SAFARI: Searching Asteroids for Activity Revealing Indicators

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Abstract

Active asteroids behave dynamically like asteroids but display comet-like comae. These objects are poorly understood, with only about 30 identified to date. We have conducted one of the deepest systematic searches for asteroid activity by making use of deep images from the Dark Energy Camera (DECam) ideally suited to the task. We looked for activity indicators among 11,703 unique asteroids extracted from 35,640 images. We detected three previously identified active asteroids ((62412), (1) Ceres and (779) Nina), though only (62412) showed signs of activity. Our activity occurrence rate of 1 in 11,703 is consistent with the prevailing 1 in 10,000 activity occurrence rate estimate. Our proof of concept demonstrates (1) our novel informatics approach can locate active asteroids and (2) DECam data are well-suited to the search for active asteroids.

Key words: methods: analytical – minor planets, asteroids: general – techniques: image processing

Online material: color figures, supplementary material

1. Introduction

Active asteroids appear to have tails like comets (Figure 1), but follow orbits predominately within the main asteroid belt. Although the first active asteroid (Wilson–Harrington) was discovered in 1949 (Cunningham 1950), 27 of the 31 objects (87%) were identified as active in the last decade (Table 1). Asteroid activity is thought to be caused by several different mechanisms, combinations of which are undoubtedly at work (e.g., an impact event exposing subsurface ice to sublimation). The number of times (i.e., orbits) an object has displayed activity (Table 1: Act.) is especially diagnostic of the mechanism (Table 1: Cause). A singular (non-recurring) event likely originates from an impact event, e.g., (596) Scheila. Rotational breakup, as in P/2013 R3 of Figure 1, may be a one-time catastrophic event, or a potentially repeating event if, for example, only a small piece breaks free but the parent body remains near the spin breakup limit. Ongoing or recurrent activity has been observed ~15 times, e.g., 133P/Elst–Pizarro, and is suggestive of sublimation or, in the case of (3200) Phaethon, thermal fracture. These last two mechanism (sublimation and thermal fracture) should be more likely to occur when an object is closer to the Sun, i.e., perihelion (Table 1: q). The Sun-object distance (Table 1: R) indicates the absolute distance, but it is can be simpler to consider how close (Table 1: %peri) to perihelion the object was when activity was first observed (Table 1: 1st Act), where 100% represents perihelion (q) and 0% indicates aphelion:

\[ \%_{\text{peri}} = \left[ 1 - \left( \frac{d_{\text{disc}} - d_{\text{peri}}}{d_{\text{ap}} - d_{\text{peri}}} \right) \right] \cdot 100\%, \]  

where \( d_{\text{disc}} \) is the heliocentric object distance at the activity discovery epoch, \( d_{\text{peri}} \) the perihelion distance, and \( d_{\text{ap}} \) the aphelion distance.

While the term “Main Belt Comets” often refers to this sublimation-driven subset of active asteroids, we use the more inclusive “active asteroid” term throughout this paper. We aimed to include all objects termed “active asteroids” in the literature for completeness, but we only include objects which have provided observable signs of activity. Objects known to host surface water ice but which have yet to shown signs of activity, such as (24) Themis (Campins et al. 2010; Rivkin & Emery 2010), are outside the scope of this paper.

Orbital characteristics also provide insight into the dynamical evolution and even the composition of an object. Objects with conspicuously similar orbital properties may have originated from a catastrophic disruption event that created a family (Table 1:Family) of asteroids (Hirayama 1918). More generally, asteroids can be categorized (Table 1: Orb.) as interior to the Main Asteroid Belt, within the Main Asteroid Belt (and further subdivided into inner, mid, and outer main belt as IMB, MMB, and OMB respectively), or exterior to the Main Asteroid Belt (e.g., Kuiper Belt). Objects interior to the Main Asteroid Belt, including Near Earth Objects (NEOs), include Earth-crossing (Apollo, Earth-orbit nearing (Amor),
undergoing a breakup. The orbital elements are given by Equations (1) to Comet 2P and Mars-crossing asteroids. Objects whose orbits are similar to Comet 2P/Encke are said to be Encke-type.

The Tisserand parameter $T_J$ (Table 1TJ) describes the degree to which an object’s orbit is influenced by Jupiter:

$$T_J = \frac{a_J}{a} + 2 \sqrt{1 - e^2} \frac{a}{a_J} \cos(i). \quad (2)$$

The orbital elements are given by $a_J$ the orbital distance of Jupiter (5.2 AU), plus the semimajor axis $a$, eccentricity $e$, $i$ the inclination (Table 1). For the case where $a = a_J$ you can see $T_J = 3$. Asteroids in the main-belt are typically inside the orbit of Jupiter (i.e., $a < a_J$) and usually have $T_J > 3$ (Jewitt 2014); however, as Equation (2) indicates, it is the combination of all three free parameters ($a$, $e$, $i$) which describes the magnitude of Jovian influence on the object’s orbit. One active asteroid definition also constrains membership to objects whose orbits are interior to Jupiter but whose Tisserand parameters are $>3.08$ (Jewitt 2014).

Objects not identified in the literature as active asteroids, yet still appear orbitally asteroidal (e.g., Comet 2P/Encke), are not included in this paper, but objects with $T_J < 3$ which are identified in the literature as active asteroids (e.g., (3552) Don Quixote), are included; see e.g., Hsieh & Jewitt (2006) and Tancredi (2014) for further discussion on distinguishing objects within this regime.

We would like to understand active asteroids in part because they may hold clues about solar system formation and the origin of water delivered to the terrestrial planets. The recent discovery of interstellar asteroid ‘Oumuamua (Bacci et al. 2017a) intensifies interest in understanding our own indigenous asteroid population in order to better understand and characterize ejectoids we encounter in the future, an estimated decadal occurrence (Trilling et al. 2017). There has also long been an interest mining asteroids for their metals, and water could prove an invaluable resource providing, for example: energy, rocket fuel, breathable oxygen, and sustenance for plant and animal life (O’Leary 1977; Dickson 1978; Kargel 1994; Forgan & Elvis 2011; Hasnain et al. 2012; Lewicki et al. 2013; Andrews et al. 2015).

Our knowledge of active asteroids has been limited due to small sample size: only $\sim20$ active asteroids have been discovered to date (Jewitt et al. 2015c). As such, the statistics presented in Table 2 are poorly constrained (e.g., the thermal fracturing rate is based upon a single object: (3200) Phaethon). Spacecraft visits have been carried out or planned to a number of the active asteroids (Table 1: Visit), and while we may learn a great deal from these individual objects, spacecraft visits will not substantially increase the number of known active asteroids. While spectroscopy has recently shown potential for discovering activity, the overwhelming majority of activity detections have been made by visual examination (Table 1: Method). One notable exception was the 1984 (2201) Oljato outburst first detected by magnetic field disturbances (2201) Oljato outburst (Russell et al. 1984).

