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Data mining of NEAs in the Subaru Suprime-Cam archive[⋆]

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Abstract: Using the EURONEAR PRECOVERY server, almost 70,000 mosaic Suprime-Cam images taken between 1999 January and 2013 May were data mined for about 9,800 near Earth asteroids (NEAs) known by 2013 May. We identified 4,186 candidate images possibly holding 518 NEAs, using a new tool FindSubaruCCD which overlays the NEAs and their uncertainties over the Suprime-Cam CCD mosaic layout, identifying which CCDs should be searched. This search yielded 113 NEAs found as faint as $V < 25$ magnitude, which were measured with Astrometrica in 589 images and reported to the Minor Planet Center. Among these findings, 18 objects represent observations of previously single opposition NEAs, orbital arcs being extended by up to 10 years. In the second part of this work we searched for unknown NEAs in 78 sequences (780 CCD fields) of 4-5 mosaic images selected from the entire Suprime-Cam archive and totaling 16.6 deg^2, with the aim to assess the faint NEA distribution observable with an 8-m class survey. From the total number of 2,018 measured moving objects, the use of two rating tools identified 18 better NEA candidates and a further 124 lower scored objects. Using the Rc filter in good weather conditions, mostly dark time and sky directions slightly biased towards the ecliptic, we conclude that at least one NEA could be discovered in every 1 deg^2 surveyed (equivalent to 4 Suprime-Cam fields). This is an average of one NEA every 0.5 deg^2 near the ecliptic and a lower NEA density elsewhere.

1 Introduction

The continuous astrometric monitoring of near Earth asteroids (NEAs) and potentially hazardous asteroids (PHAs) is an important task for their orbital improvement and assessment of future risk of impact, as well as longer time follow-up necessary to study gravitational perturbations and other subtle effects such as the YORP/Yarkovsky (Vokrouhlický et al., 2015), especially when very accurate astrometry is available.

Within the EURONEAR project (EURONEAR, 2016a), in 2007 we started to data mine some larger field image archives for known NEAs. As part of this project, Vadu-

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[⋆] Based on data collected at Subaru Telescope and obtained from the SMOKA, which is operated by the Astronomy Data Center, National Astronomical Observatory of Japan. The total data transfer disk space used for this project was above 2.5 TB, supported by Matei Conovici.

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vescu et al. (2009) implemented the first online application (known as "PRECOVERY") to search for the serendipitous encounters of all known NEAs and PHAs in one particular image archive, based on the IMCCE SkyBoT server (Berthier et al., 2006). We applied this tool first to the Bucharest Observatory archive including 13,000 photographic plates.

In our second similar project we data mined the Canada-France-Hawaii Telescope Legacy Survey (CFHTLS, numbering about 25,000 images), in which 143 known NEAs (including 27 PHAs) were found and measured in 508 images. As part of this project, 41 arcs were prolonged at their first or last opposition, 35 orbits were refined by adding new opposition data and 6 NEAs were recovered at their second opposition (Vaduvescu et al., 2011a).

Our third project applied the same tool to data mine two larger field 2-meter class telescope archives located in the North (the ING/INT 2.5m) and South (the ESO/MPG 2.2m) comprising together 330,000 images, finding 152 NEAs (including 44 PHAs) and reporting the resulting astrometry from 761 images to the Minor Planet Center (Vaduvescu et al., 2013a).

The present project and last in this suite applies PRECOVERY to an 8-meter class image archive, namely Subaru Suprime-Cam. This effort started at the end of 2011 and it was announced first in the ACM2012 meeting in Japan (Vaduvescu et al., 2012). In Section 2 we describe briefly the camera and its great survey capabilities, introducing also the SMOKA image archive. In Section 3 we recall the image reduction and search tools, and their application to find and measure known NEAs. Section 4 assesses the unknown NEA distribution at this faint level.

2 The Camera and Archive

2.1 Suprime-Cam on Subaru Telescope

Installed in 1999 at the fast $F/1.86$ prime focus of the Subaru 8.2-meter national Japanese telescope located at 4,200 meters altitude atop Mauna Kea in Hawaii, the $34' \times 27'$ 80-mega pixel Suprime-Cam CCD mosaic camera consists of ten CCDs of 4k×2k (4096×2048) pixels with a scale of $0.202''$ (15μ pixel size) in order to fit the excellent seeing at Mauna Kea - median value $0.61''$ in i band (Miyazaki et al., 2002) matched by a study analyzing the first seven years actual Suprime-Cam PSF data (Noda et al., 2010).

