Technical Research on Relative Photometry of CCD Images and the Precision Return Phenomenon (Postprint)

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Abstract

The temporal luminosity variations of celestial bodies can reflect their physical properties. Research on high-precision photometric techniques helps us better analyze and investigate the photometric variability of celestial objects, which is of great significance for studies of stellar evolution. This paper introduces relevant photometric tools and techniques, explores the photometric technology that combines MaxIm DL software with the photutils photometric library and its applications, and proposes a solution for rapid matching of photometric data of stellar images in continuous frames. Through the analysis of M35 star cluster images captured by the 1m optical telescope at Yunnan Observatories, Chinese Academy of Sciences, this study discovers the existence of a precision premium phenomenon in differential photometry, where relative photometry between two nearby stars yields higher measurement precision, and the significance of this phenomenon is correlated with airmass. In response to the precision premium phenomenon in differential photometry, this paper proposes a reference method for high-precision differential photometry.

Full Text

Technology Research and Precision Premium in Relative Photometry Based on CCD Images

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Abstract: The temporal variation of celestial luminosity reflects the physical properties of astronomical objects, and research on high-precision photometric techniques enables better analysis and investigation of these light variations, which is of great significance for studying stellar evolution. This paper introduces relevant photometric tools and techniques, explores a photometric method combining MaxIm DL software with the photutils library, and proposes a solution for rapid matching of photometric data across consecutive images. Through analysis of M35 cluster images captured by the 1m optical telescope at Yunnan Observatory, Chinese Academy of Sciences, we discover a precision premium phenomenon in relative photometry—namely, that relative photometry of two nearby stars yields higher measurement precision, with the significance of this phenomenon being correlated with airmass. In response to this precision premium phenomenon, this paper proposes reference methods for high-precision relative photometry.

Keywords: Relative Photometry; Precision Premium in Photometry; CCD Image Processing; photutils; MaxIm DL

1 Introduction

Photometric measurements of celestial bodies primarily investigate temporal variations in brightness, which reflect physical properties and are crucial for understanding stellar evolution. For instance, reference [1] analyzed asteroid rotation periods and shapes from light variation curves, reference [2] studied Kuiper Belt objects' light variation periods to analyze physical properties such as albedo, and reference [3] utilized medium-to-long period light variations to investigate quasar physics. However, high-precision photometry faces numerous challenges. Earth' s atmosphere introduces significant extinction and refraction effects that substantially impact measurement precision. Since nearby stars (with small angular separation on the sky plane) experience similar atmospheric conditions and minimal relative positional changes, relative photometry is commonly employed. For solar system objects (particularly near-Earth asteroids) that move rapidly relative to background stars and traverse different airmasses, absolute photometry (all-sky photometry) becomes preferable. In ground-based observations, atmospheric extinction and nightly zero-point coefficients can be accurately determined to mitigate atmospheric effects, with Landolt providing detailed parameters for standard stars [4] that establish a solid foundation for absolute photometry research. Nevertheless, absolute photometry precision remains inferior to relative photometry. To eliminate atmospheric influences, detectors have been deployed in space (e.g., Hubble Space Telescope and Gaia satellite), yielding significant improvements in photometric precision.

This study focuses on ground-based photometric techniques and the precision premium phenomenon. In ground observations, targets are typically observed near the meridian to minimize atmospheric effects and improve positional and photometric precision. In astrometry, Pascu discovered improved positional measurement precision when two Galilean satellites approached each other [5], Morgado et al. subsequently developed mutual approximation astrometric techniques [6], and Lin et al. statistically characterized the positional precision premium phenomenon based on M35 cluster observations [7]. In relative photometry, researchers primarily focus on reference star stability while paying less attention to angular separation between target and reference stars. If a precision premium phenomenon exists in relative photometry—where, given multiple candidate reference stars at different distances with similar and stable brightness, closer reference stars yield higher measurement precision—this would have important implications. Based on M35 cluster observations from the Yunnan Observatory 1m telescope, this paper investigates the precision premium phenomenon in relative photometry.