We chose to visually examine (“by-eye”) images of active asteroids because this technique has so far produced the greatest yield. Other methods have been applied (Table 3) but with varied degrees of success. Cikota et al. (2014) examined a large number of objects and searched for unexpected deviations in object brightness; this technique positively identified one known active asteroid, but (so far) the other candidates (1) have not been observed to be active. Sonnett et al. (2011) examined the regions immediately surrounding asteroids, searching for photometric excess (i.e., a photon count above the sky background level). Waszczak et al. (2013) formulated a way to quantify “extendedness” of Palomar Transient Factory objects, with a 66% comet detection rate and a 100% Main Belt Comet detection efficiency. Hsieh et al. (2015a) compared point-spread function (PSF) widths between background stars and other objects and flagged exceptionally large PSF radii for further follow-up. All of the aforementioned techniques rely upon visual inspection for confirmation of activity. Spectroscopic detection of activity has also been carried out (Table 1), but so far only (1) Ceres has been observed to be visually active in follow-up, and, in that case, in situ by the Rosetta spacecraft orbiting it. Hayabusa 2 recently arrived at (162173) Ryugu but as of yet no tail or coma has been observed.

Conservative activity occurrence rates of $>1$ in 10,000 are constrained by the magnitude limits of prior surveys (Jewitt et al. 2015c). We reached past the 17–22.7 mag limits of previous large-sky surveys (Table 3) by making use of existing Dark Energy Camera (DECam) data (Sheppard & Trujillo 2016) probing a magnitude fainter than other large-sky active asteroid survey. Note that while we are sensitive to more

Figure 1. Active asteroid P2013/R3 was imaged in 2013 October while undergoing a breakup (into components A–D) likely caused by rotational instability. The antisolar and negative heliocentric velocity vector arrows are labeled $\odot$ and $-V$, respectively. Reprinted Figure 2 of Jewitt et al. (2017). © AAS.
| Asteroid Name       | a   | e   | i   | Orbit | T_i | P   | q   | R_e | f^a | % Peri^b | Act. d | Cause |
|---------------------|-----|-----|-----|-------|-----|-----|-----|-----|-----|----------|--------|-------|
| (1) Ceres           | 2.77| 0.08| 10.6| MB    | 3.310| 4.6| 2.60| 2.72| 279.3| 62       | 3+     | 🌍, 🛐 |
| (145) Adeona        | 2.67| 0.14| 12.6| MB    | 3.331| 2.28| 2.29| 2.69| 258.8| 47       | 2      | ☀      |
| (315) Constantia    | 2.24| 0.17| 2.4 | MB    | 3.614| 3.36| 1.86| 1.94| 315.9| 92       | 0°     | (?)    |
| (493) Griseldis     | 3.12| 0.18| 15.2| OMB   | 3.140| 5.5 | 2.57| 3.34| 122.4| 31      | 1      | ❄❄❄❄ |
| (596) Scheila       | 2.93| 0.16| 14.7| OMB   | 3.209| 5.01| 2.45| 3.11| 239.2| 90       | 1      | ❄❄❄❄ |
| (704) Internania    | 3.06| 0.15| 17.3| MB    | 3.148| 5.35| 2.59| 2.62| 19.6 | 97       | 1      | ☀      |
| (779) Nina          | 2.66| 0.23| 14.6| MB    | 3.302| 4.35| 2.06| 2.15| 36.9 | 93       | 1      | ☀      |
| (1026) Ingrid       | 2.25| 0.18| 5.4 | MB    | 3.597| 3.38| 1.85| 2.23| 97.5 | 16       | 0°     | (?)    |
| (1474) Beira        | 2.73| 0.49| 26.7| Mars  | 3.033| 4.52| 1.39| 1.57| 310.9| 93       | 1      | ☀      |
| (2201) Oljato       | 2.17| 0.71| 2.5 | Apollo| 3.298| 3.21| 0.62| 0.88| 73.1 | 92       | 1      | (?)    |
| (3200) Phaethon      | 1.27| 0.89| 22.2| Apollo| 4.510| 1.43| 0.14| 0.14| 5.1  | 87       | 3      | ☀      |
| (3552) Don Quixote  | 4.26| 0.71| 31.1| Amor  | 2.315| 8.78| 1.24| 1.23| 343.6| 100      | 2      | ☀, (?) |
| (3646) Aduatiques   | 2.75| 0.11| 0.6 | MB    | 3.336| 4.57| 2.46| 2.56| 300.0| 90       | 0°     | (?)    |
| (4015) Wil-Har.     | 2.72| 0.63| 2.8 | Apollo| 3.082| 4.26| 0.97| 1.17| 51.0 | 95       | 2°     | ☀, (?) |
| (24684) 1990 EU4    | 2.32| 0.08| 3.9 | MB    | 3.572| 3.53| 2.13| 2.28| 277.9| 77       | 0°     | (?)    |
| (75101) 1991 PL16   | 2.60| 0.18| 12.3| MB    | 3.365| 4.17| 2.12| 2.86| 227.0| 21       | 0°     | (?)    |
| (62412)             | 3.15| 0.08| 4.7 | OMB   | 3.197| 5.6 | 2.90| 3.06| 74.5 | 68       | 1      | ☀      |
| (162173) Ryugu      | 1.19| 0.19| 5.9 | Apollo| 5.308| 1.3 | 0.96| 1.08| 288.4| 8        | 1      | ☀      |
| (457175)            | 3.96| 0.28| 15.6| OMB   | 2.926| 7.89| 2.85| 3.28| 66.0 | 81       | 1      | (?)    |
| (133P) Elst-Pizarro | 3.16| 0.16| 1.4 | OMB   | 3.184| 5.63| 2.66| 2.65| 21.7 | 100      | 4      | ☀      |
| (176P) LINEAR       | 3.20| 0.19| 0.2 | OMB   | 3.166| 5.71| 2.58| 2.59| 10.1 | 1        | 1      | (?)    |
| 233P/La Sagra       | 3.04| 0.41| 11.3| Encke | 3.081| 5.28| 1.78| 2.01| 309.1| 91       | 1      | (?)    |
| 238P/Read           | 3.16| 0.25| 1.3 | OMB   | 3.154| 5.64| 2.37| 2.42| 26.5 | 97       | 3      | ☀      |
| 259P/Garradd        | 2.73| 0.34| 15.9| MMB   | 3.217| 4.51| 1.81| 1.85| 27.6 | 99       | 2      | ☀      |
| 288P (300163)       | 3.05| 0.20| 3.2 | OMB   | 3.204| 5.32| 2.44| 2.45| 12.2 | 99       | 2      | ☀      |
| 311P/PS             | 2.19| 0.12| 5.0 | IMB   | 3.661| 3.24| 1.94| 2.15| 272.8| 58       | 2      | ☀, ☀   |
| 313P/Gibbs          | 3.16| 0.24| 11.0| Encke | 3.132| 5.62| 2.42| 2.40| 8.0  | 100      | 2      | ☀      |
| 324P/La Sagra       | 3.10| 0.15| 21.4| OMB   | 3.100| 5.45| 2.62| 2.64| 20.0 | 98       | 2      | ☀      |
| 331P/Gibbs          | 3.00| 0.04| 9.7 | OMB   | 3.229| 5.21| 2.88| 3.10| 140.4| 11       | 2      | ❄❄❄❄ |
| 348P/PS             | 3.17| 0.30| 17.6| OMB   | 3.062| 5.63| 2.18| 2.51| 60.8 | 83       | 1      | (?)    |
| 354P/LINEAR         | 2.29| 0.12| 5.3 | OMB   | 3.583| 3.47| 2.00| 2.01| 12.2 | 99       | 1      | ☀, ☀   |
| 358P                | 3.15| 0.24| 11.1| Encke | 3.135| 5.59| 2.39| 2.42| 7.5  | 99       | 2      | ☀, (?) |
| P/2013 R3           | 3.03| 0.27| 0.9 | OMB   | 3.184| 5.28| 2.20| 2.22| 14.0 | 99       | 1      | ☀, ☀   |
| P/2015 X6           | 2.75| 0.17| 4.6 | MMB   | 3.318| 4.57| 2.28| 2.64| 274.5| 62       | 1      | ☀      |
| P/2016 G1           | 2.58| 0.21| 11.0| MMB   | 3.367| 4.15| 2.04| 2.52| 264.7| 56       | 1      | ❄❄❄❄ |
| P/2016 J1           | 3.17| 0.23| 14.3| OMB   | 3.113| 5.65| 2.45| 2.46| 345.9| 99       | 1      | ☀, ☀   |
We set out to determine the viability of DECam data for locating active asteroids. We aimed to create a novel, streamlined pipeline for locating known asteroids within our data set. We planned to examine our new library of asteroid thumbnails to find active asteroids and to test published asteroid activity occurrence rates (Table 4). We applied our technique to 35,640 DECam images (~5 Tb) to produce 15,600 thumbnail images comprising 11,703 unique objects. We examined the asteroid thumbnails by-eye to identify signs of activity. We show our technique can be applied to distant populations (e.g., Centaurs, Trans-Neptunian Objects), 99.7% of our population is from the main asteroid belt.