Thanks to the large aperture of the telescope (effective collecting area 51.65 m^2) and the large field of view of the prime focus camera, Subaru and Suprime-Cam offered the largest *etendue*[1] in the world ($A\Omega = 13.17$ $\text{m}^2\cdot\text{deg}^2$), being matched in 2006 by the larger field Pan-STARRS 1 (similar etendue but $\sim$ 3 mag shallower), then in 2012 being surpassed by the DECam camera installed on the 4.2-meter Blanco telescope (etendue 25$\text{m}^2\cdot\text{deg}^2$ but $\sim$ 1 mag shallower than Suprime-Cam).

In order to improve the quantum efficiency at redder wavelengths, in 2008 July Suprime-Cam was fitted with fully-depleted back-illuminated Hamamatsu Photonics KK (HPK) CCDs which replaced the old MIT/Lincoln Laboratory (MIT/LL) CCDs. The number of CCDs, their pixel size, plate scale and total field of view of the camera remained the same, the only change being the CCD numbering in the mosaic. We accommodate this change in our present project.

2.2 The SMOKA Image Archive

Since 2002, SMOKA, acronym of the Subaru-Mitaka-Okayama-Kiso-Archive public science archive (SMOKA, 2016) has provided access to the images and spectra observed with the Subaru national telescope plus other (mostly 1-2 meter) telescopes of the Mitaka, Okayama, Kiso (University of Tokyo) and Higashi-Hiroshima observatories in Japan (Baba et al., 2002).

A total of 81,878 Suprime-Cam raw science images have been incorporated by 2016 February 22 into the SMOKA archive. We used them to study some statistics, namely the distribution of sky pointings, and exposure times and filters used.

Figure 1 plots the sky pointings of the Suprime-Cam archive between 1999 January 5 and 2014 July 29 (accessible by 2016 February 22). The observed fields are plotted as small dots (in cyan color). Most of the fields are distributed quite randomly on the sky, with the ecliptic covered by a few Solar System projects and other patterns representing mostly extragalactic projects. We overlay with dots (in blue color) the NEAs (p)recovered in this work (see Section 3.3), located mostly close to the ecliptic.

Figure 2 represents the distribution of the exposure times for the Suprime-Cam 1999-2014 archive (81,878 images). The great majority of the images used relatively short exposures (below 500 s, with about half below 250 s), which is feasible for data mining of NEAs and other Solar system objects, so that most trails remain small (a few pixels).

Broad band filters were most popular (86%) either in the Johnson-Cousins (46%) or the Sloan system (40%), while the intermediary band filters were used in only 2% of cases, accounting together to 88% of images feasible for data mining asteroids and other Solar system objects. The narrow band filters were used in 9% of images, while other visitor filters (mostly narrow band) accounted for 3%.

3 Data Mining the Subaru Suprime-Cam Archive

In 2013 May almost 70,000 existing Suprime-Cam images (more exactly 69,333 observed between 1999 January and 2013 May) were searched for about 9,800 known NEAs (at

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[1] The *etendue* $A\Omega$ is defined as the product between the telescope light gathering power (effective aperture expressed in square meters) and the area of the sky imaged in a single exposure (deg^2).

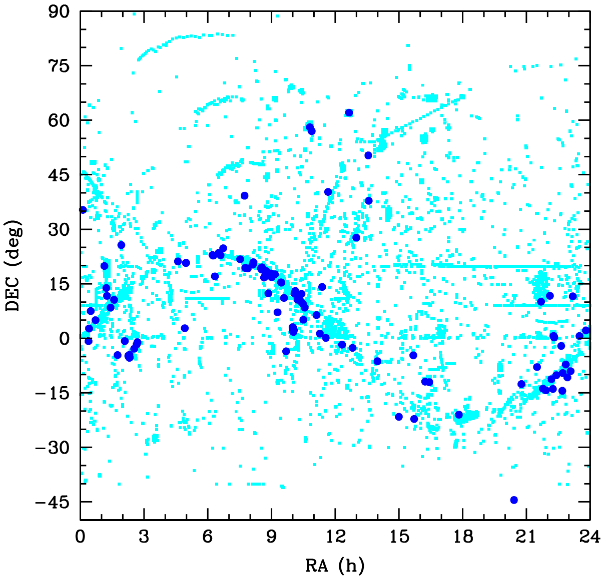

Fig. 1 The sky pointings of the Suprime-Cam archive (1999-2014: 81,878 images). The observed fields are plotted as small dots (cyan) and the NEAs (p)recovered in this project as larger dots (blue).

