replace the APASS catalog.

A detailed description of the data reduction steps and results from single exposure images are discussed in Zheng et al. (2018). The current SDP produces a final catalog from the single exposure image, based on which we have done the following corrections and calibrations.

5 REDUCTION OF SAMPLE DATA

In order to test the SDP, we perform a detailed and thorough reduction process on a test area as shown in Figure 1. Besides the data reduction for single-epoch images, we also merge the catalogs into a master catalog. In this catalog, objects from different exposures with the same position (R.A. and Decl.) will be regarded as one object, and their photometric data will be merged.

5.1 Balance the Flux of Images

For a single-epoch image, the flux calibration is simple: just match the detected objects with the reference catalog and calculate the zero point to calibrate the flux of the single image.

However, for the test fields, there are 16 frames to be considered. For the first step, we need to do the internal calibration for all of the images. By matching the common stars in the overlapping part of any two images, we compute the zero-point offset and then neutralize to calibrate the two frames into the same flux level. The balancing operation includes the following steps. First, we identify all overlapped pairs of images in the test area, including fields overlapping by sides or corners, and multiple observations of the same fields. For the test observations of NGC 6791, any two exposures are overlapped. Then for each pair, we match their catalogs by coordinates and compute the offset and standard deviation of the calibrated magnitudes. Now we can start the neutralization. For each image, we adjust its zero point with the weighted mean of its relevant offsets.

After adjustment of one image, we need to update the offsets related to it before adjusting other images. To prevent the transmission effect, we adjust images in a random order, without a fixed reference image. We perform multiple rounds of adjustment until the adjustments are low enough.

After the balancing, the offsets have been neutralized. As shown in Figure 2, the root mean square (RMS) of offsets reduces from 0.0525 mag to 0.0055 mag in the $u_{\rm SC}$-band and from 0.0244 mag to 0.0089 mag in the $v_{\rm SAGE}$-band.

5.2 Columns of the Catalog

After merging the catalogs of the single-exposure images, we obtain the master catalog. Meanwhile, we also keep a complete catalog of individual stars from the single exposure, so that we can trace the data reduction routes. Descriptions of the columns of the master catalog and the complete catalog are listed in Tables 1 and 2 respectively.

We cross-match objects by coordinates into groups from different images. The magnitudes of objects in the master catalog are weighted means of their original magnitudes, while the errors are evaluated as the standard deviations of their original magnitudes. For those objects detected only once, we use their original magnitudes and errors. Coordinates and their errors are computed from all bands.

We use 32-bit flag columns to indicate the different situations during merging. The meaning of each bit is listed in Table 3. Flags of different photometric bands are independent. Not all bits of the flag are occupied.

We cross-match objects in different photometric bands by their positions and then cross-match with the PS1 catalog. For those objects that do not have a matched object in other bands, we put 99 as the absent magnitudes and errors, and 0 as counts.

5.3 The Complete Magnitudes in the Two Bands

The test area is only ∼3 deg^2, which is only a tiny part compared to our survey. We show the magnitude distribution of all the detected sources in both the $u_{\rm SC}$-band and $v_{\rm SAGE}$-band from our master catalog in Figure 3. These inflexion points are ∼20.0 mag in the $u_{\rm SC}$-band and ∼21.0 mag in the $v_{\rm SAGE}$-band, which are in fact the complete magnitudes in the two bands.