| Asteroid Name | Family | 1st Act\(^a\) (years) | Facility\(^b\) | Method | Last\(^d\) (years) | Visit | Refs\(^e\) |
|---------------|--------|------------------------|--------------|--------|-------------------|------|---------|
| Ceres         | None   | 2014                   | Herschel     | Spec.  | 2017              | Yes  | [1]     |
| Adeona        | Adeona | 2017                   | Terksol      | Spec.  | 2016              | No   | [2]     |
| Constantia    | Flora  | 2013                   | MPCAT        | Phot.  | 2013              | No   | [3]     |
| Griseldis     | Eunomia| 2015                   | Subaru       | Visual | 2015              | No   | [4]     |
| Scheila       | None   | 2010                   | CSS          | Visual | 2010              | No   | [5]     |
| Interamnia    | None   | 2017                   | Terksol      | Spec.  | 2012              | No   | [6]     |
| Nina          | …      | 2017                   | Terksol      | Spec.  | 2012              | No   | [7]     |
| Ingrid        | Flora  | 2013                   | MPCAT        | Phot.  | 2013              | No   | [8]     |
| Beira         | …      | 2017                   | Terksol      | Spec.  | 2012              | No   | [9]     |
| Ojato         | …      | 1984                   | Pioneer      | Mag.   | 1984              | No   | [10]    |
| Phaethon      | Pallas | 2009                   | STEREO       | Visual | 2017              | Yes  | [11]    |
| Don Quixote   | …      | 2009                   | Spitzer      | Visual | 2018              | No   | [12]    |
| Adidasquites  | …      | 2013                   | MPCAT        | Phot.  | 2013              | No   | [13]    |
| Wil.-Har.     | …      | 1949                   | Palomar      | Visual | 1979\(^f\)        | No   | [14]    |
| 1900 EU4      | Eunomia| 2013                   | MPCAT        | Phot.  | 2013              | No   | [15]    |
| 1991 PL16     | Eunomia| 2013                   | MPCAT        | Phot.  | 2013              | No   | [16]    |
| Hygiea        | …      | 2015                   | DECam        | Visual | 2014              | No   | [17]    |
| Ryugu         | …      | 2017                   | MMT          | Spec.  | 2017              | Yes  | [18]    |
| Hilda         | …      | 2017                   | CSS          | Visual | 2017              | No   | [19]    |
| Themis        | …      | 1996                   | ESO          | Visual | 2014              | No   | [20]    |
| Themis        | …      | 2009                   | LSSS         | Visual | 2009              | No   | [21]    |
| Gorkhakov     | …      | 2005                   | SW           | Visual | 2016              | No   | [22]    |
| Garradd       | …      | 2008                   | SS           | Visual | 2017              | No   | [23]    |
| Themis        | …      | 2011                   | PS           | Visual | 2017              | No   | [24]    |
| Behrens       | …      | 2013                   | PS           | Visual | 2014              | No   | [25]    |
| Lixiaohua     | …      | 2014                   | CSS          | Visual | 2015              | No   | [26]    |
| Alauda        | …      | 2011                   | LSSS         | Visual | 2015              | No   | [27]    |
| Gorkhakov     | …      | 2017                   | PS           | Visual | 2017              | No   | [28]    |
| Movius        | …      | 2017                   | PS           | Visual | 2017              | No   | [30]    |
| Baptistina    | …      | 2010                   | LINEAR       | Visual | 2017              | No   | [31]    |
| Lixiaohua     | …      | 2012                   | PS           | Visual | 2017              | No   | [32]    |
| Mandragora    | …      | 2013                   | PS           | Visual | 2013              | No   | [33]    |
| Acolia        | …      | 2015                   | PS           | Visual | 2015              | No   | [34]    |
| Adeona        | …      | 2016                   | PS           | Visual | 2016              | No   | [35]    |
| Theobalda     | …      | 2016                   | PS           | Visual | 2016              | No   | [36]    |

Notes:
\(a\) Heliocentric discovery distance.
\(b\) True anomaly.
\(c\) Percentage toward perihelion.
\(d\) Number of times object reported active.
\(e\) Authors declare object a candidate (activity not yet confirmed).
\(f\) Year activity discovered.
\(g\) Facility originally reporting activity.
\(h\) As of 2018 January submission.
\(i\) Object-specific references in the Appendix.
an orders-of-magnitude larger publicly available data set to elevate active asteroids to a regime where they can be studied as a population.

2. Methods

2.1. Dark Energy Camera

We made use of data taken by the Dark Energy Camera (DECam) instrument on the 4 m Blanco telescope at the Cerro Tololo Inter-American Observatory in Chile. The instrument has a ∼3 square degree field of view, capturing data via a mosaic of 62 charge-coupled device (CCD) chips, each 2048 × 4096 with a pixel scale of 0′′/263 per pixel (Dark Energy Survey Collaboration et al. 2016). Our data consisted of 594 × 2.2 Gb frames in the VR filter (500 ± 10 nm to 760 ± 10 nm), each containing 62 × 33 Mb subsets of data, one per CCD. The mean seeing across all images was 1′′14 ± 0′′13. We made use of software which required each multi-extension Flexible Image Transport System (FITS) file be split into its 62 constituent parts, which we refer to as images for the remainder of this paper. Note: some files contained only 61 chips due to an instrument hardware malfunction.

2.2. High Performance Computing

We utilized Monsoon, the Northern Arizona University (NAU) High Performance Computing (HPC) computing cluster. Monsoon uses the Slurm Workload Manager (Yoo et al. 2003) software suite to manage the 884 Intel Xeon processors to deliver up to 12 teraflops of computing power. The majority of our tasks each utilized 8 cores and 48 Gb of memory. The online supplementary material at stacks.iop.org/PASP/130/114502/mmedia contains the complete listing of requirements necessary for each task.

2.3. photometrypipeline

We utilized the photometrypipeline (Mommert 2017) software package to carry out source extraction via Source Extractor (Bertin & Arnouts 1996, 2010), photometry and astrometry via SCAMP (Bertin 2006; Bertin & Arnouts 2010), and asteroid identification via SkyBot (Berthier et al. 2006) and Horizons (Giorgini 2015). We chose the Anaconda4 Python programming language distributions (versions 2.7 and 3.5) and the Python package AstroPy (Astropy Collaboration et al. 2013).

