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Abstract

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Full Text

The Mini-SiTian Array: Light Curve Analysis of Asteroids

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Abstract

The SiTian project, with its vast field of view, will become an ideal platform for scientific research on asteroids. In this study, we develop a pipeline to analyze the photometry of asteroids and derive their periods from the data collected by the SiTian pathfinder project Mini-SiTian (MST). The pipeline is applied to the MST f02 region, an MST test region with a sky area of $2^{\circ}.29 \times 1^{\circ}.53$. Rotation periods of 22 asteroids are derived by the obtained light curve analysis. Among them, there are eight asteroids available in the Asteroid Lightcurve Photometry Database (ALCDEF), and six of them with more photometric points (>200) that have similar period parameters as the ones in ALCDEF. Additionally, the periods for 14 of these asteroids are newly obtained and are not listed in ALCDEF.

This study demonstrates the feasibility of asteroid photometric research by the SiTian project. It shows that future observations from the SiTian project will provide even more photometry of asteroids, significantly increasing the number of available light curves. The potential vast photometric data on asteroids will help us to further understand the physics of asteroids, their material composition, and the formation and evolution of the solar system.

Key words: minor planets, asteroids: general — telescopes — instrumentation: photometers — methods: observational — techniques: image processing

1. Introduction

Asteroids are vital members of the solar system. They are closely related to key questions such as the origin of the solar system, the formation of planetary systems, and the origin of life on Earth. In recent years, asteroids have become one of the hot research topics in astronomy and space science with the increasing observation data on asteroids, a series of successful deep space exploration missions to asteroids such as Hayabusa2 (Tsuda et al. 2019) and OSIRIS-Rex (Lauretta et al. 2021), and ongoing planetary defense programs like DART (Cheng et al. 2023).

The study of asteroid light curves is an important aspect of researching the physical properties of asteroids. Most studies of the rotation characteristics of asteroids are based mainly on light curve-derived rotation periods and rotation rates (Pravec et al. 2002). Concurrently, physical parameters such as shape can be analyzed (Kaasalainen & Torppa 2001; Durech et al. 2015; Scheeres et

al. 2015; Feng et al. 2024). Moreover, large data volume studies of asteroid light curves can conduct statistical analyses on the distribution of asteroid rotation periods (Pál et al. 2020), finding that all main-belt asteroids between 0.4 and 10 km have rotation rates less than 2.2 hr (Warner et al. 2009), and ascertaining the characteristics of rotation periods in different asteroid families (Szabó et al. 2022). Even more, such studies can provide deeper insights into the evolution of the solar system (DeMeo & Carry 2014). Furthermore, the activity of asteroids can also be studied in concert with their physical parameters (Hsieh et al. 2004; Shi et al. 2019), even exploring the origin of water on Earth (Lauretta et al. 2019).

Now, with the rise of time-domain astronomy, numerous wide-field time-domain sky surveys are being promoted both domestically and internationally, simultaneously presenting opportunities for research on asteroids. Domestic wide-field survey facilities, such as the Tsinghua University-Ma Huateng Telescopes for Survey (Zhang et al. 2020), the Multi-channel Photometric Survey Telescope of Yunnan University (Mephisto, Liu 2019), the “Mozi” Wide Field Survey Telescope (Lou et al. 2016), and so on, all possess the potential capability for photometric study of asteroids (Xu et al. 2023). In this work, we focus on conducting asteroid photometry with the SiTian project (Liu et al. 2021), with plans to extend this effort to other wide-field surveys in the future.

The SiTian project consists of approximately 20 groups, each equipped with three 1 m telescopes. SiTian will scan at least 10,000 square degrees of sky using three bands in half an hour, down to a 5σ detection limit of $V = 21$ mag. This large-field observation mode is highly suitable for conducting research on asteroids in the solar system (Liu et al. 2021).