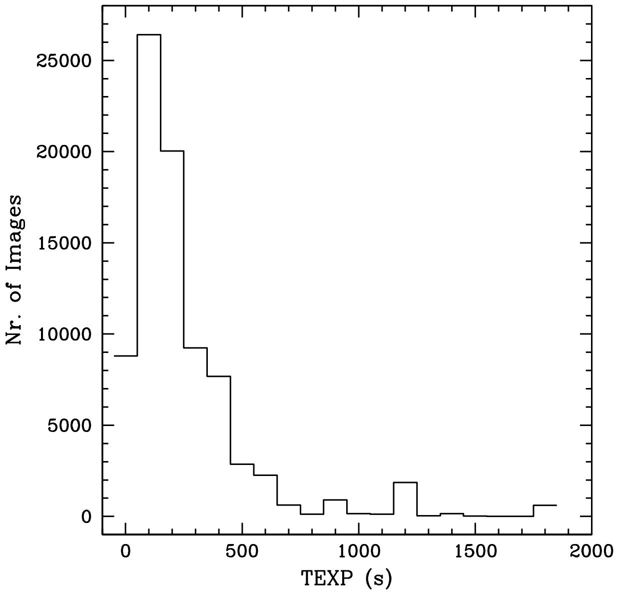

Fig. 2 The histogram of exposure times used by the Suprime-Cam archive (1999-2014: 81,878 images). The great majority of shots used exposures below 500s, and about half are shorter than 250s, allowing data mining of Solar system objects.

that time) using the PRECOVERY server (EURONEAR, 2008). We assumed for the search a safe $V = 26$ limiting magnitude, possible to reach with Subaru in 100 s at $S/N = 4$ detection level[2] in dark conditions and good seeing, consistent with the proper motion and trailing loss effect for the large majority of NEAs. The search resulted in 4,186 candidate images possibly holding 518 NEAs. These findings include only asteroids encountered in at least two (typically 4-5) images of the same field taken at a short interval (typically less than 1 h), to allow image blinking needed to confirm the object's proper motion.

3.1 Image Reduction

In a team of 10 people we used the SMOKA server to manually retrieve all the raw candidate mosaic images possibly holding the asteroids. Appropriate flat fields corresponding to the observing filters and dates were selected and downloaded from SMOKA, while the bias was taken from the overscan CCD regions of each science image. The raw science images (4,186 images of 10 CCDs each, totaling 700 GB) were reduced locally by Matei Conovici using the SDFRED Suprime-Cam software (Ouchi et al., 2004; Yagi et al., 2002), then posted on his private server (ca. 1,400 GB) for download and carefully searched by our remotely distributed team.

3.2 FindSubaruCCD

To search for the CCDs possibly holding the asteroids, the dedicated tool $FindSubaruCCD$ was written in PHP by Marcel Popescu and deployed on the EURONEAR website (EURONEAR, 2013), which could be freely used for other asteroid Suprime-Cam data mining projects. Given the candidate image number (as reported by PRECOVERY) and the correct position angle[3] (upon checking for possible rotation), $FindSubaruCCD$ plots all known NEAs in any observed Suprime-Cam field (using the SkyBoT server (IMCCE, 2016)), overlaying the 10 CCD fields and the uncertainty region of poorly observed NEAs (obtained by querying NEODyS (NEODyS, 2016)), so that the user can easily identify all CCDs possibly holding the object. Figure 3 plots one example run with the $FindSubaruCCD$ output.

3.3 Found NEAs

We distributed the fields randomly, to be searched by a team of about 10 people (amateur astronomers and students, co-authors of this paper) who used the *Astrometrica* software (Raab, 2016) to blink all candidate images. We searched the targets around their expected ephemerides (if the uncertainty σ was small) or along the uncertainty regions predicted by NEODyS (if σ was larger than $\sim 10''$).

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[2] Using the Subaru Imaging Exposure Time Calculator, http://www.naoj.org/cgi-bin/img_etc.cgi

[3] It was found that the camera position angle was not always recorded correctly in the Suprime-Cam image headers.

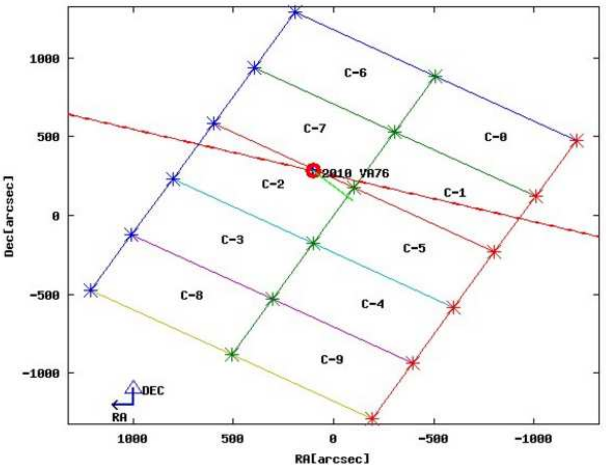

Fig. 3 Sample of the $FindSubaruCCD$ output searching for NEAs in the field SUPA0057368 ($PA = 120$ deg), overlaying the Suprime-Cam mosaic and the uncertainty (red crossing) line of the encountered object 2010 VA76.

