Astronomical Observations and Scientific Research with Amateur-Level Telescopes: Postprint

Authors: Chen Xunhao, Hong Wu, Mu Haiyang

Date: 2023-12-06T00:00:00+00:00

Abstract

We conducted astronomical observation tests using a popular-science-grade small telescope Sky-Watcher 150PDS equipped with an amateur-level ZWO ASI120MM-S Complementary Metal Oxide Semiconductor (CMOS) camera to explore the feasibility of employing popular-science equipment for professional astronomical observations and scientific research. The basic performance and parameter curves of the CMOS camera were first tested, with results meeting the fundamental requirements for professional astronomical observations. Subsequently, at the Xinglong Observatory Station of the National Astronomical Observatories, the CMOS camera was installed on the popular-science telescope for basic astronomical observation tests. We observed the open cluster M35 and the short-period variable star V∗V2455Cyg, and obtained corresponding photometric calibration images (bias, flat field, etc.). Following processing with professional astronomical image preprocessing methods, astrometric calibration, aperture photometry, and flux calibration were performed on the target sources, and photometric results, light curves, and simple period analysis were presented. Comparison of the photometric results with known star catalogs yielded a photometric accuracy better than 0.02 mag and a differential photometric precision of approximately 0.005 mag. The test results demonstrate that popular-science-grade telescopes and CMOS cameras possess the capability to conduct astronomical scientific observations and research, indicating that primary and secondary school students and astronomy enthusiasts also have the opportunity to participate in astronomical scientific observations and research.

Full Text

Astronomical Observation and Scientific Research with Popular Science Telescopes

Chen Xunhao[1], **Wu Hong**[1], **Mu Haiyang**[1],[2]
[1]National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China
[2]School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China

---

Abstract

We conducted a test using a popular science small telescope, the Sky-Watcher 150PDS, equipped with an amateur-grade ZWO ASI120MM-S CMOS camera to explore the feasibility of using popular science equipment for professional astronomical observation and scientific research. First, we tested the basic performance and parameter curves of the CMOS camera, and the results met the fundamental requirements for professional astronomical observation. Subsequently, at the Xinglong Observatory of the National Astronomical Observatories, we observed the open cluster M35 and the short-period variable star V*V2455 Cyg, while acquiring the necessary photometric auxiliary images (bias and flat field). After processing with professional astronomical image preprocessing techniques, we performed astrometric calibration, aperture photometry, and flux calibration on the target sources, obtaining photometric results, light curves, and conducting simple period analysis. Comparing our photometric results with known star catalogs, we achieved a photometric precision better than 0.02 mag, with differential photometric precision of approximately 0.005 mag. These results demonstrate that popular science telescopes and CMOS cameras have the capability for astronomical scientific observation and research, opening opportunities for primary and secondary school students as well as astronomy enthusiasts to actively participate in astronomical scientific observation and research.

Keywords: popular science telescope; CMOS; astronomical observation; photometric precision; differential photometry

---

1. Introduction

In the field of optical astronomical observation, Charge Coupled Devices (CCDs) have a development history of several decades and have become the most common professional detectors. However, limitations such as slow readout speed have restricted their widespread use among the general public. With the flourishing development of astronomy, CMOS (Complementary Metal Oxide Semiconductor) cameras, with advantages including high time sampling rate and high cost-effectiveness, have gradually emerged as new favorites among astronomical detectors [1]. As imaging quality improves under the promotion of mobile phone photography and digital cameras, an increasing number of astronomy enthusiasts have begun attempting astronomical observations.

Constructing large-aperture telescopes involves high costs and numerous technical challenges, making it difficult to meet the requirements of rapid, large-area sky surveys in the era of time-domain astronomy. An important future direction is monitoring networks composed of multiple smaller aperture telescopes. The Sitian project [2], aimed at time-domain surveys, will construct an array cluster system of over 70 meter-class, large-field telescopes to achieve high-frequency, wide-field sky surveys that meet rapid surveying requirements. Therefore, the Sitian project will utilize large-area tiled scientific-grade CMOS detectors. However, large-area CMOS cameras have high manufacturing costs and slow readout speeds. Although CMOS cameras have now 具备了 astronomical observation conditions, they still require continuous testing, use, and improvement during observations. Due to their small dynamic range and inconsistent inter-pixel gain, CMOS cameras have not been widely applied in professional astronomical scientific observations.

Professional astronomical telescopes are clearly unsuitable for broader populations due to high costs and significant technical maintenance difficulties. To enable more people, especially primary and secondary school astronomy enthusiasts, to participate in astronomical scientific observation and research, we conducted astronomical observation tests using popular science small-aperture telescopes configured with low-cost CMOS cameras. This also provides an effective pathway for numerous astronomy enthusiasts to engage in astronomical observation and scientific research.