Section 2 introduces existing photometric tools and techniques, proposing a combined MaxIm DL and photutils approach. Section 3 statistically analyzes the relationship between relative photometric precision and separation in M35 at different altitudes, confirming the precision premium phenomenon and proposing methods for high-precision relative photometry. The final section provides concluding remarks.

2.1 Photometric Measurement Tools

With advances in information technology and industrial development, numerous open-source photometric tools and software are currently available. IRAF offers robust image processing and photometric capabilities but requires Linux environment configuration and operation. Aperture Photometry Tool (APT) serves as an educational software for aperture photometry and growth curve analysis [8]. SExtractor is widely applied in source extraction and measurement for deep-sky surveys. MaxIm DL facilitates batch flat-field processing, image quality assessment, image stacking, and aperture photometry [9]. With computer technology advancement and the rise of Python, PyRAF (https://pypi.org/project/pyraf/) and photutils (https://photutils.readthedocs.io/en/stable/index.html) have emerged as convenient Python libraries for photometry.

2.2 Photometric Technique Combining MaxIm DL and Photutils

Photutils is a Python-based photometric library and an Astropy-affiliated package that provides convenient programmatic access to source detection and photometric measurement functions. DaoStarFinder and IRAFStarFinder are two source detection functions that interface with DAOPHOT and IRAF star-finding routines, respectively. Photutils offers both aperture photometry and point spread function (PSF) photometry methods; this study focuses on aperture photometry using the photutils.aperture library. This library enables aperture radius settings with floating-point values, providing higher precision than MaxIm DL and APT, which restrict aperture radii to integer values. Furthermore, the `exact` method in the `aperture_{photometry}` function precisely handles fractional pixel contributions in aperture photometry, offering higher measurement precision than subpixel methods.

However, applying Photutils to ground-based observations presents challenges. Both source detection functions (DaoStarFinder and IRAFStarFinder) require mandatory input parameters for pixel threshold (the `threshold` parameter) and stellar full width at half maximum (FWHM). Typically, the pixel threshold is set to several times (e.g., 3–5×) the standard deviation of background pixels, though survey work may require smaller values. Accurate detection of most stars in observational data requires the FWHM parameter to closely match each image. Ideally, FWHM values remain stable throughout a night' s observations, contingent on weather and equipment conditions. In practice, however, ground-based observations exhibit FWHM fluctuations even in consecutive images from the same telescope. Consequently, batch processing with a single approximate FWHM value may fail to detect most stars in some images. While such cases could be handled through individual processing or adaptive FWHM adjustment algorithms, these approaches are operationally complex. This paper proposes an integrated method with MaxIm DL. MaxIm DL (version 5.24 used herein) provides batch image quality assessment during image stacking, conveniently exporting FWHM and roundness information for each image (as shown in the left panel of [Figure 1: see original paper]). Using MaxIm DL's exported FWHM values as input parameters for source detection functions effectively addresses star detection issues arising from significant FWHM variations across images. In practice, we found that adding 0.5 to the MaxIm DL-exported FWHM value yields better source detection results.

Analyzing and statistically characterizing brightness variations for all stars in the field is crucial for variable star surveys and stellar feature analysis. The key challenge lies in matching stars across multiple images. For observations with stable telescope pointing and orientation, obtaining positions and photometry for all stars in a master frame (typically a high-quality image) enables adequate matching with other images (e.g., using pixel and magnitude thresholds) to construct light curves. However, when telescope pointing or tracking is unstable (e.g., with 5-pixel shifts between frames), characterizing photometric variations for all field stars becomes difficult. This paper proposes a rapid solution combining MaxIm DL. First, MaxIm DL' s alignment function conveniently exports pixel coordinate offsets for each image relative to the first frame (as shown in the right panel of [Figure 1: see original paper]). Then, corresponding offsets (XShift and YShift) are subtracted from the detected star coordinates in each frame. This eliminates field offsets caused by telescope pointing instability, facilitating star matching and statistical analysis across images. For studies requiring additional stellar information (e.g., color indices, parallaxes), catalog-based matching methods are necessary, though more time-consuming.

[Figure 1: see original paper] The left and right panels show the quality evaluation and image alignment files exported by MaxIm DL, respectively.