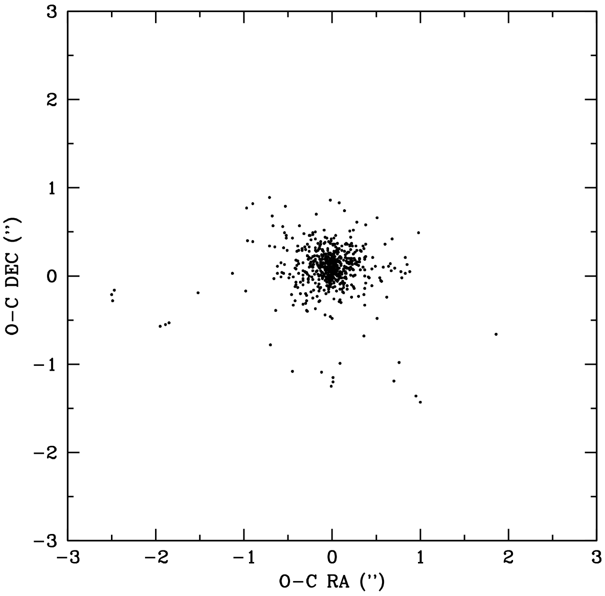

Fig. 4 The O$-$C (observed minus calculated) residuals for the 589 measured positions of 113 NEAs, calculated based on ephemerides derived from the improved orbits (2016 Feb 24). Most residuals are confined close to zero (standard deviations $0.37''$ in α and $0.27''$ in δ), and only 2% of points reside outside the $1'' \times 1''$ box.

A total of 113 known NEAs (plotted with large blue dots in Figure 1) were found in 589 images, representing only 22% of the candidate objects, due to the high PRECOVERY threshold used $V = 26$. Of these 113 objects, 26 are PHAs, 95 corresponded to multiple opposition NEAs and 18 were one-opposition NEAs (poorly observed objects, including two PHAs). Most encounters resulted in small trails (typically under $\sim 3''$) whose centroids were easily measured by *Astrometrica*, even though most asteroids were slightly elongated into ellipses instead of circular sources. For longer trails we carefully visually measured the two ends which were averaged to report positions at standard mid-observed time. The astrometric reductions used the PPMXL reference system (Roeser et al., 2010). The measured positions of the 113 known NEAs were reported to MPC between 2013 December and 2014 September.

Figure 4 plots the O$-$C residuals (observed minus calculated) for all 589 measurements, obtained with our O$-$C calculator (EURONEAR, 2016b) querying very accurate NEODyS ephemerides based on the improved orbits (by 2016 February 24). Most of the points are confined around the origin, with standard deviation $0.37''$ in α and $0.27''$ in δ. Only 16 points (2% of all data) sit outside $1''$ in either α or δ, most of these measurements being affected by longer and fainter trails whose ends are more difficult to assess.

Subsequently to our Suprime-Cam (p)recoveries and thanks to the greatly improved orbits, two objects were found in the SDSS archive by Lucian Hudin (2012 HC34 and 2010 DM21), being measured and reported to the Minor Planet Center as part of the same project. Also, following our data submission, some objects were data mined by other authors in other archives, being reported and then published together with our data in the same publication (e.g., 2012 HC34) or later.

Table 1 presents our 18 one-opposition recoveries. From these, the following six cases deserve special status, because these objects could have been lost without the Suprime-Cam recovery data. 2010 SZ3 was discovered by the Catalina survey in 2010 September, its one day arc being prolonged by us (Lucian Hudin) almost one month later at high uncertainty (about 2 degrees), after which it remains unobserved until today. 2007 TK15 was discovered by Catalina in 2007 October and followed during one month, being precovered by Adrian Sonka 20 months before discovery, which allowed its recent recovery in 2015 at a very faint $V = 23$ limit. 2011 GM44 is a PHA discovered by the Catalina Siding Spring survey in 2011 April, observed during one month, and precovered by Adrian Sonka five years before discovery, then easily recovered recently in 2016. 2011 KW19 was discovered by Pan-STARRS in 2011 May and observed for two months, precovered by Lucian Hudin seven years before discovery; it is unobserved since but the hugely reduced future sky plane uncertainty allows easy recovery, for example in 2023. 2007 UA2 was discovered by Catalina in 2007 October, followed during four months, precovered by Lucian Hudin three years before, and is since unobserved but again is now easy to find in future (e.g., in 2022). 2002 VR14 is a very old NEA (not observed for 14 years) discovered by the NEAT survey in 2002 Novem-