5.4 Color-Color Diagram of Stars

In order to check the zero points of the magnitude and colors in the flux calibration, we explore the distribution of
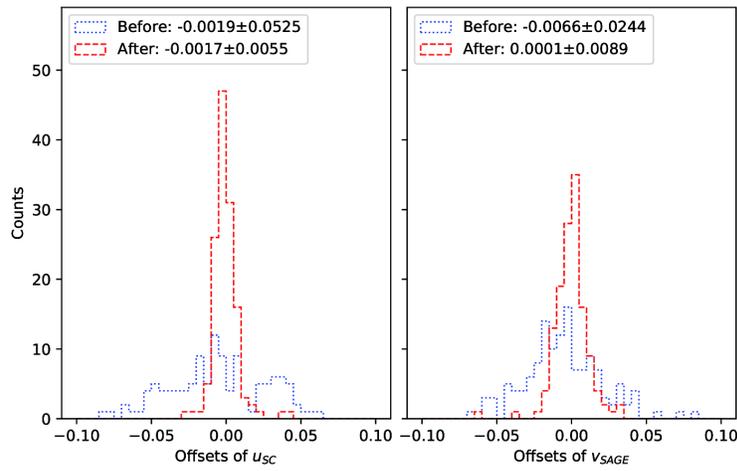
Fig. 2 The distribution of zero-point offsets of overlapped images in $u_{\rm SC}$-band (*left*) and $v_{\rm SAGE}$-band (*right*), before (*blue dotted histogram*) and after (*red dotted histogram*) the balancing operation.
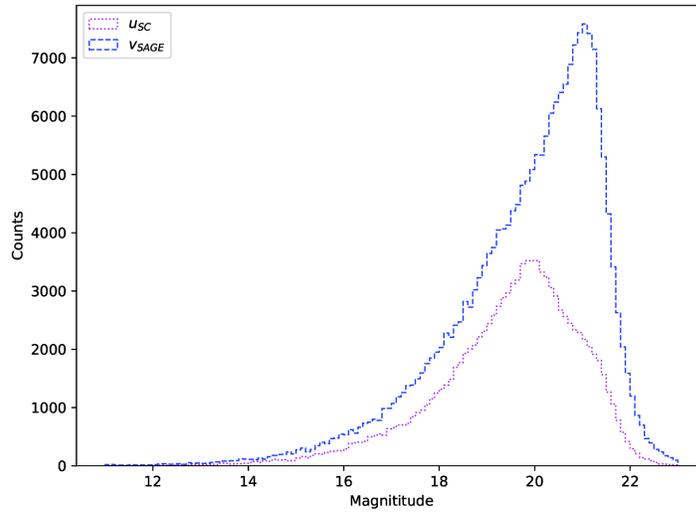
Fig. 3 Magnitude distributions for the two photometric bands, the $u_{\rm SC}$-band complete magnitude at ∼20.0 mag and the $v_{\rm SAGE}$-band complete magnitude at ∼21.0 mag.
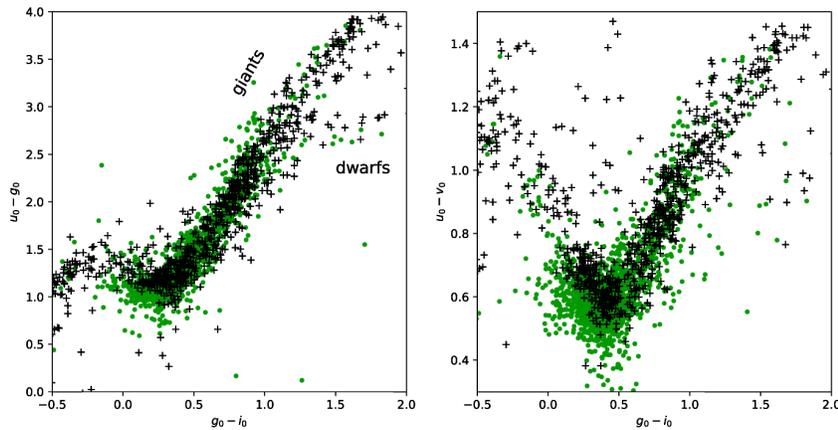
Fig. 4 Dereddened SAGE color measure for stars with good photometry (S/N higher than 50). The *black crosses* are predicted colors of stars from the MILES stellar library. Clearly, we can see the cool dwarfs branch and cool giants branch in the left panel.