As the pathfinder project of the SiTian project, Mini-SiTian (MST) is equipped with three 30 cm catadioptric Schmidt telescopes named Mini-SiTian-01 (MST1), Mini-SiTian-02 (MST2), and Mini-SiTian-03 (MST3) (Huang et al. 2025). Each telescope is equipped with a commercial-grade Complementary Metal-Oxide-Semiconductor (CMOS) sensor, the SONY IMX455, with 9576×6388 pixels. Covering a $2^\circ.29 \times 1^\circ.53$ field of view (FOV), the pixel scale is 0.862 pixel^{-1} . MST1, MST2, and MST3 are equipped with filters similar to the SDSS system filters *i*, *g*, and *r*, respectively (Xiao et al. 2025; He et al. 2025). In this series of works, Zhang et al. (2025) demonstrated that the dark current and readout noise of the MST’s CMOS camera are negligible, with the dark current approximately $0.002 \text{ e}^- \text{ pixel}^{-1} \text{ s}^{-1}$ at 0°C and the readout noise below 1.6 e^- . Xiao et al. (2025) showed that the MST’s zero-point correction accuracy is 1 mmag, with an uncertainty of 4 mmag for $G = 13$ mag. MST’s CMOS achieves photometric accuracy comparable to CCDs under current exposure conditions.

During the test observation period of MST, three regions were chosen to test the performance of long-duration continuous observations, which were named f01, f02, and f03. Among them, the f02 region is located at $\alpha = 72^\circ.947$ and $\delta = +41^\circ.015$ and has the richest data from observations (Gu et al. 2025). Using

the observations of the f02 region, we conduct a study on the light curves of asteroids, in order to demonstrate the feasibility of MST for asteroid light curve research.

The structure is as follows: Section 2 briefly introduces the data and methods. The photometric results of the asteroids are presented in Section 3. A comparison of the results with existing databases is provided in Section 4, and the summary is given in Section 5.

2.1. Observation

Observations of the f02 region began on 2022 December 24, and ended on 2023 February 6. MST2 with SDSS-g band and MST3 with SDSS-r band were used in this observation, and 3636 images were taken by MST2 and 3554 images were taken by MST3 for the f02 region. The exposure time for each observation was 300 s (Gu et al. 2025). Based on the actual observations, the full width at half maximum (FWHM) for the frames during each night is mostly between 2 and 3. However, the FWHM of each frame also varies with the seeing conditions at the site, which may change during the night. The worst FWHM is mostly between 3 and 4. The 3σ magnitude limit for a single image could reach 20.0 mag in the g-band under the best observational conditions, and 19.4 mag in the r-band (He et al. 2025).

During continuous observations, the positions of asteroids vary over time, and the related photometry may be affected by background stars. To ensure the accuracy of subsequent analysis, we use the image differencing method to effectively reduce the influence of background stars. Gu et al. (2025) developed the Mini-SiTian Real-Time Image Processing system (STRIP) and completed the preprocessing and image subtraction of the images from the f02 field. Raw images were processed with bias-field subtraction and flat-field division by STRIP. STRIP used the World Coordinate System (WCS) solving tool from “astrometry.net” to compute the WCS for all images and then used Scamp (Bertin 2006) to obtain a more precise WCS solution. A WCS template was created by STRIP, and all images were aligned to this template using SWarp (Bertin 2010). A template image was produced by stacking past high-quality observations. Finally, the subtracted images were produced by differencing them against the template image using HOTPANTS (Becker 2015).

Figure 1 [Figure 1: see original paper] shows an example of the difference between the reference image and a single image in the f02 region taken by MST2. Their subtracted image is displayed in the right panel. At the center of the subtracted image is the asteroid 1524 Joensuu. The asteroid does not appear in the template image because after applying the 3σ clipping method, moving objects will be removed in the template image. Therefore, asteroid photometry using the subtracted image can eliminate most interference from background stars.

In this series of works, Gu et al. (2025) utilize BP/RP (XP) spectra from Gaia

Data Release 3 (DR3) in conjunction with the filter transmission curves of the MST array to obtain two-band theoretical magnitudes for stars within the MST filter system. After coadding template images of the f02 field, aperture photometry is performed using SExtractor (Bertin & Arnouts 1996), producing a catalog for the f02 field. This catalog is then cross-matched with the catalog derived from XP spectra, generating a table that associates aperture photometry values (measured in Analog-to-Digital Units (ADUs)) with theoretical magnitudes from Gaia XP spectra. By taking the logarithm of the ADU values and multiplying by -2.5, ADU values are converted into instrumental magnitudes. These instrumental magnitudes are subtracted from the theoretical magnitudes from the XP spectrum to determine the zero-points of the template images. A 3σ clipping is applied to the results, and the methodologies are separately applied to template images from both MST2 and MST3, each with a distinct filter, yielding two unique zero-points: 28.03 mag (MST2) and 27.30 mag (MST3).