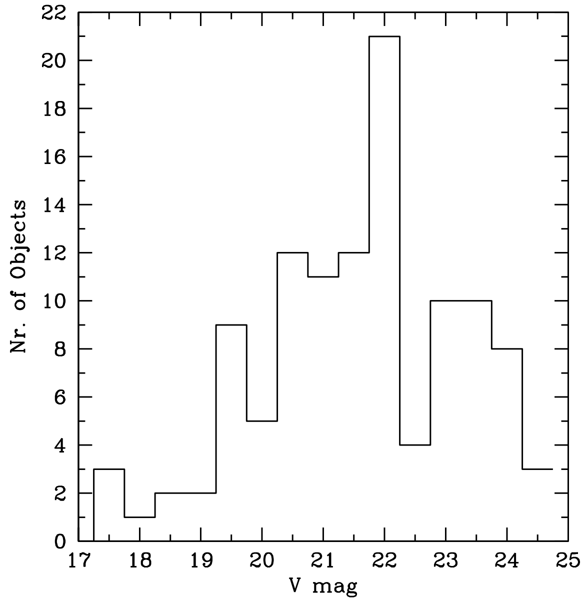

Fig. 5 Histogram of the V magnitudes (as given by Minor Planet Center ephemerides) of the 113 (p)recovered NEAs. Most objects were recovered between $V = 19 - 24$ with a few faintest NEAs close to $V = 25$.

ber, followed during seven days only, and precovered by us (Ovidiu Vaduvescu) one month before discovery; the 1-month arc will enable correct linkage when it is found again (e.g., by LSST).

Figure 5 presents the histogram showing the distribution of the V magnitudes of the 113 (p)recovered NEAs. The peak is around $V \sim 22$, with the faintest objects recovered close to $V \sim 25$, as expected based on the capabilities of Subaru. The faintest objects were 2007 UA2 ($V = 24.6$ found by Lucian Hudin), 2007 TK15 and (283457) 2001 MQ3 (both at $V = 24.8$ found by Adrian Sonka), with the first two among the above special cases.

4 Statistics of the Faint NEA Distribution

Using the entire Suprime-Cam archive existing by 2013, we assessed the NEA density observed with an 8-m class telescope in random directions and good weather conditions (seeing around $0.8''$, according to Noda et al. (2010)). Using SMOKA we considered all the Suprime-Cam images observed between 1999 January 4 and 2011 July 2 (69,333 mosaic images).

4.1 Sample Selection

Based on the ASCII Suprime-Cam pointing archive alone, we selected all suitable "sequences" defined as sets of 4 or 5 Suprime-Cam mosaic images having matching observation date and time (within 1 hour), telescope pointing (within maximum $2'$ dithering) and filter (accepting only the Rc-band images). No other conditions were imposed regarding the weather (seeing), Moon phase or distance, observed airmass, ecliptic latitude or Solar elongation. Using the first three criteria, we selected 108 sequences of 4-5 images, a total of 498 Suprime-Cam mosaic images for visual search and identification of moving sources. As the mosaic camera has 10 CCDs, there were potentially 1080 CCD sequences to search.

4.2 Search for Moving Objects

Matei Conovici used the SMOKA server to automatically retrieve all 1080 selected images. Appropriate flat fields corresponding to the Rc filter and observing dates were selected and downloaded from SMOKA, while the bias was taken from the overscan CCD regions of each science image. The raw science images (498 images of 10 CCDs each, totaling 90 GB) were reduced locally by Matei Conovici using the same SDFRED Suprime-Cam software (Ouchi et al., 2004; Yagi et al., 2002), then posted on his private server (ca. 180 GB) and distributed for download by a team of 10 co-authors. We visually inspected all images, finally dropping 30 Suprime-Cam fields plus a few CCDs from 6 other fields, owing to bad weather, bad seeing, shifted images, or nebulae producing a lack of enough astrometric stars.

We carefully analyzed the remaining 78 Suprime-Cam fields which total 16.6 deg^2 on the sky (taking into account the dithers), measuring 2,018 moving objects (8,783 positions). To blink the images, identify all moving objects and obtain the astrometry, we used *Astrometrica* (Raab, 2016) by loading all (4 or 5) images available for each CCD and matching the stationary sources with PPMXL catalog stars. Whenever *Astrometrica* did not work, we used first the *Astrometry.net* webtool (Lang, 2009; Lang et al., 2010) to find the correct CCD centers and position angle (in some cases found inconsistent in the Suprime-Cam headers).

4.3 Search for NEA Candidates

Having measured the astrometry of the 2,018 moving objects, we ran the Minor Planet Center's NEO Rating Tool (MPC, 2016), identifying 141 objects with NEO scores more than 10% (a very low threshold compared with the recommended 65% value of the MPC). All these 141 higher scored objects were submitted to the MPC on 2016 September 5 (674 positions). To double check the actual number of NEA candidates, we considered these 141 candidates scored above 10% against our own $\epsilon - \mu$ model (Vaduvescu et al., 2011b) which is based on two observational quantities (the Solar elongation ϵ measured along the ecliptic and the proper motion μ).