2.4. Procedure

1. Image reduction. We employed standard image reduction techniques where each frame was bias subtracted, then flat-fielded using a combination of twilight flats and a master flat; full details of our imaging techniques can be found in Sheppard & Trujillo (2016).

2. Splitting multi-extension FITS files. DECam produces multi-extension FITS files, where each extension contains data from one CCD; because photometrypipeline was incompatible with this format, we split each file into 62 separate FITS files via the FTOOLS (Blackburn 1995) software package. We replicated global and extension headers for each output file to preserve metadata required for our image processing.

3. Coordinate correction. Each DECam image came pre-encoded with right ascension (R.A.) and declination (decl.) information indicating the coordinates of the telescope pointing center. We shifted the R.A. and decl. of each remaining CCD to their true coordinate values. The R.A. and decl. offsets used for each CCD are provided with the online supplement.

4. World Coordinate System purging. We discovered World Coordinate System (WCS) headers encoded in the FITS files were preventing photometrypipeline and/or astrometry.net from performing astrometry. We were able to resolve the issue by purging all WCS header information

References. (a) Drake et al. (2009), (b) estimated from aperture, (c) Sesar et al. (2011), (d) Chambers et al. (2016), (e) Larsen et al. (2007), (f) Larson et al. (1998), (g) Stoss (2011), (h) Stokes et al. (2000), (i) Jedicke (2008), (j) Gehrels (1981).

Table 2

| Suspected Mechanism       | N | %  |
|---------------------------|---|----|
| Sublimation               | 15| 44 |
| Rotational Breakup        | 7 | 21 |
| Impact/Collision          | 4 | 12 |
| Thermal Fracturing        | 1 | 3  |
| Cryovolcanism             | 1 | 3  |
| Binary Interaction        | 1 | 3  |
| Unknown                   | 5 | 15 |

Note. ∗ Objects with multiple mechanism are counted more than once; objects listed in Table 1 as candidates were not included in this computation.

Table 3

| AA Discovered by (survey name) | AAs (N) | Limit (mag) | Operation (years) |
|--------------------------------|---------|-------------|-------------------|
| Catalina Sky Survey            | 5       | 22(a)       | 1998(f)           |
| La Sagra Survey                | 2       | 17(b)       | 2008(g)           |
| LINEAR                         | 1       | 19.6(c)     | 1997(h)           |
| Pan-STARRS                     | 8       | 22.7(d)     | 2008(i)           |
| Spacewatch                     | 2       | 21.7(e)     | 1981(j)           |
| Total                          | 18      | ...         | 98                |

References. (a) Drake et al. (2009), (b) estimated from aperture, (c) Sesar et al. (2011), (d) Chambers et al. (2016), (e) Larsen et al. (2007), (f) Larson et al. (1998), (g) Stoss (2011), (h) Stokes et al. (2000), (i) Jedicke (2008), (j) Gehrels (1981).

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References. (a) Drake et al. (2009), (b) estimated from aperture, (c) Sesar et al. (2011), (d) Chambers et al. (2016), (e) Larsen et al. (2007), (f) Larson et al. (1998), (g) Stoss (2011), (h) Stokes et al. (2000), (i) Jedicke (2008), (j) Gehrels (1981).

References. (a) Drake et al. (2009), (b) estimated from aperture, (c) Sesar et al. (2011), (d) Chambers et al. (2016), (e) Larsen et al. (2007), (f) Larson et al. (1998), (g) Stoss (2011), (h) Stokes et al. (2000), (i) Jedicke (2008), (j) Gehrels (1981).
as part of our optimization process. The header record names are listed in the online supplement.

5. WCS population via astrometry.net. We installed the astrometry.net (Lang et al. 2010) v0.72 software suite on Monsoon. We processed all 35,640 FITS files to retrieve coordinate information for each image by matching the image to one or more index files (catalogs of stars for specific regions of sky, designed for astrometric solving).

6. Photometrypipeline image processing. We performed source extraction, photometry, astrometry and image correction via the photometrypipeline software suite.

7. Identifying known asteroids. We identified known asteroid in our data by making use of pp_distill, a module of photometrypipeline.

8. FITS thumbnail generation. We extracted the R.A., decl., and (x, y) pixel coordinates of each object. We then produced 480 × 480 pixel, lossless, FITS format asteroid thumbnails, each a small image centered on an asteroid. For cases where the object was too close (<240 pixels) to one or more image edges, we found it best to use the NumPy Python routine to “roll” the image array; the technique shifts an array as if it were wrapped around a cylinder. For example: array [0, 1, 2, 3] rolled left by 1 would result in array [1, 2, 3, 0].

9. Create PNG thumbnails. We used an iterative-rejection technique to compute contrast parameters, then produced Portable Network Graphics (PNG) image files via MatPlotLib.

10. Animated GIF creation. We combined thumbnails of asteroids observed more than once (Figure 3(c)) to create animated Graphic Interchange Format (GIF) files (Figure 4) using the Python Image Library software package. There are a number of advantages to this inspection approach, including (1) the opportunity to inspect one asteroid at multiple epochs, (2) activity may not occur at every epoch, and (3) activity may be easier to spot if the inspector has the opportunity to become familiar with an object (e.g., the general shape or streak pattern), even if only briefly.

11. Examination of image products. Three authors served as asteroid thumbnail inspectors. Each inspector conducted a procedure consisting of rapid by-eye examination of asteroid thumbnails and animated GIFs, covering each thumbnail at least once. We flagged thumbnails and animations containing potential active asteroids for a later en masse review.

### 3. Results

**Pipeline.** We created a pipeline (Figure 2) that takes as its input DECam multi-extension FITS files, and returns individual asteroid thumbnails and animated GIF files. The initial total compute time requested across all tasks was 13,000 hr (1.5 compute-years), but after optimization (see Optimization section below) only ~500 compute hours were required. See the online supplement for a comprehensive table of resources utilized during this project.

**Image products.** We extracted 15,600 asteroid thumbnails from 35,640 DECam images (~2 Tb total). Most of our data consisted of exposure times >300s (Figure 3(a)). These longer integration times allowed us to probe deeper (fainter), with asteroids captured down to 25th mag (Figure 3(b)). Each of the 11,703 unique objects identified in our data were observed between 1 and 5 times, with 3029 objects imaged more than once (Figure 3(c)).

To compute our coverage area on sky (depicted in Figure 3(e)) we employed a nearest neighbor algorithm to identify the distinct (non-overlapping) regions of our data set.
Two fields were considered overlapping if their center-to-center distance was <1.8 degrees, the width of one DECam field. We computed our coverage to be ~200 distinct 3 deg² patches comprising ~1000 square degrees.

**Active asteroids.** We imaged one asteroid previously discovered to be active (Sheppard & Trujillo 2015): (62412). The object shows activity in our image (Figure 5; see the online supplement for additional image color map and interpolation permutations) and we were able to identify activity in two other DECam frames that were not part of this work. Sheppard & Trujillo (2015) confirmed activity with Magellan Telescope follow-up observations. We also imaged two other objects listed as active: (1) Ceres and (779) Nina, but neither showed signs of activity.