2.2. The Asteroid Ephemeris

To perform photometry on asteroids, it is essential to identify them in the images and determine their positions. For this purpose, we download the catalog of all known asteroids in the solar system from the Lowell website⁶ (Moskovitz et al. 2022), which contains high-precision orbital elements of asteroids and other related parameters, such as the absolute magnitude H (Bowell et al. 1989). We use the data version of 2024 January 5, which includes information on 1,340,596 asteroids.

Next, we use the Aleph software package⁷ to compute the α and δ of asteroids. Aleph integrates with the Lowell Asteroid Orbital Elements Database and directly reads the orbital elements of asteroids from the `astorb.dat` file. Through the integral of orbit, it calculates the positions of asteroids in the International Celestial Reference System (ICRS) at different times. We provide four key parameters to Aleph: the equatorial coordinate of the FOV center ($\alpha = 72^\circ.947$ and $\delta = +41^\circ.015$), the search range (a conical search centered on the FOV center with a diameter of $1^\circ.5$), the Julian Day (JD) at which the observation images were taken, and the station coordinates of the Xinglong Station of the National Astronomical Observatories, where MST is located. Based on these parameters, Aleph calculates the positions of asteroids within the search area at the time that each image was captured, finally obtaining the precise α and δ of the target asteroids.

Based on the quality of the images, we select asteroids with $V \leq 20$ mag. Using the WCS⁸ information of the images, we convert the α and δ of the target asteroids into pixel coordinates for each image. Finally, we obtain the asteroid ephemeris table (see Table 1), which includes asteroid number and name, JD, ICRS coordinate (α and δ), the number in MST, and pixel coordinates. From the MST2 data, we identify 26 asteroids, 24 of which are main-belt asteroids and two of which are Trojan objects. From the MST3 data, we identify 24 asteroids, 22 of which are main-belt asteroids and two of which are Trojan objects. The

reason why MST3 finds fewer asteroids than MST2 is that fewer images are taken by MST3.

We incorporated the positional coordinates of the asteroids from each image taken by MST2 into a scatter plot, where each asteroid in each image is represented by a point. As the position of the asteroid changes across consecutive images, these points connect to form tracks, with the length of the tracks reflecting the number of images taken. Figure 2 [Figure 2: see original paper] shows the identified asteroids in an original image taken by MST2, clearly indicating that the asteroids were passing through the FOV during the MST f02 observation.

2.3. Data Analysis

As diagrammed in Figure 3 [Figure 3: see original paper], we provide a detailed introduction to the data processing pipeline for the asteroid photometry in the MST project.

2.3.1. Image Cropping

Based on the asteroid ephemeris table, we extract observation times for each asteroid and match them with the images to precisely locate the pixel coordinates of the target asteroids. Using the Cutout2D package in Astropy⁹ (Astropy Collaboration et al. 2022), we crop the subtracted image to 100×100 pixel Target Pixel Files (TPFs) centered on each asteroid. After cropping, we obtain 13,218 TPFs for the f02 region from MST2 and 9,447 TPFs from MST3.

Through image quality analysis, we find that some images are unsuitable for photometric measurement. Due to the instability inherent in image subtraction methods, the presence of saturated pixels, and variable stars appearing in the subtracted images, asteroids may be obscured. Some asteroids are not fully captured because they are on the edge of the image, and some low-quality images make it difficult to identify asteroids. During photometry, we further eliminate affected images to ensure the accuracy of the analysis. This includes images where asteroids cannot be found in the TPFs, images with significant photometric deviations (more than 3σ), or images with other issues.

2.3.2. Aperture Photometry

After obtaining the TPFs, we find that some targets are not precisely centered in the images because the orbit integration is not accurate enough. To achieve more accurate photometry, we use the DAOSStarFinder program (Stetson 1987) from the photutils package¹⁰ (Bradley et al. 2023) to realize star finding in the TPFs for precise localization of the asteroids. We conduct aperture photometry using the localization center as the center of the aperture. Based on the MST observation data described in Section 2.1, we set the FWHM to 3.448 (4 pixels) and use 1.5 times the FWHM as CircularAperture and aperture photometry

methods¹¹ from the photutils package. While obtaining the total flux of the asteroids, we construct two large circles with radii of 5 times and 7 times the FWHM, centered on the localization center, and detect the total flux values within these large circles. The average flux value of all pixels in the annulus between the two outer circles is calculated and termed as the sky background flux (Msky). The target flux is obtained using the formula $\text{Flux} = \text{Sum} - \text{Area} \times \text{Msky}$.

