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Ground-based optical imaging of near-Sun asteroids

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ABSTRACT

We obtained imaging of the expected positions of 31 near-Sun asteroids using Lowell Observatory's 4.3-m Lowell Discovery Telescope (LDT; formerly known as the Discovery Channel Telescope, DCT) and the 4.1-m Southern Astrophysical Research (SOAR) telescope, supplemented by data from the Isaac Newton Telescope (INT) and Lowell Observatory's 42-in and 31-in telescopes between 2017 January and 2020 March. Twenty-four asteroids were successfully detected, while nine objects were predicted to be within our FOVs and above our detection limit but were not recovered, most likely due to the very large uncertainty in their orbits. Combined, the collection contains images from 33 unique nights of observations.

1. INTRODUCTION

This collection contains observations of the expected positions of 31 near-Sun asteroids with a perihelion distance less than 0.15 au (except for asteroid 2004 LG which previously had $q < 0.15$ au) obtained between 2017 January and 2020 March in support of the NASA Solar System Observation program "Characterizing the Properties of Near-Sun Objects: the Least Understood Class of PHOs" to original Principal Investigator (PI) Matthew M. Knight and current PI Michael S. P. Kelley (grant NNX17AK15G).

Observations were obtained using Lowell Observatory's 4.3-m Lowell Discovery Telescope (LDT; formerly known as the Discovery Channel Telescope, DCT) and the 4.1-m Southern Astrophysical Research (SOAR) telescope, supplemented by data from the Isaac Newton Telescope (INT) and Lowell Observatory's 42-in and 31-in telescopes. The LDT collection contains images of the expected positions of 18 unique asteroids, including formerly near-Sun asteroid 2004 LG, observed on 17 nights. The SOAR Goodman collection contains images of 7 unique asteroids observed on 4 nights. The SOAR SOI collection contains images of 3 unique asteroids observed on one night.

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Table 1. Instruments

Telescope	Instrument	tel	Aper Size	FOV	Pix Sc[a]	Binning	Filters
Lowell Discovery Telescope (LDT)	Large Monolithic Imager (LMI)	`ldt`	4.3m	$12.3' \times 12.3'$	$0.36''$	3×3	g', r', i', z'
Southern Astrophysical Research (SOAR)	Goodman Spectrograph	`sor`	4.1m	$7.2'$ diameter	$0.30''$	2×2	g', r', i', z'
Southern Astrophysical Research (SOAR)	SOAR Optical Imager (SOI)	`soi`	4.1m	$5.26' \times 5.26'$	$0.154''$	2×2	g', r', i', z'
Isaac Newton Telescope (INT)	Wide Field Campera (WFC)	`int`	2.5m	$11.5' \times 23.0'$	$0.33''$	None	g', r', i', z'
Lowell Observatory 31-inch	NASAcam	`l31`	0.8m	$15.7' \times 15.7'$	$0.46''$	None	B, V, R, I
Lowell Observatory 42-inch	NASA42 Camera	`l42`	1.1m	$25.3' \times 25.3'$	$1.11''$	3×3	B, V, R, I

[a] Effective pixel scale after binning

The INT collection contains images of 6 unique asteroids observed on 3 nights. Asteroid 2000 BD19 was observed on 3 nights and 2002 AJ129 was observed on 2 nights using the Lowell 31-inch telescope. Finally, asteroid 2006 HY51 was observed on 2 nights using the Lowell 42-inch telescope. Combined, the collection contain images of the expected positions of 31 unique asteroids from 33 unique nights of observations. We do not include two of the nine undetected objects that have since had their orbits constrained and we now know they were outside of the FOV during our observations.

2. OBSERVATIONS

2.1. *Data Collection*

Broadband SDSS g', r', i', z' filters were used at all telescopes except for Lowell Observatory's 31-inch and 42-inch, where Johnson-Cousins B, V, R, I filters were used. A summary of the instruments used can be found in Table 1. All images were acquired at the asteroid's ephemeris rate, which frequently resulted in trailed stars. Whenever possible, we kept the star trails to less than two times the seeing in order to accurately register the image, but for some objects long trails were unavoidable. Exposure times varied with the asteroid's brightness and telescope size, but were typically 180–300 seconds. The number of images acquired for each target varied with time available, though at least two cycles of filters were achieved for all observations, ordered in a way so that the mid-time of the observations for each filter is approximately the same to mitigate rotational variability. Asteroids 2000 BD19, 2002 AJ129, and 2006 HY51 were targeted for lightcurve studies and have many more images than the rest of the asteroids in this archive, which were otherwise targeted for the measurement of photometric colors.

2.2. *Instruments*

Northern hemisphere targets were primarily observed with Lowell Observatory's 4.3-m LDT located near Flagstaff, AZ. All observations were made using the Large Monolithic Imager (LMI; Massey et al. 2013). LMI has a field-of-view (FOV) of $12'.3 \times 12'.3$ and a pixel scale of $0''.36$ after an on-chip 3×3 binning.