**Optimization.** The final pipeline resulted from a series of iterative optimizations carried out with a subset of our large data set. These optimizations produced order-of-magnitude reductions in compute time, and improved successful pipeline completion from the initial ~35% to the final 94%. The implemented optimizations and their results are broken down below by number (matched to the corresponding procedure number of Section 2.4). The final optimized Slurm parameters used on Monsoon can be found in the online supplement.

1. **Image reduction.** No optimization needed.
2. **File-splitting.** Splitting each multi-extension FITS file into 62 separate FITS files resulted in a larger number of smaller tasks which were better suited for parallel processing.
3. **Coordinate correction.** Coordinate corrections proved cumbersome and inefficient, so we added astrometry.net to our pipeline.
4. **WCS purging.** We identified mismatched distortion coefficients as the primary culprit behind roughly 1/3 of our images failing photometrypipeline analysis. We purged all World Coordinate System (WCS) headers, allowing us to employ astrometry.net which increased our overall throughput and output.
5. **astrometry.net astrometry.** We cached all (~32 Gb) astrometry index files (described in Section 2.4 item 5) locally so astrometry.net would not be dependent on the speed of the internet connection and file host. We optimized the astrometry.net computation by supplying the following parameters we extracted from our FITS files. Providing a pixel scale range (~0.25 pixel to ~0.28 pixel) and R.A./decl. values narrowed the range of indices that required searching. We found a 15″ search radius further reduced computation time without impacting image recognition efficacy. We disabled astrometry.net plotting due to a Slurm incompatibility, and computation time decreased further still. We found submitting astrometry.net “solve-field” tasks directly to
Slurm was much faster. All but 41 images successfully matched for astrometry on first pass, and we improved astrometry.net image recognition speed roughly tenfold.

6. photometrypipeline. Proper configuration of prerequisite software and photometrypipeline proved crucial; the online supplement contains the necessary parameters we
used. We made minor modifications to the photometry-pipeline code, described in the online supplement. We found out astropy was using home directory temporary storage space, a fatal error for systems with enforced quotas; the home storage space was also slower than the scratch space. Proper configuration reduced computation time and increased the pipeline success rate.

7. Known asteroid identification. We added an initial SkyBot query to identify the asteroids within each image. We then populated the requisite OBJECT FITS header keyword in each of our images, thereby enabling us to call Horizons to locate asteroids in our images and provide accurate astrometry. Preparing the SkyBot query and populating the OBJECT keyword enabled us to run asteroid identification tasks in parallel, reducing processing time by three orders-of-magnitude.

8. FITS thumbnails. We “rolled” images (described in Section 2.4, item 8) so we could create full-sized (480 × 480 pixel) thumbnails. While thumbnails sometimes looked peculiar when rolled, this method preserved image statistics used to compute the narrow range of contrast achieved in the next section.

9. PNG thumbnails. While photometry-pipeline does output thumbnails by default, we were unable to see enough detail with the default scaling. Therefore, we employed an iterative rejection technique. Figures 3(a) and (b) compare the two contrast ranges. For each of the 15,600 asteroid thumbnails, we chose to output different colormap/interpolation combinations: two modes of interpolation (Mitchell–Netravali balanced cubic spline filter and one set unfiltered), each in 11 color schemes (afmhot, binary, bone, gist_stem, gist_yarg, gray, hot, hsv, inferno, Purples, and viridis), examples of which are shown in the online supplement. The optimized dynamic ranges allowed faint trails to become more visible. These colormap/interpolation schemes gave us, as thumbnail inspectors, the ability to choose a comfortable theme for use while searching thumbnails for asteroid activity, thereby increasing our productivity.

10. Animated GIFs. We produced animated GIFs enabling an alternative inspection format.

11. Examination. We uncovered common sources of false positives (discussed in Section 4.3) and incorporated their presence into our visual examination procedures, resulting in a streamlined examination process while simultaneously reduced the number of false-positives.

4. Discussion

We set out to determine if DECam data would provide a suitable pool from which to search for active asteroids. We crafted a method to extract asteroid thumbnails from DECam data, and the large number of asteroids encountered (11,703) along with the exceptional depth our images probed (Figures 3(b) and (d)) indicate our data are well-suited to locating active asteroids.

4.1. Population Traits

As indicated by Figures 3(a)–(d), the population imaged during our survey were subject to selection effects caused by the depth (m_R = 23.7) of our survey (e.g., closer objects would have appeared as long trails which would have been difficult to identify with our pipeline). We classified the objects following the procedure of Hsieh et al. (2018); we categorized our population as Inner Main Belt (IMB), Mid Main Belt (MMB), and Outer Main Belt (OMB), plus two additional regions: “Interior” (to the IMB) and “Exterior” (to the OMB). Table 5 indicates the boundaries, along with their Asteroid:Jupiter (A:J) resonances.

The synthetic proper semimajor axis a_p aims to minimize the influence of transient perturbations (Knežević & Milani 2000). We made use the AstDyn-2 online catalog service (Knežević & Milani 2003) in determining proper orbital parameters for asteroids in our data set (Table 5).

Our target (object) aperture photometry was computed with a fixed diameter of 10 pixels, though photometric calibration was performed with an aperture radius determined by curve-of-growth analysis (see Mommaert 2017 for details). To determine the surface brightness limit of our catalog, we first computed the limit SB of each image:

\[ SB_{\text{lim}} = \sum_{k=1}^{N} (m_{k} - 2.5 \log_{10}(n\sigma_{bg}\sqrt{1/A})) / N, \]

where m_o is the photometric zero point (determined by PhotometryPipeline), n the order of detection level for background noise standard deviation \( \sigma_{bg} \), and A is the area of one pixel in square arcseconds (H. Hsieh 2018, personal communication).

\[ \text{Table 5} \]

| Zone          | \( R_{i} \) (A:J) | \( a_{p,i} \) (au) | \( a_{p,o} \) (au) | \( R_{o} \) (A:J) | SAFARI |
|---------------|-------------------|--------------------|--------------------|-------------------|-------|
| Int.          | 0                 | 2.064              | 3.10               | 115               | 1     |
| IMB           | 4:3               | 2.064              | 3.10               | 3605              | 26    |
| MMB           | 3:1               | 2.501              | 5:2                | 5358              | 39    |
| OMB           | 5:2               | 2.824              | 2.1                | 4599              | 33    |
| Ext.          | 2:1               | 3.277              | \( \infty \)       | 162               | 1     |
| Total         | …                 | …                  | …                  | 13,839            | 100   |

Note. Int., Ext.: Interior, Exterior to the main belt, IMB, MMB, OMB: Inner, Mid, Outer Main Belt; \( a_{p,i} \), \( a_{p,o} \): inner, outer proper semimajor axis; A:J Asteroid:Jupiter; \( R_{i} \), \( R_{o} \): inner/outer resonances.