2. Performance Parameters and Testing of CMOS Camera and Telescope

To ensure our tests are more universal and representative, we selected equipment that general primary and secondary school enthusiasts and institutions can afford: the Sky-Watcher 150PDS Newtonian reflector telescope and the ZWO ASI120MM-S monochrome high-speed astronomical camera. The telescope includes a trackable equatorial mount, electric focuser, counterweight, and tripod, commonly used for mobile phone and digital camera sensors. The telescope has a primary mirror aperture of 150 mm and a focal length of 750 mm.

shows partial parameters of the CMOS camera and telescope. The camera performance parameters include gain, full well capacity (FWC), dynamic range, and read noise (RN), which vary with different shooting gain settings. Our testing method involved capturing two bias images at different gain settings (0-100), with *bias* representing the average of corresponding images, and two flat field images (*flat* and *flat*). The standard deviation of the images is denoted by σ. The parameter calculation formulas are [4-5]:

The camera's dark current remained stable at 0.5 $e^-/(\text{pixel} \cdot \text{s})$, and since the exposure time was short, we ignored the dark current effect in this test. Due to different pixel designs in CMOS cameras, inter-pixel gain may be inconsistent [6]; therefore, formulas (1)-(4) represent approximate calculation methods for CMOS camera parameters.

Figure 2 shows our test results compared with official results. The parameters from top to bottom are full well charge, dynamic range, and read noise. The horizontal axis represents the camera shooting gain setting, while the vertical axis represents the conversion coefficient between electrons and count values (e^-/ADU). Compared with official test results (https://zwoasi.com/product-detail/asi120mm-s-mono), the performance curves show good agreement, confirming that the official performance parameters for this CMOS camera are reliable.

The filter set used in this test was the ZWO LRGB filter set. Table 2 compares the central wavelengths and bandwidths of ZWO RGB filters with the Johnson photometric system. Based on central wavelength comparison, ZWO B, G, and R filters correspond to Johnson B, V, and R bands respectively. To avoid confusion, we refer to the data obtained from ZWO B, G, and R filters as B, V, and R bands.

3. Observations and Data Processing

Astronomical auxiliary images mainly include bias images, flat field images in different bands, and dark field images. Since the CMOS camera used in this test has low dark current, we did not consider dark field images. Bias, also called offset, represents the inherent reading due to bias voltage and inherent structure of the camera, which must be subtracted before scientific images. The shooting method involves first setting the same camera parameters as nighttime observations, then closing the mirror cover in a dark environment and shooting 10 bias images each night before observation.

Flat fields correct for non-uniformity in the optical path caused by mirrors, filters, or optical components. Flat field acquisition requires shooting uniformly illuminated images to calculate the non-uniformity when light of the same intensity reaches each pixel. For this popular science small telescope, we chose to shoot twilight sky flats. Before astronomical dawn and after dusk each day, we pointed the telescope at the zenith and, under the same camera parameters as nighttime observations, controlled the average count value of images at 20,000-40,000 ADU to select the correct exposure time, shooting 10 flat field images for each band.

3.1 Observation Targets and Information This test was conducted at the Xinglong Observatory of the National Astronomical Observatories. We observed one open cluster and one short-period variable star: M35 and V*V2455 Cyg. M35 is an open cluster in Gemini with a magnitude of 5.3 mag and an apparent* *diameter of about 28 , similar to the telescope's field of view. It was bright and visible during observation with suitable altitude.* *V*V2455 Cyg is a Delta Scuti type variable star, which is a short-period pulsating star located in the instability strip with spectral type A-F and a photometric period shorter than 0.3 days. The light variation period of V*V2455 Cyg is 0.094206 days with an amplitude of 0.44 mag, allowing us to obtain data for 2-3 periods during an observation night, making it suitable as an observation target. Table 3 shows the observation strategy and information.

3.2 Image Preprocessing **Bias Correction:** We median-combined the 10 bias images captured before each night's observation to obtain a combined bias image. Bias correction involves subtracting the combined bias image from all images (Figure 3(a)).

Flat Field Correction: Flat field correction must be performed band by band. We first applied bias correction to each flat field image. Due to rapid sky brightness changes, the count values of each flat field vary, requiring image normalization before median-combining multiple flat fields. Flat field correction involves dividing the observed image by the combined normalized flat field image of the corresponding band.

Image Correction and Combination: Scientific image correction requires both bias and flat field corrections, with the basic formula:

Corrected Image = (Science Image - Bias Image) / Normalized Flat Field Image

Due to the small dynamic range of the CMOS camera and poor tracking precision of the equatorial mount, long exposures easily cause pixel saturation and star trailing. Therefore, we chose single 2-second exposures and improved signal-to-noise ratio by continuously shooting 100 images for mean combination. Image alignment used the Python Astroalign package [10]. The signal-to-noise ratio of the combined image improved by $\sqrt{N}$ compared with single images (where N is the number of combined images). Figure 4 shows single and combined images of M35 in B and V bands.