In Figure 6 we plot all the 141 higher scored objects, focusing on those located above the 1.3 a.u. NEA border (the upper curve plotted with magenta color). Three objects are located above the plot (moving very fast between 5 and

Table 1 One opposition NEAs recovered in the Subaru Suprime-Cam archive. The sky plane uncertainty σ at the time of (p)recovery is in arcsec.

Asteroid	Class	σ ($''$)	Nr. pos.	Arc (before/after)	Reference	Reducers
2012 HC34	NEA	2200	10	6m/10y precovery	MPS 504077	L. Hudin
2010 SZ3	NEA	6600	11	1d/1m recovery	MPS 504065	L. Hudin
2012 KC6	PHA	140	6	2m/4y precovery	MPS 504077	D. Lacatus
2010 DM21	NEA	2100	15	2m/7m precovery	MPS 505427, 504060, 505428	M. Conovici, L. Curelaru
2009 UE2	NEA	25	4	5m/2y precovery	MPS 505424	F. Ursache
2008 TJ157	NEA	10	12	48d/52d precovery	MPS 505415	D. Lacatus, A. Paraschiv
2007 TK15	NEA	76	3	1m/20m precovery	MPS 505407	A. Sonka
2011 GM44	PHA	2247	4	1m/5y precovery	MPS 506465	A. Sonka
2008 UE202	NEA	15	6	19d/30d precovery	MPS 505416	D. Lacatus, A. Paraschiv
2008 TZ	NEA	1	6	8d/10d precovery	MPS 505415	D. Lacatus, A. Paraschiv
2011 KW19	NEA	524	2	2m/7y precovery	MPS 506468	L. Hudin
2007 UA2	NEA	38	3	4m/3y precovery	MPS 506380	L. Hudin
2008 BC22	NEA	59	6	5m/3y recovery	MPEC 2014-Q72	D. Lacatus
2001 XP	NEA	25	3	11d/1m precovery	MPS 528063	A. Tudorica
2006 QY5	NEA	254	3	2m/5y precovery	MPEC 2006-Q15	A. Sonka
2002 VR14	NEA	29	3	7d/1m precovery	MPS 528068	O. Vaduvescu
2001 HK31	NEA	1	3	51d/59d precovery	MPS 528059	L. Hudin
2007 DD	NEA	2	7	14m/4y recovery	MPEC 2007-D15	L. Hudin

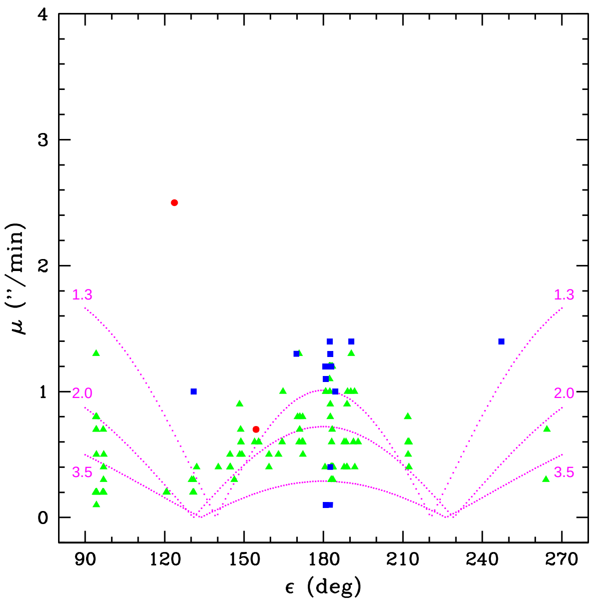

Fig. 6 The 141 higher scored objects (MPC NEO Rating scores above 10%) plotted against our $\epsilon - \mu$ model (Vaduvescu et al., 2011b). Using these two criteria, we believe there are at least 15 real NEOs in the 78 Suprime-Cam analyzed fields (16.6 deg^2 total). Three very fast moving objects not shown (above top).

25$''$/sec) and left faint trails on images due to their fast motion: in these cases the trail ends were carefully measured and averaged to improve the accuracy. Red dots correspond to objects scored above 90% by the MPC NEO Rating tool, blue squares to objects between 40% and 90%, and green triangles to lowest scored objects between 10% and 40%. Table 2 includes the 18 NEA candidates with score above 40% (red and blue squares in Figure 6). We list our designation, observing date and time (mid of first image), the Suprime-Cam images (last digit representing the CCD number), the MPC NEO Rating, the ecliptic latitude β, Solar elongation ϵ, proper motion μ, magnitude and the field reducer.