* Not included: 791 objects with unknown parameters.

\[ \text{Note.} \ 	ext{Int., Ext.: Interior, Exterior to the main belt, IMB, MMB, OMB: Inner, Mid, Outer Main Belt; } a_{p,i}, a_{p,o} \text{: inner, outer proper semimajor axis; A:J Asteroid:Jupiter; } R_{i}, R_{o} \text{: inner/outer resonances.} \]

\[ \text{Note.} \ 	ext{Int., Ext.:} \ 	ext{Interior, Exterior to the main belt, IMB, MMB, OMB: Inner, Mid, Outer Main Belt; } a_{p,i}, a_{p,o} \text{: inner, outer proper semimajor axis; A:J Asteroid:Jupiter; } R_{i}, R_{o} \text{: inner/outer resonances.} \]

\[ \text{Note.} \ 	ext{Int., Ext.: Interior, Exterior to the main belt, IMB, MMB, OMB: Inner, Mid, Outer Main Belt; } a_{p,i}, a_{p,o} \text{: inner, outer proper semimajor axis; A:J Asteroid:Jupiter; } R_{i}, R_{o} \text{: inner/outer resonances.} \]
communication). The DECam camera had a pixel scale of $0^\prime.263$/pixel, give a pixel area

$$A = (0^\prime.263)^2 = 0.069169 \text{ arcsec}^2. \tag{4}$$

For our surface brightness analysis we made use of $N = 32,790$ chips for which we had been able to determine a photometric zero point. We computed the $3\sigma$ mean surface brightness limit of our data set to be $\text{SB}_{\text{lim}} = 27.9 \pm 1.2 \text{ mag/arcsec}^2$.

4.2. Occurrence Rates

We also aimed to validate the published asteroid activity occurrence rates of Table 4. Occurrence rates have been conservatively set at 1 in 10,000 (for all main belt asteroids), with the limiting magnitude of surveys the primary bottleneck. As shown in Figure 3(d), the DECam instrument reaches an average magnitude of 24 (Sheppard & Trujillo 2016), an unprecedented depth for large area active asteroid surveys. While our complete data set was consistent with the 1:10,000 activity occurrence rate estimate, it is somewhat surprising we did not discover additional asteroidal activity.

Hsieh et al. (2015a) postulated many active asteroids could be continuously active throughout their orbits (not just at perihelion), but with weaker activity. We expected then to find active asteroids more frequently in our search, given the objects we observed were indeed of a fainter magnitude (Figure 3(b)), though our outer main belt occurrence rate (~1:4000) was slightly higher than that reported by Hsieh et al. (2015a) which is in line with their prediction. Small number statistics may have contributed to the possible discrepancy, and it is plausible we missed activity indications due to the limitations of visual inspection which were further compounded by an increased prevalence of background sources compared to shallower surveys. The use of a point-spread function (PSF) comparison technique (e.g., Hsieh et al. 2015a) or a photometric search (e.g., Cikota et al. 2014) could help us identify candidates, features we plan to investigate in future work.

4.3. False Positives

We found false-positive management to be a formidable task, with specific mechanisms responsible for creating false-positives recurring throughout the project. For the rare cases where one of the authors involved in inspecting thumbnails found potential activity in an asteroid thumbnail, we checked other interpolation and color schemes, other thumbnails of the same asteroid, and the animated GIF if available. We checked frames showing the same region on the sky, including original CCD images, for background sources or image artifacts. What follows is a discussion of the primary culprits in order to convey the challenges faced during by-eye inspection (which is subjective by nature).

**Juxtaposition.** Figure 6(A) marks asteroid (432345); the object is in close proximity to a galaxy, which, if juxtaposed in a confusing manner, could give the appearance of a coma. 6(D) shows how a cosmic ray can be juxtaposed with a star. Figure 6(E) demonstrates how multiple objects may appear to be an extended source.

**Extended sources.** Extended sources, especially galaxies, were present in a myriad of orientations and configurations. They can appear like active asteroids, as in the edge-on galaxy shown in Figure 6(C). For a given brightness, galaxies occupied more sky area in a frame than other types of natural (i.e., non-artifact) objects and were more likely to be juxtaposed with other objects.

**Scattered light.** Figure 6(B) is scattered light associated with an especially bright star; the flare originates from the star and tapers off the further the “tail” gets from the source. While obvious in Figure 6, the “tail” can be more difficult to identify as scattered light if the source is outside of the thumbnail.

**Cosmic rays.** Cosmic rays (e.g., Figure 6(D)) are common throughout our images, most of which have exposure times of 300 s or longer (see Figure 4(a)). Figure 6(D) demonstrates how cosmic rays may not appear as straight lines, and they may seem to connect two or more objects together.

**Poor seeing.** Images with poor and/or rapidly varying seeing conditions suffered from fuzziness (potentially coma-like) and elongation implying a trailed object (e.g., an asteroid).
4.4. Limitations of By-eye Inspection

As proof-of-concept for future projects making use of larger data sets, we sought a general understanding of our throughput as thumbnail inspectors. It is worth noting we did not impose time limits upon ourselves. We noted markedly different inspection rates, with the time required to inspect all thumbnails ranging from 2 to 6 hr. Furthermore, our attention spans varied, with inspection sessions lasting roughly between 10 minutes to 3 hours before requiring a break. The false positive handling described above undoubtedly impacted our image examination efficacy to some degree. Given these challenges, it is evident a computational approach to screen for potential active asteroids (through e.g., PSF comparison) would improve our detection rate.

4.5. Asteroid Selection

We examined only known asteroids during this work, but certainly many unknown asteroids are present within our data. Future efforts involving Citizen Scientists could locate these objects and quantify previously unrecognized biases inherent to locating activity among known asteroids. We used observations from a southern observatory, and while there may be little to no effect on observed activity occurrence rates, we acknowledge this selection effect nonetheless.

4.6. Future Work

A broader study of the efficacy of human inspectors should be carried out if employing a larger number of inspectors. Injecting artificial active asteroids into the data sets would enable quantifying detection rates. The enormous data sets (2M+ thumbnails) we plan to generate will necessitate the deployment of a Citizen Science project, an endeavor that would thoroughly flush out these detection rates.

Citizen Science endeavors enable scientists to analyze otherwise prohibitively large data sets, with the added benefit of providing the scientific community with invaluable outreach opportunities proven to engage the public and spark far-reaching interest in science. Zooniverse,9 designed with the average scientist in mind, facilitates deployment of crowdsourcing science projects. Volunteers are enlisted to interpret data too complex for machines, but accomplishable by anyone with minimal training. Zooniverse has a proven track record, with notable successes such as Galaxy Zoo which, within 24 hours of launch, reached 70,000 identifications/hour (Cox et al. 2015). While traditional and social media coverage undoubtedly boosted the performance of Galaxy Zoo and other exemplary Citizen Science projects, the platform is designed to facilitate such exposure, especially through social media connectivity.

Our aim is to expand our survey to a second, comparably sized data set already in-hand. We will first explore strategies to quantify active asteroid candidacy through computational techniques such as PSF comparison. We will then use the combined data sets to design, implement and test a Citizen Science project. We plan to start with a moderate (~10 member) group of thumbnail inspectors consisting of undergraduate and graduate students, whose feedback will inform the documentation and training system which is crucial to the success of a Citizen Science project. We subsequently intend to expand our data set to the entire DECam public archive, at which point we would open our analysis system to public participation. We hope to incorporate machine learning into our pipeline as a means of reducing the number of thumbnails sent to the Citizen Science project or to help locate candidates missed at any point in the process.

5. Summary

We have developed an approach for finding active asteroids, rare objects visually like comets but dynamically like asteroids. We show DECam data are suitable for active asteroid searches. The approach involved processing 35,640 FITS files and extracting 15,600 asteroid thumbnails (small images centered on an asteroid) consisting of 11,703 unique objects. Upon visual examination of all thumbnails, we identified one previously known active asteroid (62412); our discovery rate of 1 in 11,703 is consistent with the currently accepted active asteroid occurrence rate of 1 in 10,000. We did observe (1) Ceres and (779) Nina, though the former is a special case of a priori activity knowledge (A’Hearn & Feldman 1992; Küppers et al. 2014), and neither object has ever shown signs of activity visible from Earth; as we did not observe activity in either object, we did not include them in our activity occurrence rate estimate. From our proof-of-concept study, we conclude a significantly larger survey should be carried out to locate active asteroids, finally placing them into a regime where they may be studied as a population.