The relationship between ADU values and magnitudes, as derived from the established zero-points (see Section 2.1), is expressed in Equation (1):

$$\text{mag} = \text{ZP} - 2.5 \log_{10}(\text{Flux})$$

where ZP represents the zero-point magnitude. Based on the readout noise, dark current, and gain values provided by Zhang et al. (2025), this study estimates asteroid photometric errors by considering Poisson noise, skylight background noise, readout noise, and dark current noise. For bright targets ($G < 12$ mag), the uncertainty is around 2 mmag, but it increases to 0.6 mag for fainter targets at the dim end. For most targets around magnitude 18, the uncertainty is approximately 0.1 mag.

Due to the finite speed of light and the asteroid's motion relative to the observation station, aberration must be taken into account. The heliocentric Cartesian coordinates (x , y , z) of the asteroid at each epoch can be calculated using the Aleph software package (see Section 2.2). By combining these coordinates with the station's location (obtained from astropy.coordinates), an iterative algorithm is employed to correct the impact of light aberration on the observed epoch.

To improve period analysis, the observed magnitude of the asteroid was converted to absolute magnitude (H) using the formula from Bowell et al. (1989) (see their Equation (36)), considering distance and the phase angle (α) corrections.

3. Result

Figure 4 [Figure 4: see original paper] presents the light curves of 22 asteroids obtained through accurate aperture photometry in the g-band and r-band (with r-band data unavailable for two asteroids), using epoch data corrected for aberration and original observed magnitudes. Due to the non-uniform sampling of photometry points, we use the Lomb–Scargle (LS) analysis technique¹² (Lomb 1976; Scargle 1982) to derive the best-fit period. In the LS implementation, we followed McNeill et al. (2019) and Lam et al. (2023) and set the asteroids period at twice the best-fit LS period. The reason is that we assume the light variation of the asteroid is caused by the rotation. Besides, the asteroid should have a double-peaked light curve generated by the rotation of an elongated body (Pál et al. 2020). Figure 5 [Figure 5: see original paper] displays two examples of

periodograms by the LS method. According to this figure, the best-fit LS period of 2000 NQ23 is 2.12 hr (double best-fit LS period is 4.24 hr), and the best-fit LS period of 117 Lomia is 4.59 hr (double best-fit LS period is 9.18 hr).

Figure 6 [Figure 6: see original paper] features folded light curves with the best-fit rotation period for the 22 asteroids detected by the g-band MST2 which have more data than MST3. Using each asteroid's best-fit period as a reference, we fold the light curves and divide one period into 20 equal parts. Here, epoch data corrected for aberration and magnitude converted to absolute magnitude (H) are used. Because some asteroids have too few photometric points to cover the whole period, only the portion covered by the photometric points is counted such as 2001 VK58, 2002 CZ133, and so on.

To ensure the accuracy of periodic analysis, we also apply the “phase dispersion minimization” (PDM)¹³ method (Stellingwerf 1978; Sheppard et al. 2008; Wang & Wang 2012). For better comparison and to emphasize the double-peaked property of asteroid light curves, the period derived from the PDM method is also multiplied by two. Figure 7 Figure 7: see original paper depicts the relationship between the period measured by LS and PDM. Since we assume that the asteroid light curve is double-peaked, the periods of 1:1 or 1:2 by two methods are credible. The period obtained for the asteroids with more than 200 photometric points is similar, and the one obtained with less than 200 light points is not stable due to inadequate data.

In this work, the rotation period uncertainty is estimated using half the height of the main peak in the periodogram (VanderPlas 2018). Specifically, in the LS or PDM analysis, the position of the main peak is identified, and the half-width at half-maximum of the main peak is used to quantify the error during the period measurement. The method achieves a maximum precision of 0.01 hours. All the period and error data can be viewed in Table 2 .

4.1. Comparison with Existing Databases

After the photometric analysis of the periods for the 22 asteroids in both the g-band and r-band, we obtain their magnitude and period. By averaging over all the photometric points of each asteroid, we get their average magnitude. We compared the average magnitude with the average magnitude predicted in the Lowell database (Moskovitz et al. 2022) which is used in Section 2.2 and the period with the ALCDEF¹⁴ (Warner et al. 2011), as shown in Table 2. ALCDEF is hosted by the NASA Planetary Data System (PDS), which stores raw asteroid time-series photometry and includes more than 24,000 asteroids.