Integrating Photutils with MaxIm DL, this section proposes solutions for target detection failures caused by large FWHM variations and offers a rapid local star matching and statistical method, provided the CCD chip does not undergo significant rotation during observations.

3 Precision Premium Phenomenon in Relative Photometry

Atmospheric turbulence causes varying positional deviations between actual and measured star positions on CCD chips. Since nearby stars in the field of view experience similar atmospheric turbulence effects, a precision premium effect exists in positional measurements—relative position measurements achieve higher precision when angular separation between stars is small. We hypothesize that in relative photometry, different stars experience varying degrees of atmospheric extinction due to different airmasses within the same field of view. If two nearby stars experience similar atmospheric extinction, they should also exhibit higher relative photometric precision.

This section examines the relationship between relative photometric precision and separation in M35 cluster observations to investigate the precision premium phenomenon.

3.1 Observation Data Selection

The ideal method for investigating this phenomenon would involve finding two closely separated celestial objects with constant brightness. However, locating objects with large angular separation variations and stable brightness is challenging. While solar system asteroids can approach background stars, their brightness varies due to rotation, phase, and satellite effects, making them unsuitable for investigating this phenomenon's existence. Using typical stars is also problematic because their relative angular separations remain nearly constant, making it difficult to establish a relationship between photometric precision and distance. Additionally, many stars are intrinsically variable. This study employs star cluster observations for investigation. The large stellar population in clusters facilitates statistical analysis of the relationship between distance and photometric precision, and cluster statistics can demonstrate whether the phenomenon is universal rather than confined to specific sky regions or individual objects. Thus, star clusters provide an excellent testbed for investigating the relative photometry precision premium phenomenon. However, clusters also contain variable stars or stars significantly affected by nearby bright objects; Section 3.2 discusses the handling of such stars in detail.

3.2 Data Processing and Analysis

We investigated the photometric precision premium phenomenon using M35 cluster images captured by the 1m optical telescope at Yunnan Observatory, Chinese Academy of Sciences (detailed specifications in). The cluster was observed at different altitude angles with stable telescope pointing; observation details are summarized in .

Specifications of the Telescope and CCD
Parameter | Value
Focal Length | 1330 cm
Diameter of Primary Mirror | 101.6 cm
CCD Field of View | 16 $×$16
Pixel Size | 15 m × 15 m
CCD Array Size | 4096 × 4112
Scale | ~0.234 /px

Observations Overview
Date (y-m-d) | Frames/Filter | Altitude (°) | Exptime (s) | FWHM (px)

For data preprocessing, we performed flat-field correction using MaxIm DL and filtered images based on quality assessment, selecting those with small FWHM (e.g., <6 px, corresponding to <1.4 arcseconds) and good roundness (e.g., <0.2). The frame counts listed in represent quantities after quality screening. While this screening method should be applied cautiously in photometry as it may exclude critical variability data, our experiment investigating the precision premium phenomenon assumes constant stellar brightness and requires eliminating variable stars to the greatest extent possible. This method effectively reduces effects from atmospheric instability and focus variations.

We employed aperture photometry for this investigation. Due to the dense stellar environment in M35, background estimation using annuli often suffers from contamination by nearby stars. Therefore, we adopted a fixed sky background value for each star in every image. Specifically, we first clipped background pixels at 3σ, then applied the "3-2" formula (3×median − 2×mean) [10] for sky background estimation. We performed source detection using Photutils and matched photometric data across images with MaxIm DL, as described in Section 2.2. Since we must assume constant brightness for each star across all images in a given dataset, we measured relative photometric precision using the standard deviation of instrumental magnitudes. To avoid low-precision measurements for faint stars, we selected bright stars with high signal-to-noise ratios to investigate the relationship between relative photometric precision and separation. These bright stars were distributed across different field positions and were pairwise differentially photometered, yielding n(n−1) relationships between photometric precision and distance for n selected bright stars.