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This research has made use of the VizieR catalog access tool, CDS, Strasbourg, France. The original description of the VizieR service was published in A&AS 143, 23 (Ochsenbein et al. 2000). This research has made use of data and/or services provided by the International Astronomical Union’s Minor Planet Center. This research has made use of NASA’s Astrophysics Data System. This research has made use of the The Institut de Mécanique Céleste et de Calcul des Éphémérides (IMCCE) SkyBoT Virtual Observatory tool (Berthier et al. 2006). This work made use of the FTOOLS software package hosted by the NASA Goddard Flight Center High Energy Astrophysics Science Archive Research Center.

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Based on observations at Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory (NOAO Prop. IDs 2015A-035I 2016B-0288, 2017A-0367, 2015B-0265, 2013B-0453, 2014B-0303, 2016A-0401, and 2014A-0479; PIs: Scott Sheppard), which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.
Neslušan et al. (2016); Absence of Family Association: Hsieh et al. (2018)

6. (704) Interamnia, 1910 KU, 1952 MW, SPK-ID=2000704; Activity Discovery, Mechanism: Busarev et al. (2016); Activity Obs.: 1 (2012)—Busarev et al. (2016); Absence of Family Association: Rivkin et al. (2014); Shape Model: Satô et al. (2014); Additional: Busarev et al. (2018)

7. (779) Nina, 1914 UB, A908 YB, A912 TE, SPK-ID=2000779; Activity Discovery, Mechanism: Busarev et al. (2016); Activity Obs.: 1 (2012)—Busarev et al. (2016)*; 2 (2016)—Busarev et al. (2018)

8. (1026) Ingrid, 1923 NY, 1957 UC, 1963 GD, 1981 WL8, 1986 CG2, 1986 ES2, SPK-ID=2001026; Candidacy: Cikota et al. (2014); Follow-up Observation (negative): Betzler et al. (2015); Flora family association: Alfvén (1969); Additional: Nakano (1986), Busarev et al. (2018)

9. (1474) Beira, 1935 QY, 1950 DQ, SPK-ID=2001474; Activity Discovery: Busarev et al. (2016); Mechanism: Busarev et al. (2016); Activity Obs.: 1 (2012)—Busarev et al. (2016)*; Chaotic Cometary Orbit: Hahn & Rickman (1985); Additional: Busarev et al. (2018)

10. (2201) Oljato, 1947 XC, 1979 VU2, 1979 XA, SPK-ID=2002201; Activity Discovery: Russell et al. (1984); Activity Obs.: 1 (1984)—Russell et al. (1984), Negative (1996)—Chamberlin et al. (1996); Visit: Perozzi et al. (2001); Additional: Kerr (1985), McFadden et al. (1993), Connors et al. (2016)

11. (3200) Phaethon, 1983 TB, SPK-ID=2003200; Activity Discovery: Battams & Watson (2009); Mechanism: Activity Obs.: Negative—Chamberlin et al. (1996), Hsieh & Jewitt (2005), 1 (2009)—Battams & Watson (2009), Jewitt & Li (2010) 2 (2012)—Li & Jewitt (2013), Jewitt et al. (2013c), 3 (2016)—Hui & Li (2017); Visit: Destiny Plus (Iwata et al. 2016); Pallas Family Association: Todorović (2018); Additional: Jewitt & Li (2010), Ryabova (2012), Li & Jewitt (2013), Jewitt et al. (2013c), Ansdell et al. (2014), Jakubík & Neslušan (2015), Hanuš et al. (2016), Sarli et al. (2017)

12. (3552) Don Quixote, 1983 SA, SPK-ID=2003552; Activity Discovery, Mechanism: Mommer et al. (2014); Activity Obs.: 1 (2009)—Mommer et al. (2014), (2018)—Mommer et al. (2018); Chaotic Cometary Orbit (as 1983 SA): Hahn & Rickman (1985)

13. (3646) Aduatiques, 1985 RK4, 1979 JL, 1981 WZ6, SPK-ID=2003646; Candidacy: Cikota et al. (2014); Follow-up (inconclusive): Sosa Oyarzabal et al. (2014)

14. (4015) Wilson–Harrington, 1979 VA, 107P, SPK-ID=2004015; Activity Discovery: Cunningham (1950); Activity Obs.: 1 (1949)—Cunningham (1950), 2 (1979)—Degewij et al. (1980); Negative (1992)—Bowell et al. (1992), Negative (1996) Chamberlin et al. (1996), Negative (2008)—Licandro et al. (2009), Negative (2009–2010)—Ishiguro et al. (2011c), Urakawa et al. (2011), 3–6 (1992, 1996, 2008, 2009–2010) Ferrin et al. (2012); Visits: Failed (Rayman & Varghese 2001), Concept (Sollitt et al. 2009); Chaotic Cometary Orbit (as 1979 VA): Hahn & Rickman (1985); Additional: Harris (1950), van Biesbroeck (1951), Helin & Gaffey (1980), Helin (1981), Osip et al. (1995), Fernández et al. (1997)

15. (24684) 1990 EU4, 1981 UG28, SPK-ID=2024684; Candidacy: Cikota et al. (2014)

16. (35101) 1991 PL16, 1998 FZ37, SPK-ID=2035101; Candidacy: Cikota et al. (2014); Eunomia Family Association: Cikota et al. (2014)

17. (62412), 2000 SY178, SPK-ID=2062412; Activity Discovery: Sheppard & Trujillo (2015); Activity Obs.: 1 (2014) Sheppard & Trujillo (2015); Hygiea Family Association: Sheppard & Trujillo (2015), Hsieh et al. (2018)

18. (162173) Ryugu, SPK-ID=2162173; Activity Discovery, Mechanism, Activity Obs.: 1 (2007)—Busarev et al. (2018)*; Visit: Hayabusa 2 (Tsuda et al. 2013); Clarissa Family Association: Campins et al. (2013), Le Corre et al. (2018); Thermal Inertia: Liang-liang et al. (2014); Additional: Suzuki et al. (2018), Perna et al. (2017)

19. (457175), 2008 GO98, 362P, SPK-ID=2457175; Activity Discovery: Kim et al. (2017a); Activity Obs.: 1 (2017) Masi (2017); Hilda Family Association: Warner & Stephens (2018); Additional: Sato (2017), Yoshimoto (2017), Birtwhistle (2017), Bacci et al. (2017b), Bell (2017), Bryssinck (2017)

20. 133P/Elst–Pizarro, (6968), 1979 OW7, 1996 N2, SPK-ID=2007968; Activity Discovery: Elst et al. (1996); Mechanism: Hsieh et al. (2004), Jewitt et al. (2014b); Activity Obs.: 1 (1996) Elst et al. (1996), 2 (2002) Hsieh et al. (2004), Negative (2005) Toth (2006), 2 (2007) Hsieh et al. (2010), Bagulo et al. (2010), Rousselot et al. (2011), 3 (2013) Jewitt et al. (2014b); Visit: Castalia (Snodgrass et al 2017a); Themis Family Association: Boehnhardt et al. (1998); Additional: Toth (2000), Ferrin (2006), Prialnik & Rosenberg (2009)