4.4 NEA Sky Density and Comparison with Past Work

In a similar study, applying both the $\epsilon - \mu$ model and MPC NEO Ratings to 47 known NEAs, Vaduvescu et al. (2013b) found that at least three quarters are quite clearly identified as NEAs, with several more being marginally identifiable as NEAs using these criteria, and a few being impossible to separate from main belt asteroids (MBAs) based on a single night's observation. The converse question is of false positives, whether MBAs can appear slightly above the 1.3 a.u. border (Figure 6) which we use to highlight NEAs. While the objects a long way above that border are unambiguously NEAs, our statistic of total NEAs found in these Suprime-Cam sequences depends quite strongly on whether most of our several suspected NEAs visible around $\epsilon \sim 180°$ in Figure 6 are indeed NEAs. Sky motion is an especially good NEA discriminator near opposition (Jedicke et al., 2003), and our own random trial to check sky motions of known asteroids, normalizing to ∼1,300 with $170 < \epsilon < 190°$ (1,200+ of our 2,018 unknown Suprime-Cam objects being within this range), yielded only one non-NEA around $\mu = 1.4''$/min and three more just above the 1.3 a.u. border but below 1.2$''$/min.

Based on the above and on our experience from other projects regarding follow-up of similar NEA candidates observed with the Isaac Newton Telescope (INT) and other telescopes from the EURONEAR network (Vaduvescu et al., 2011b, 2013b, 2015), in Figure 6 we estimate at least

Table 2 New NEA candidates with MPC NEO Rating above 40% detected in the selected sequences from the Subaru Suprime-Cam archive (78 fields). First group of 5 objects represents the best NEO candidates (MPC scores above 90%). Moving object SDZV168 detected in two different sequences from same night. Moon below horizon except for VUVb147 (34% illuminated at distance 99°) and SDZV189 (23% at 69°).

Designation	Obs. date (UT)	Suprime-Cam image numbers	NEO Rating (%)	β (°)	ϵ (°)	μ (″/min)	Rc mag	Reducer
SAS0151	2001 10 21.58980	00067640 660 681	100	+2	183	25.3	23.0	A. Sonka
SLH0213	2006 01 01.38699	00447847 877 907 937 967	100	+17	171	16.4	22.1	L. Hudin
VUVb147	2004 08 09.58900	00332646 676 700 730 760	100	+1	171	5.6	22.4	V. Inceu
SDZV189	2004 01 17.61912	00267191 201 211 221 281	97	−33	124	2.5	21.9	D. Zavoianu
SATV071	2003 04 04.57860	00199203 213 233	97	+48	155	0.7	20.0	M. Conovici
SAS0364	2003 01 30.46192	00179729 739 749 759 769	84	+16	131	1.0	23.7	A. Sonka
SLC0158	2001 01 25.35933	00034553 563 573 583	70	+6	183	1.2	19.6	L. Curelaru
SLC0153	2001 01 25.35534	00034550 560 570 580 590	64	+6	183	0.4	20.1	L. Curelaru
VDA1004	2011 05 05.34111	01314465 475 485 495 505	59	+35	247	1.4	20.7	D. Zavoianu
SDA1001	2011 05 05.57912	01314946 956 966 976 986	57	+30	184	1.0	23.1	D. Zavoianu
SLH0110	2002 09 03.33220	00120162 192 222 252 282	56	−1	182	1.4	23.8	L. Hudin
SUVI028	2002 09 03.54191	00121033 063 093 123 153	51	−1	183	1.3	23.6	V. Inceu
SDZV096	2002 09 02.33937	00118824 854 884 914 944	49	+1	181	1.2	22.5	D. Zavoianu
SLO0037	2010 06 11.27865	01228086 096 106 116	48	−3	191	1.4	22.3	L. O'Cheallaigh
SLH0122	2002 09 03.33220	00120163 193 223 253 283	45	−1	183	0.1	22.9	L. Hudin
SAS0063	2002 09 02.42399	00119204 234 264 294 324	42	+1	181	1.1	23.9	A. Sonka
SDZV168	2002 09 02.27683	00118559 589 619 649 679	41	+1	181	0.1	22.2	A. Sonka
...	...	00118829 859 889 919 949	...	...	...	...	...	D. Zavoianu
SLO0011	2005 12 31.39525	00445826 836 846 856 866	40	+17	170	1.3	21.7	L. O'Cheallaigh

15 new NEAs identified by our team in the analyzed 78 Suprime-Cam fields.

This result of at least 15 NEAs encountered in the total covered field of 16.6 deg^2 allows us to conclude that using the Suprime-Cam with the Rc-band filter, at least one NEA could be found in 1.1 deg^2 or ∼4 Suprime-Cam fields observed in random directions (ecliptic latitude distribution in Figure 7). Most image sequences (85%) were obtained in dark time, and only 15% with gray Moon typically at low altitude.