Table 1 Columns in the Master Catalog

Parameter	Description
NUMBER	Running object number
RA	Right ascension of the object (J2000)
RA_ERR	Merging right ascension of the object (J2000)
DEC	Declination of the object (J2000)
DEC_ERR	Merging declination of the object (J2000)
U_COUNT	Number of original stars contributing to this object in u_{SC}-band
U_MAG_AUTO	Merged and calibrated Kron-like elliptical aperture magnitude in u_{SC}-band
U_ERR_AUTO	Merging error for AUTO magnitude in u_{SC}-band
U_MAG_ISOCOR	Merged and calibrated corrected isophotal magnitude in u_{SC}-band
U_ERR_ISOCOR	Merging error for corrected isophotal magnitude in u_{SC}-band
U_MAG_APERCOR	Merged and calibrated corrected-aperture magnitude in u_{SC}-band
U_ERR_APERCOR	Merging error vector for fixed aperture magnitude in u_{SC}-band
U_MAG_PETRO	Merged and calibrated Petrosian-like elliptical aperture magnitude in u_{SC}-band
U_ERR_PETRO	Merging error for Petrosian magnitude in u_{SC}-band
U_FLAGS	Merging flags in u_{SC}-band
V_COUNT	Number of original stars contributing to this object in v_{SAGE}-band
V_MAG_AUTO	Merged and calibrated Kron-like elliptical aperture magnitude in v_{SAGE}-band
V_ERR_AUTO	Merging error for AUTO magnitude in v_{SAGE}-band
V_MAG_ISOCOR	Merged and calibrated corrected isophotal magnitude in v_{SAGE}-band
V_ERR_ISOCOR	Merging error for corrected isophotal magnitude in v_{SAGE}-band
V_MAG_APERCOR	Merged and calibrated corrected-aperture magnitude in v_{SAGE}-band
V_ERR_APERCOR	Merging error vector for fixed aperture magnitude in v_{SAGE}-band
V_MAG_PETRO	Merged and calibrated Petrosian-like elliptical aperture magnitude in v_{SAGE}-band
V_ERR_PETRO	Merging error for Petrosian magnitude in v_{SAGE}-band
V_FLAGS	Merging flags in v_{SAGE}-band
G_MAG_EX	g magnitude from external catalog
G_ERR_EX	Error of g-band magnitude from external catalog
R_MAG_EX	r magnitude from external catalog
R_ERR_EX	Error of r-band magnitude from external catalog
I_MAG_EX	i magnitude from external catalog
I_ERR_EX	Error of i-band magnitude from external catalog
ID_EX	Object ID from external catalog

point sources in our catalog as well as that from the stellar library in several dereddened color-color diagrams in Figure 4. We choose stars with S/N better than 0.02 and reliable photometry. As a comparison, we predict colors of stars from MILES by convolving the filter transmission curves with the stellar spectrum. Since we use PS1 as the reference catalog in flux calibration, we use g, r and i bands from the PS1 catalog. The colors from MILES are overplotted as black crosses while the calibrated stars are marked with green dots.

6 FUTURE OF THE SURVEY

We are planning to complete the observation of u_{SC}- and v_{SAGE}-bands in 2018, and start observations at the MAO 1-m telescope from the autumn of 2018. We still need to test the entire control and optical system of the MAO 1-m telescope.

For the data reduction, we also need to improve our pipeline. We will do photometry and calibration with more precision, and we will stack overlapped images to detect deeper objects. Furthermore, we will analyze the relationship between stellar abundance and real observed colors, and try to find a batch of extremely metal-poor star candidates, which could be checked by follow-up observations with other telescopes, e.g., LAMOST.

7 DISCUSSION

We began the SAGE survey in 2015. Up to now, we have finished about 2/3 of the u_{SC}- and v_{SAGE}-bands, and all of the gri-bands from the observations. In this work we merge the catalogs from single-epoch images into a master catalog. We cross-match objects from different images by coordinates and then neutralize their offsets to do the internal calibration. After that, we perform flux calibration with the PS1 catalog. Furthermore, we discuss the depths

Table 2 Columns in the Complete Catalog

Parameter	Description
OBS_DATE	Observation date, MJD
FILE_NUMBER	File number of the source
OBJ_NUMBER	Object running number from original catalog
AMP	Amplifier number where the source is located
X	Object position along x inside the amplifier
Y	Object position along y inside the amplifier
RA	Right ascension of the object center (J2000)
DEC	Declination of the object center (J2000)
FLAGS	Extraction flags by SExtractor
FINAL_ID	Id number in the final catalog

Table 3 The Meaning of Merging Flag Bits

Bit	Description (if set to 1)
0	Detected only once
1	Has other close objects but rejected while merging
2	Flux not good enough, at least 1 source is out of 3σ
3	Position not good enough, at least 1 source is out of 3σ
4–27	Reserved
28	No matched object
29–31	Reserved

and colors of the test area. We are trying to analyze the zero points of the magnitudes and colors, which are related to stellar properties, through these color-color diagrams. Tan et al. are working on the relationship between colors and stellar atmospheric parameters, while Wang et al. are trying to use deep learning methods to derive the stellar atmospheric parameters with the colors by a series of training data.

The SAGE photometric system is a self-designed photometric system with high sensitivity to stellar atmospheric parameters. We expect to obtain eight colors of about 500 million stars and derive their stellar atmosphere parameters. Meanwhile, we can also retrieve a reliable extinction map with $H\alpha_{\rm w}$ and $H\alpha_{\rm n}$ band photometry. The SAGE survey will become an important observational resource for stellar physics, and studies of the structure and evolution of the Milky Way. At the same time, this will also provide data for research on extragalactic objects.

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