Background Estimation and Aperture Photometry: Before photometry, the Python program SExtractor (Python and C library for Source Extraction and Photometry) constructs the sky background distribution by dividing the image into several local regions of equal size and performing iterative sigma-clipping on each region [12]. Photometry is then performed on the image after sky background subtraction. Figure 5 shows the sky background of B-band images and the comparison of background values between single and combined images.

Aperture photometry is suitable for star fields with large interstellar spacing, such as open clusters. For dense star fields or globular clusters, Point Spread Function (PSF) photometry is more appropriate. Figure 7 shows the growth curve of instrumental magnitude versus photometric aperture radius. The curve stabilizes at 3 times the Full Width at Half Maximum (FWHM). We selected 3 times FWHM as the photometric aperture radius. Different aperture radius R values affect photometric results. The curve rises rapidly at first, then becomes relatively flat over a range, and some curves show a second rise due to the aperture radius being too large and including more than one star.

The calculation formula for instrumental magnitude and Poisson error is [12]:

$$m = -2.5 \log_{10}(F/g)$$
$$\sigma = 1.0857 \times \sqrt{}(F/g + A\sigma^2) / (F/g)$$

where A is the photometric aperture area (pixels), σ is the noise standard deviation estimated from sky background within the aperture (ADU), F is the total count value within the aperture (ADU), and g is the gain (e^-/ADU). From previous tests, the gain here is 16.422 e^-/ADU. The calculated magnitude errors are shown in Figure 9. The σ detection limit for B band is approximately 16.422 mag, and for V band is approximately 16.461 mag.

Flux Calibration: Flux calibration involves selecting stars with high signal-to-noise ratio ($S/N > 100$) in the field of view, eliminating possible variable stars, and comparing with known star catalogs to obtain magnitude zero-point, transformation coefficient, and color correction coefficient through least-squares fitting [13]. The catalog used for this test was Gaia DR3 Synthetic Photometry. Using B and V to represent catalog magnitudes, and b and v for corresponding instrumental magnitudes, the fitting formulas are:

$$B = k\_b + b + k_1(b - v)$$
$$V = k\_v + v + k_2(b - v)$$

where k represents the instrumental magnitude zero-point, and the coefficients represent transformation and color correction factors. The fitting results are shown in Table 4.

After obtaining the fitting parameters, we substituted the instrumental magnitudes to obtain magnitude measurements in the standard system. The difference between the observed magnitude (B_{obs} or V_{obs}) and the catalog magnitude (B_{pred} or V_{pred}) represents the photometric precision matching known catalogs. As shown in Figure 10, our photometric precision is better than 0.02 mag.

Astrometric Calibration: We used the existing software Astrometry.net [15] for astrometric calibration of images, then matched the detected sources in the images with the Gaia DR3 Synthetic Photometry reference catalog. The external error of astrometric calibration is shown in Figure 11, with δ*{RA} representing right ascension error and* δ{Dec} representing declination error. The declination direction deviation standard deviation is 0.2 , indicating good precision.

3.3 Differential Photometry of Variable Stars Due to atmospheric disturbance and cloudy weather effects, even standard stars show brightness variations during observation. We can assume that stars within the field of view are affected similarly by the atmosphere. Therefore, we can use differential photometry by subtracting reference stars from the target variable star to eliminate atmospheric effects [16]. We selected reference stars and check stars with magnitudes similar to the target star. Table 5 provides information for the target variable star, check star, and reference stars.

Through aperture photometry, we obtained light curves for 5 reference stars in the field of view. As shown in Figure 13(a), the curves show similar trends. We averaged the 5 reference stars to obtain the final reference curve for differential photometry. Figure 13(b) shows the light curves before and after differential correction. The comparison shows that after correction, the light curve is no longer affected by atmospheric changes.

Light Curve Analysis: We performed Fourier transform on the differential photometry light curve of the target variable star to obtain a power spectrum with frequency units of day^{-1}. The resulting light period is 0.09708 days, with a relative error of 4.13%. We folded the light curve with this period (Figure 15). The black curve is the continuous light curve obtained by fitting. The light variation amplitude calculated from the difference between maximum and minimum values is 0.452 mag, which is very close to the previously measured value of 0.44 mag. Both the measured light period and amplitude are consistent with previous measurements.