Figure 7(b) shows that, for asteroids with more than 200 photometric points, the obtained period data are very close to those in the ALCDEF. For the 22 asteroids analyzed in this work, periodic data from ALCDEF are available for eight of them. Among them, six have more than 200 photometric points in this study, while the other two have inadequate data, making their periodic values unreliable. For the six asteroids with adequate photometric points, five

show consistent 1:1 period matches with ALCDEF, while the other shows a 2:1 period. This discrepancy is likely due to the double-period processing applied in this study.

In our study, we converted the measured asteroid magnitudes to the V-band and compared them with the predicted magnitudes from Lowell Observatory. The average magnitude difference is only 0.14 mag, indicating good agreement with the Lowell database (see Table 2). Moreover, as MST has the advantage of multi-band photometry, we can get the color of the asteroids. After the subsequent multi-band photometry of more samples, the relationship between color and asteroid families (Degewij et al. 1978; Ivezić et al. 2002) can be analyzed more clearly and allow us to learn more about the composition of asteroids.

We also extract historical observations of 2000 NQ23 from ALCDEF including Waszczak et al. (2015) and Rowe (2018). Since the magnitude of an asteroid changes with distance, we use a simplified formula (Gehrels & Gehrels 1978; Bowell et al. 1989; Wang 2004) based on the relationship between the reduced magnitude (M)¹⁵ and observed magnitude (M_{obs}) to convert magnitude for better comparison where R is the heliocentric distance, and Δ is the geocentric distance at the time of observation. Table 3 lists the orbital parameters during the three observations of 2000 NQ23. The phase angle (α) correction is further performed according to Bowell et al. (1989) (see their Equation (36)) to convert M into absolute magnitude (H). We apply the period analysis method employed in this work to the historical observational data, and the resulting periods are consistent with those reported in Waszczak et al. (2015) and Rowe (2018) (see Table 3).

4.2. Databases of Asteroid Light Curves

There are some important databases of asteroid light curves and rotation periods, such as the Asteroid Lightcurve Database (LCDB), ALCDEF, etc. Similar databases and studies exist for specific missions such as the Transiting Exoplanet Survey Satellite (TESS) and the Wide-Field Infrared Survey Explorer (WISE). LCDB is the most authoritative repository of asteroid light curve parameters and other such as estimated/measured diameters, absolute magnitudes (H), phase slope parameters (G), albedos, and more (Warner et al. 2009). LCDB has data for 341,131 asteroids, but only 36,259 of them have periodic analyses with at least two different observations.¹⁶ LCDB does not store the original data used to do that analysis but ALCDEF does. Pál et al. (2020) analyzed and processed the TESS Data Release 1 (DR1), and obtained the light curves of 9,912 asteroids. Myhrvold et al. (2022) analyzed some of WISE's high-quality data, obtaining the light curves of 4,412 asteroids. However, TESS and WISE do not have a more comprehensive database of asteroid light curves that is updated in time. So, the amount of available light curve data for asteroids remains significantly smaller compared to the total number of known asteroids, which exceeds 1,340,000 (see Section 2.2). These databases are listed in Table 4 .

According to the results of this work, three key factors underscore the exceptional potential of the SiTian project in asteroid photometry. First, the SiTian project will scan at least 10,000 square degrees of sky in half an hour (Liu et al. 2021). The FOV is much larger than that of MST, dramatically increasing observational coverage. Second, its detection limit of 21 mag (Liu et al. 2021) outperforms the 20 mag threshold established in this work, enabling the observation of fainter asteroids. Lastly, the ecliptic latitude of this work is $18^{\circ}.37$, and observations at lower ecliptic latitudes promise greater asteroid densities, considering that 96% of known asteroids reside within a 20° band around the ecliptic plane (Marsden 1994; Zhuang 2024). Integrating these advantages, preliminary estimates are that the SiTian project can complete the photometry of one hundred thousand asteroids within one month of observation. A more detailed evaluation and simulation of the asteroid research capabilities of the SiTian project (considering various observation modes such as long-time monitoring, all-sky surveys, and ecliptic plane surveys) are in progress.