21. 176P/LINEAR, (118401), P/1999 RE70, 2001 AR7, SPK-ID=2118401; Activity Discovery: Hsieh et al. (2006), Hsieh (2009); Mechanism: Hsieh et al. (2014); Activity Obs.: 1 (2005) Hsieh et al. (2006), Negative (2006–2009) Hsieh et al. (2011b), Negative (2011) Hsieh et al. (2014); Themis Family Association: Hsieh (2009), Hsieh et al. (2018) Additional: Hsieh et al. (2009a), Licandro et al. (2011), de Val-Borro et al. (2012)

22. 233P (La Sagra), P/2009 W50, 2005 JR71, SPK-ID=1003062; Activity Discovery: Mainzer et al. (2010), Activity Obs.: 1 (2009) Mainzer et al. (2010); Absence of Family Association: Hsieh et al. (2018)
23. 238P/Read, P./2005 U1, 2010 N2, SPK-ID=1001676; Activity Discovery: Read et al. (2005); Activity Obs.: 1 (2005) Read et al. (2005), 2 (2010) Hsieh et al. (2011c), 3 (2016) Hsieh et al. (2017b); Gorchakov Family Association: Hsieh et al. (2018); Former Themis Family Association: Haghighipour (2009); Additional: Hsieh et al. (2009b), Pittichová & Chesley (2010)

24. 259P/Garradd, 2008 R1, SPK-ID=1002991; Activity Discovery: Garradd et al. (2008); Mechanism: Jewitt et al. (2009); Activity Obs.: 1 (2008) Garradd et al. (2008), 2 (2017) Hsieh et al. (2017a), Hsieh et al. (2017b); Absence of Family Association: Hsieh et al. (2018); Additional: Kossacki & Szutowicz (2012), MacLennan & Hsieh (2012), Kleya et al. (2012)

25. 288P, (300163), 2006 VW139, SPK-ID=2300163; Activity Discovery: Hsieh et al. (2011a); Activity Obs.: 1 (2011) Hsieh et al. (2011a), 2 (2016-2017) Agarwal et al. (2017), Hsieh et al. (2017b); Themis Family Association: Hsieh et al. (2012b), Hsieh et al. (2018); Additional: Hsieh et al. (2012b), Novaković et al. (2012), Agarwal et al. (2016)

26. 311P/Pan-STARRS, P./2013 P5, SPK-ID=1003273; Activity Discovery: Micheli et al. (2013); Mechanism: Jewitt et al. (2013a), Moreno et al. (2014), Hainaut et al. (2014), Jewitt et al. (2015b); Activity Obs.: 1 (2013-2014) Micheli et al. (2013), Jewitt et al. (2015b); Behrens Family Association: Hsieh et al. (2018)

27. 313P/Gibbs, P./2014 S4, 2003 S10, SPK-ID=1003344; Activity Discovery: Gibbs & Sato (2014); Mechanism, Activity Obs.: 1 (2003) Nakano et al. (2014), Skiff et al. (2014), Hui & Jewitt (2015), 2 (2015) Jewitt et al. (2015d); Lixiaohua Family Association: Hsieh et al. (2013), Hsieh et al. (2015b), Hsieh et al. (2018); Additional: Jewitt et al. (2015a), Hsieh et al. (2015b), Pozuelos et al. (2015)

28. 324P/La Sagra, P./2010 R2, 2015 K3, SPK-ID=1003104; Activity Discovery: Nomen et al. (2010); Activity Obs.: 1 (2010-2011) Nomen et al. (2010), Hsieh et al. (2012c), Negative (2013) Hsieh (2014), 2 (2015) Hsieh & Sheppard (2015), Jewitt et al. (2016); Alauda Family Association: Hsieh et al. (2018); Additional: Moreno et al. (2011a), Hsieh et al. (2012c), Hsieh (2014), Hsieh & Sheppard (2015)

29. 331P/Gibbs, P./2012 F5, SPK-ID=1003182; Activity Discovery: Gibbs et al. (2012); Mechanism: Stevenson et al. (2012), Drahus et al. (2015); Activity Obs.: 1 (2012) Gibbs et al. (2012), 2 (2015) Drahus et al. (2015); Gibbs family association: Novaković et al. (2014); Additional: (Stevenson et al. 2012; Moreno et al. 2012)

30. 348P, P./2017 A2, P./2011 A5 (PANSTARRS), SPK-ID=1003492; Activity Discovery: Wainscoat et al. (2017); Activity Obs.: 1 (2017) Wainscoat et al. (2017); Absence of Family Association: Hsieh et al. (2018)

31. 354P/LINEAR, P./2010 A2, 2017 B5, SPK-ID=1003055; Activity Discovery: Birtwhistle et al. (2010); Activity Obs.: 1 (2010) Birtwhistle et al. (2010), Jewitt et al. (2010a); Baptista Family Association: Hsieh et al. (2018); Additional: Moreno et al. (2010), Jewitt et al. (2010b), Snodgrass et al. (2010), Jewitt et al. (2011a), Hainaut et al. (2012), Kim et al. (2012), Agarwal et al. (2012), Kleya et al. (2013), Jewitt et al. (2013b), Agarwal et al. (2013), Kim et al. (2017a), Kim et al. (2017b)

32. 358P/PanSTARRS, P./2012 T1, 2017 O3, SPK-ID=1003208; Activity Discovery: Wainscoat et al. (2012); Activity Obs.: 1 (2012) Wainscoat et al. (2012), 2 (2017) Kim et al. (2017a); Mechanism: Hsieh et al. (2013); Lixiaohua Family Association: (Hsieh et al. 2013, 2018); Additional: Moreno et al. (2013), O’Rourke et al. (2013), Snodgrass et al. (2017b)

33. P./2013 R3 (Catalina-PanSTARRS), SPK-ID=1003275; Activity Discovery: Lilly et al. (2015); Activity Obs.: 1 (2015) Lilly et al. (2015), Toubiolo et al. (2015), Moreno et al. (2016a); Aeolia Family Association: Hsieh et al. (2018)

34. P./2015 X6 (Pan-STARRS), SPK-ID=1003426; Activity Discovery: Lilly et al. (2015); Activity Obs.: 1 (2015) Lilly et al. (2015), Toubiolo et al. (2015), Moreno et al. (2016a); Aeolia Family Association: Hsieh et al. (2018)

35. P./2016 G1 (Pan-STARRS), SPK-ID=1003460; Activity Discovery: Weryk et al. (2016); Mechanism: Moreno et al. (2016b); Activity Obs.: 1 (2016) Weryk et al. (2016), Moreno et al. (2017); Adeona Family Association: Hsieh et al. (2018)

36. P./2016 J1 (Pan-STARRS), P./2016 J1-A (SPK-ID=1003464), P./2016 J1-B (SPK-ID=1003465); Activity Discovery: Wainscoat et al. (2016); Activity Obs.: 1 (2016) Wainscoat et al. (2016), Hui et al. (2017); Theobalda Family Association: Hsieh et al. (2018).

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**References**

A’Hearn, M. F., & Feldman, P. D. 1992, Icar, 98, 54
Agarwal, J., Jewitt, D., Mutchler, M., Weaver, H., & Larson, S. 2017, Natur, 549, 357
Agarwal, J., Jewitt, D., & Weaver, H. 2013, ApJ, 769, 46