Differential Photometry Precision: Standard stars have stable brightness, and their brightness variations before the telescope are only affected by the atmosphere. Therefore, we selected another standard star with brightness similar to the target star as a check star. After subtracting the reference curve from the check star's light curve to eliminate atmospheric effects, the result should be a straight line with constant magnitude values over time. Due to instrumental reasons, this curve will fluctuate near a constant, and the fluctuation range represents the differential photometry precision. By calculating the standard deviation of multiple magnitude measurements, we obtained a differential photometry precision of 0.005 mag, which is relatively high compared with professional telescope test results [17].

4. Summary and Outlook

This paper presents optical astronomical observations and data processing using a popular science small telescope and CMOS camera, achieving good test results. The photometric precision matching known catalogs is better than 0.02 mag, and the differential photometric precision is about 0.005 mag, meeting the measurement accuracy requirements for observing variable stars, exoplanets, or supernovae and other transient sources. This study also verifies that popular science telescopes and CMOS cameras can be used for scientific research.

The advantages of small telescopes lie in low cost, portability, and popularity. The small telescope aperture also avoids saturation of bright sources. If we can call on universities, primary and secondary schools, or numerous astronomy enthusiasts to conduct joint scientific observations and build large monitoring networks, we can develop many astronomical observation projects such as monitoring stellar stability and searching for transient sources. Combined with follow-up observations using large-aperture telescopes to capture abnormal phenomena, this will greatly improve the efficiency of time-domain sky surveys and achieve monitoring of celestial objects.

Acknowledgments

We thank Mao Yiming and Zhang Yu from the National Astronomical Observatories, Chinese Academy of Sciences for their help with telescope use and data processing. We also thank the staff of the Xinglong Observatory for providing observation conditions and technical support.

References

[1] Niu Bingli, Liu Chengzhi, Li Zhenwei, et al. Research on evaluation method of CMOS imager performance. *Laser & Optoelectronics Progress*, 69-74.

[2] Roberto S, Wu X F, et al. The Sitian project. *Anais da Academia Brasileira de Ciências*, 89-96.

[3] Allysse R, Talawanda M, Sean L. Determination of the STIS CCD gain. 2016. https://www.stsci.edu/files/live/sites/www/files/home/hst/instrumentation/stis/documentation/instrument-science-reports/*{documents}/2016*{01}.pdf

[4] Li Dan, Shang Yuanyuan, Song Qian, et al. Measuring the system gain of the TDI CCD camera for remote sensing. *Proceedings of SPIE*, 2005: 520-526.

[5] Song Qian. A 2K$×$2K astronomical high-speed CMOS camera and its test. *Astronomical Research & Technology*, 380-386.

[6] Allyssa R, Talawanda M, Sean L. Determination of the STIS CCD gain. 2016.

[7] Shang Yuanyuan, Zhang Weigong, Song Yu, et al. Research on evaluation method of CMOS imager performance. *Laser & Optoelectronics Progress*, 69-74.

[8] Liu Jifeng. The sCMOS camera in large sky area telescope: photometric accuracy analysis. *Acta Astronomica Sinica.*

[9] Bertin E, Sanchez B. Astroalign: a Python module for astronomical image registration. *Astronomy and Computing.*

[10] Python Astroalign package.

[11] Arnaouts S. SExtractor: software for source extraction. *Astronomy and Astrophysics Supplement Series*, 393-404.

[12] Bertin E, Arnouts S. SExtractor: software for source extraction. *Astronomy and Astrophysics Supplement Series*, 393-404.

[13] Qian Bochen, Tao Jun, Pan Hongjian. The determination of extinction and transformation coefficients for CCD camera system of 1.56 m telescope. *Annals of Shanghai Observatory*, 190-195.

[14] Gaia Collaboration. Gaia Data Release 3: synthetic photometry from Gaia low-resolution spectra. *Astronomy and Astrophysics.*

[15] Mierle K, et al. Astrometry.net: blind astrometric calibration of arbitrary astronomical images. *The Astronomical Journal*, 1782-1800.

[16] Huang Kai, Zhou Yu, Zhai Dongsheng, et al. Photometric accuracies of the YNAO 1.2 m telescope. *Astronomical Research & Technology*, 55-61.

[17] Chochol D. High-precision UBVRJ photometry with a new 50 cm telescope at Baldone. *Baltic Astronomy*, 555-560.

[18] Pribulla T, et al. High-precision photometry with small telescopes. *Astronomical Research & Technology.*

[19] Wang Shuhong, Hu Moufa, Chen Zengping. Noise analysis and SNR model study on astronomical CCD camera. *Semiconductor Optoelectronics*, 731-734.

[20] Ruan Zhifeng, Wu Wentao. SExtractor and its applications in deep sky surveys. *Astronomical Research & Technology*, 266-272.

Note: Figure translations are in progress. See original paper for figures.