5. Conclusion

In this work, a pipeline is prepared for asteroid photometry in the SiTian project. Using this pipeline we complete the photometry for 22 asteroids with $V \leq 20$ mag in the MST f02 region and obtain light curves and periods. After comparison with ALCDEF, the periods of asteroids with more than 200 photometric points match well, which verify that MST can perform the photometric work of $V \leq 20$ mag asteroids. We present the procedure of data processing in detail.

This work utilizes the SiTian pathfinder project, MST, to demonstrate its potential for advancing research on small solar system bodies. MST's wide-field observational capability enables the collection of extensive data for constructing light curves, determining rotation periods, and studying asteroid shapes and sizes in the future. These preliminary efforts aim to enhance databases like ALCDEF, deepen our understanding of future spectroscopic and asteroid properties, and support dynamical studies.

Acknowledgments

The SiTian project is a next-generation, large-scale time-domain survey designed to build an array of over 60 optical telescopes, primarily located at observatory sites in China. This array will enable single-exposure observations of the entire sky with a cadence of only 30 minutes, capturing true color (gri) time-series data down to about 21 mag. This project is proposed and led by the National Astronomical Observatories, Chinese Academy of Sciences (NAOC). As the pathfinder for the SiTian project, the Mini-SiTian project utilizes an array of three 30 cm telescopes to simulate a single node of the full SiTian array. The Mini-SiTian began its survey in 2022 November. The SiTian and Mini-SiTian have been supported from the Strategic Pioneer Program on Astronomy Large-Scale Scientific Facility, Chinese Academy of Sciences and the Science and Education

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References

- Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., et al. 2022, *ApJ*, 935, 167
- Becker, A., 2015 HOTPANTS: High Order Transform of PSF ANd Template Subtraction, *Astrophysics Source Code Library*, ascl:1504.004
- Bertin, E. 2006, in *ASP Conf. Ser.* 351, *Astronomical Data Analysis Software and Systems XV*, ed. C. Gabriel et al. (San Francisco, CA: ASP), 112
- Bertin, E., 2010 SWarp: Resampling and Co-adding FITS Images Together, *Astrophysics Source Code Library*, ascl:1010.068
- Bertin, E., & Arnouts, S. 1996, *A&AS*, 117, 393
- Bowell, E., Hapke, B., Domingue, D., et al. 1989, in *Asteroids II*, ed. R. P. Binzel, T. Gehrels, & M. S. Matthews (Tucson, AZ: Univ. Arizona Press), 524
- Bradley, L., Sipőcz, B., & Robitaille, T. 2023, *astropy/photutils: v1.10.0*
- Cheng, A. F., Agrusa, H. F., Barbee, B. W., et al. 2023, *Natur*, 616, 457
- Degewij, J., Gradie, J., & Zellner, B. 1978, *AJ*, 83, 643
- DeMeo, F. E., & Carry, B. 2014, *Natur*, 505, 629
- Durech, J., Carry, B., Delbo, M., Kaasalainen, M., & Viikinkoski, M. 2015, in *Asteroids IV*, ed. P. Michel, F. E. DeMeo, & W. F. Bottke (Tucson, AZ: Univ. Arizona Press), 183
- Feng, S., Hu, S., Chen, X., et al. 2024, *MNRAS*, 528, 3523
- Fukugita, M., Ichikawa, T., Gunn, J. E., et al. 1996, *AJ*, 111, 1748
- Gehrels, T., & Gehrels, N. 1978, *AJ*, 83, 1660
- Gu, H. R., Huang, Y., Sun, Y. K., et al. 2025, *RAA*, 25, 044007
- He, M., Wu, H., Ge, L., et al. 2025, *RAA*, 25, 044005
- Hsieh, H. H., Jewitt, D. C., & Fernández, Y. R. 2004, *AJ*, 127, 2997
- Huang, Y., Liu, J. F., Wu, H., et al. 2025, *RAA*, 25, 044001
- Ivezić, Ž., Lupton, R. H., Jurić, M., et al. 2002, *AJ*, 124, 2943