Observations of southern hemisphere targets were made using the 4.1-m SOAR Telescope on Cerro Pachón in Chile. The Goodman Spectrograph Red Camera (Clemens et al. 2004) and the SOAR Optical Imager (SOI) were used. The Goodman Spectrograph camera has a circular FOV of 7.′2 diameter. The observations were done in 2 × 2 binning mode with an effective pixel scale of 0.″30. SOI uses two adjacent CCD chips read out through two amplifiers per chip that cover a 5.′26 × 5.′26 FOV and have a scale of 0.″154/pixel after 2 × 2 binning.

We conducted an observing run in January 2017 using the 2.5-m INT at the Rogue de Los Muchachos Observatory in La Palma, Spain. Observations were made using the Wide Field Camera (WFC), which has an effective FOV of 11.′5 × 23.′0 and a pixel scale of 0.″33.

Supplemental observations were made using Lowell Observatory's Hall 31-inch (0.8 m) and 42-inch (1.1 m) telescopes. The 31-inch telescope has a square field of view of 15.′7 on a side and an unbinned pixel scale of 0.″46. The 42-inch telescope has a square field of view of 25.′3 on a side and a 3 × 3 binned pixel scale of 1.″11. We included Landolt standard star fields (Landolt 1992, 2009) with the 31-inch collection because the images did not contain a sufficient amount of stars for in-field calibration due to a brighter limiting magnitude. Observations using the 31-inch were robotically acquired. All other telescopes used classic observing mode.

3. PROCESSING

Each observation followed the same reduction routine. A master bias frame for each night was created by averaging 10–20 individual bias frames. The master bias frame was then subtracted from each frame. At least five sky or dome flats taken during the same observing period were normalized and median combined for each filter used. Images were flat-field corrected by dividing each frame by the median-combined flat-field.

Raw images are named `tel_YYYYMMDD_XXX_raw.fits`, where `tel` is the telescope abbreviation listed in Table 1, `YYYYMMDD` is the date of observation, and `XXX` is the individual extension number. Median-combined bias files are named `tel_YYYYMMDD_Bias_master.fits`. Median combined flat fields are named `tel_YYYYMMDD_Flat_FILTER.fits` if using dome flats and `tel_YYYYMMDD_Skyflat_FILTER.fits` if skyflats were used where `FILTER` is the filter used. Calibrated science data is named `tel_YYYYMMDD_XXX_ppp.fits` where `ppp` stands for partially processed product and `XXX` is the same individual extension number as the raw image.

4. PUBLISHED RESULTS

Photometric analysis of this data has been published in Holt et al. (2022). The paper includes tabulated photometry for the 23 detected objects. Asteroid 2017 TC1 was detected, but meaningful photometry could not be measured due to contaminated field. Asteroid 2011 XA3 was also detected, but contained limited data in a single

Table 2. Summary file column information.

Col.	Positions	Col. Name	Type	Definition
1	1-17	File Name	string	Root image name (`tel_YYYYMMDD_XXX`)
2	18-29	Target	string	Asteroid designation
3	30-41	ObsDate	string	Date of observation (YYYY-MM-DD)
4	42-54	ObsStartTime	string	UT Start time of observation (HH:MM:SS.S)
5	55-63	ExpTime	int	Exposure time, in seconds
6	64-71	Filter	string	Filter
7	72-81	RA	string	Right Ascension (HH:MM:SS)
8	82-92	Dec	string	Declination (DD:MM:SS)
9	93-101	RA_rate	float	Rate of change of RA, in arcsec/hr
10	102-111	Dec_rate	float	Rate of change of Dec, in arcsec/hr
11	112-117	r	float	Heliocentric distance, in au
12	118-124	delta	float	Geocentric distance, in au
13	125-134	PhaseAng	float	Sun-object-Earth phase angle, in degrees
14	135-144	DetectObj	int	Nondetection flag (1 if not detected)

filter, so we did not include it in the paper, but it is included in the archive. The images were assessed visually and no activity (e.g., deviations from a point source, visible tail) was identified.

5. ORGANIZATION

The collection is separated into `raw/` and partially processed products (`ppp/`) directories. Within each directory, there are `tel/` directories containing the date of observations in `YYYYMMDD/` format. Further division happens in the `ppp/` directory into `calibration_data/` and `science_data/` subdirectories.

There is also a summary file for each telescope, named `target_table_tel.txt` where `tel` is the telescope abbreviation listed in Table 1. The summary file contains a single line for each observation, which includes the telescope pointing information and various geometric information about the asteroid. We also include a flag that indicates if the object was detected. The summary file is a fixed-width text table, with the columns defined in Table 2.

6. KNOWN ISSUES

Future users who wish to measure astrometry from these data should be mindful of potential timing uncertainties. The times given in the headers for LDT observations are those recorded by the software when the data were acquired. However, these are known to be uncertain by at least ∼2 sec. A ∼2 sec time offset was characterized by Lowell staff in 2018 using satellites[1], but follow-up testing by Quanzhi Ye (priv. comm.) in 2021 suggested an additional ∼2 sec uncertainty remained during that epoch even after making the correction suggested by Lowell staff. We've included the

[1] https://confluence.lowell.edu/download/attachments/20545959/180530_shutter_delay.pdf?version=2&modificationDate=1544027286000&api=v2

2018 document as `LMI_shutterdelay_Levine18.pdf`. We have no information about timing uncertainties at other epoch for LDT or for the other telescopes included in this archive.

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