[Figure 2: see original paper] The left panel shows the relationship between relative distance and photometric precision for observations on December 8, 2020, for instrumental magnitudes 11-13. Relative pixel distance is calculated using the formula $\sqrt{\Delta x^2 + \Delta y^2}$, where Δx and Δy are differences in pixel coordinates between star centers (same hereinafter). The right panel shows results after applying the "standard deviation mean elimination" method (threshold set to 0.0055), with the red solid line representing a power-law fit.

However, bright stars selected by signal-to-noise ratio or magnitude are not necessarily photometrically stable. Variable stars, binary systems, or stars significantly affected by nearby bright objects exhibit lower photometric precision and are unsuitable for investigating the precision premium phenomenon. We must identify and exclude these lower-precision stars. A star showing large brightness variations across a dataset will exhibit low precision (large standard deviation) regardless of the reference star used. This paper proposes a "standard deviation mean elimination" method to exclude such stars. First, we calculate the standard deviation of magnitude differences between each star and all other stars in the field, yielding n−1 standard deviation values per star. Second, we compute the mean of these n−1 standard deviations for each star. Third, we set a threshold (typically near the upper edge of the precision concentration region, as shown in the left panel of [Figure 2: see original paper]) and exclude stars with mean standard deviations exceeding this threshold. This method effectively eliminates low-precision stars, facilitating investigation of the precision premium phenomenon. The figure shows the relationship between relative photometric precision and pixel distance for M35 cluster images taken on December 8, 2020, using instrumental magnitudes 11–13. The left panel displays results before elimination, while the right panel shows results after applying the "standard deviation mean elimination" method with a threshold of 0.0055, demonstrating effective removal of low-precision stars.

We applied the same method to three M35 datasets taken on January 15, 2021, at different altitude angles to investigate airmass effects on the precision premium phenomenon, with results shown in [Figure 3: see original paper]–[Figure 5: see original paper].

[Figure 3: see original paper] The left panel shows the relationship between relative distance and photometric precision for observations on January 15, 2021 (altitude 36–31°, instrumental magnitude 12–14 mag), with elimination threshold set to 0.008. The right panel shows residual distribution after power-law fitting.

[Figure 4: see original paper] The left panel shows the relationship between relative distance and photometric precision for observations on January 15, 2021 (altitude 50–43°, instrumental magnitude 11–13 mag), with elimination threshold set to 0.006. The right panel shows residual distribution after power-law fitting.

[Figure 5: see original paper] The left panel shows the relationship between relative distance and photometric precision for observations on January 15, 2021 (altitude 83–78°, instrumental magnitude 11–13 mag), with elimination threshold set to 0.005. The right panel shows residual distribution after power-law fitting.

These results reveal that photometric precision increases with target altitude on the same night. Near the zenith, bright stars (magnitude <13) achieve photometric precision of 0.002 mag. At low altitudes, relative photometric precision decreases and exhibits a more pronounced precision premium phenomenon. As shown in [Figure 3: see original paper], photometric precision degrades from

0.003 mag to 0.006 mag as relative pixel distance increases.

3.3 Discussion of Precision Premium Phenomenon

Starlight traversing different airmasses experiences varying extinction. Since two stars with small angular separation traverse similar airmasses, a precision premium phenomenon exists in relative photometry. This phenomenon becomes more pronounced at low target altitudes where airmass is larger.

In ground-based observations, targets are typically observed near the zenith to minimize atmospheric extinction effects. However, some targets remain at low altitudes when crossing the meridian, where using nearby reference stars for relative photometry yields significant benefits. When atmospheric quality at the zenith is poor, the precision premium phenomenon may also become notable, making nearby reference stars a valuable alternative. The existence of this phenomenon suggests we should seek nearby isolated bright stars as references while ensuring their photometric stability.

4 Summary and Outlook

This paper introduced existing photometric tools and techniques, proposing a method combining MaxIm DL software with Python' s photutils library. This approach addresses detection failures caused by large FWHM variations and enables rapid matching and statistical analysis of stellar photometric data. Analysis of M35 cluster images from the Yunnan Observatory 1m telescope at different altitude angles revealed a pronounced photometric precision premium phenomenon at low target altitudes. Future work will integrate positional and photometric precision premium phenomena to further investigate correlations between brightness and positional variations in celestial objects.

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