- Jurić, M., Ivezić, Ž., Lupton, R. H., et al. 2002, *AJ*, 124, 1776
- Kaasalainen, M., & Torppa, J. 2001, *Icar*, 153, 24
- Lam, A. L. H., Margot, J.-L., Whittaker, E., & Myhrvold, N. 2023, *PSJ*, 4, 61
- Liu, X. 2019, *Galactic Archaeology in the Gaia Era (Sesto Pusteria: SCfA)*, 14
- Lomb, N. R. 1976, *Ap&SS*, 39, 447
- Lou, Z., Liang, M., Yao, D., et al. 2016, *Proc. SPIE*, 10154, 101542A
- Marsden, B. G. 1994, in *IAU Symp. 161, Astronomy from Wide-field Imaging*, ed. H. T. MacGillivray (Cambridge: Cambridge Univ. Press), 385
- McNeill, A., Mommert, M., Trilling, D. E., Llama, J., & Skiff, B. 2019, *ApJS*, 245, 29
- Moskovitz, N. A., Wasserman, L., Burt, B., et al. 2022, *A&C*, 41, 100661
- Myhrvold, N., Pinchuk, P., & Margot, J.-L. 2022, *PSJ*, 3, 30
- Pál, A., Szakáts, R., Kiss, C., et al. 2020, *ApJS*, 247, 26
- Pravec, P., Harris, A. W., & Michalowski, T. 2002, in *Asteroids III*, ed. W. F. Bottke, Jr. et al. (Tucson, AZ: Univ. Arizona Press), 113
- Rowe, B. 2018, *MPBu*, 45, 203
- Scargle, J. D. 1982, *ApJ*, 263, 835
- Scheeres, D. J., Britt, D., Carry, B., & Holsapple, K. A. 2015, in *Asteroids IV*, ed. P. Michel, F. E. DeMeo, & W. F. Bottke (Tucson, AZ: Univ. Arizona Press), 745
- Sheppard, S. S., Lacerda, P., & Ortiz, J. L. 2008, in *The Solar System Beyond Neptune*, ed. M. A. Barucci et al. (Tucson, AZ: Univ. Arizona Press), 129
- Shi, J., Ma, Y., Liang, H., & Xu, R. 2019, *NatSR*, 9, 5492
- Stellingwerf, R. F. 1978, *ApJ*, 224, 953
- Stetson, P. B. 1987, *PASP*, 99, 191
- Szabó, G. M., Pál, A., Szigeti, L., et al. 2022, *A&A*, 661, A48
- Tsuda, Y., Yoshikawa, M., Saiki, T., Nakazawa, S., & Watanabe, S.-i. 2019, *AcAau*, 156, 387
- VanderPlas, J. T. 2018, *ApJS*, 236, 16
- Wang, X.-B. 2004, PhD thesis, Yunnan Observatory, Chinese Academy of Sciences
- Wang, Y.-B., & Wang, X.-B. 2012, *RAA*, 12, 1714
- Warner, B. D., Harris, A. W., & Pravec, P. 2009, *Icar*, 202, 134
- Warner, B. D., Stephens, R. D., & Harris, A. W. 2011, *MPBu*, 38, 172
- Waszczak, A., Chang, C.-K., Ofek, E. O., et al. 2015, *AJ*, 150, 75
- Xiao, K., Li, Z. R., Huang, Y., et al. 2025, *RAA*, 25, 044006
- Xu, X., Wang, X., Muinonen, K., et al. 2023, *MNRAS*, 521, 3925
- Yeh, T.-S., Li, B., Chang, C.-K., et al. 2020, *AJ*, 160, 73
- Zhang, J.-C., Wang, X.-F., Mo, J., et al. 2020, *PASP*, 132, 125001
- Zhang, Y., Du, L., Hu, Y., et al. 2025, *RAA*, 25, 044003
- Zhuang, Y.-Y. 2024, Master's thesis, Univ. of Science and Technology of China

Notes:

⁶ <https://asteroid.lowell.edu>

⁷ <https://github.com/josepenaz/ephs>

⁸ <https://docs.astropy.org/en/stable/wcs/index.html>

⁹ <https://github.com/spacetelescope/astrocut>

¹⁰ <https://photutils.readthedocs.io/en/stable/api/photutils.detection.DAOSTarFinder.html>

¹¹ <https://photutils.readthedocs.io/en/stable/aperture.html>

¹² <https://docs.astropy.org/en/stable/timeseries/lombscargle.html>

¹³ <https://pyastronomy.readthedocs.io/en/latest/pyTimingDoc/pyPDMDoc/pdm.html>

¹⁴ <https://alcddef.org>

¹⁵ The reduced magnitude of the asteroid refers to the magnitude when the asteroid is 1 au away from both the Sun and the Earth, where the phase angle (α) is not taken into account.

¹⁶ <https://minplanobs.org/mpinfo/php/lcdb.php>

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

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