Among the 18 best NEA candidates (Table 2), none are beyond Rc=24.0 but several are beyond 23.0 and several more beyond 22.0 magnitudes. The faint object detectability is similar to Figure 5 but many brighter NEAs are already known rather than waiting to be found as unknown. Terai et al. (2013) obtained near-completeness just beyond $r = 24.0$ for high latitude MBAs with Suprime-Cam: trailing loss would remove a few NEAs that have higher sky motions.

In a similar teamwork survey covering 24 deg^2 with 2-m class telescopes capable to reach limiting magnitude $V \sim 23$ (ESO/MPG and ING/INT), Vaduvescu et al. (2011b) found that on average one NEA could be observable scanning randomly 2 deg^2 of dark sky. Later, using only INT 2.5m data covering 44 deg^2, Vaduvescu et al. (2015) concluded that in dark conditions one NEA could be discovered in at least 2.8 deg^2.

None of our best 7 NEA candidates found with the 4.2m Blanco telescope capable to reach $V \sim 24$ was fainter than $R = 22.5$ though we found a small number of likely MBAs fainter than 23.0 mag (Vaduvescu et al., 2013b). Our conclusion from those limited data was one NEA per ∼1.4 deg^2, possible to discover with a 4-m class telescope.

In 2001 February and October, Yoshida et al. (2003) and Yoshida and Nakamura (2007) used the Suprime-Cam for two small surveys around opposition (covering 3 and 4 deg^2, respectively) to investigate the very small MBA populations (sub 1-km, up to limiting apparent magnitudes $R = 25 - 26$). Based on their past work, their actual hypothesis is that about one NEA could be found in every Suprime-Cam field (Fumi Yoshida - private communication), which apparently exceeds our present findings by 4 times. However, their surveys were conducted at opposition (within $\pm 3°$ from the ecliptic) and in dark conditions, in comparison with our randomly selected fields covering various ecliptic latitudes.

The ecliptic latitude distribution of our sample (Figure 7) probably affected our findings, as most NEAs are found closer to the ecliptic (Raymond et al., 2004; Vereš et al., 2009). Our Blanco likely NEA candidates (Vaduvescu et al., 2013b) showed the same pattern, with 6 of the 7 objects having β within $\pm 5°$ despite only about half the fields searched being in that range. The β values in Table 2 suggest that near the ecliptic at least one NEA per 0.5 deg^2 could be discovered with Subaru/Suprime-Cam.

4.5 Search of Possible Pairings with Virtual Impactors

We tested the entire known Virtual Impactor (VI) population, namely 631 bodies available from the NASA/JPL Sentry Risk Table (NASA, 2016) for possible pairings with our 141 Subaru NEA candidates. The automatic PHP tool

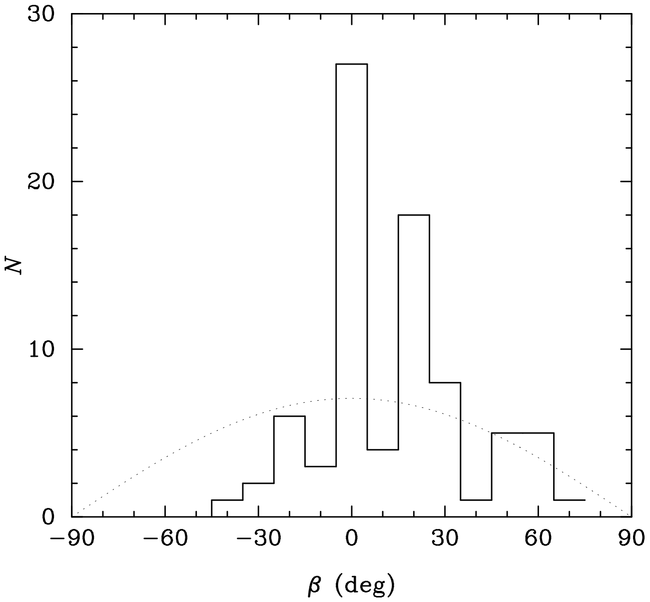

Fig. 7 Ecliptic latitudes of the 78 image sequences that were suitable for searching. There is some concentration towards low latitudes compared to an isotropically random distribution (dotted line) but not the exclusive choice of near-ecliptic fields that characterizes some Solar system surveys.

$VICheck$ was built by Marcel Popescu, to test all possible combinations (631 VIs × 141 candidates = 88,971 combinations) using the MPC Orbits/Observations database and our Subaru observations, running the FO batch orbital fit software provided with the $Find\_Orb$ package by Gray (2016). After almost 12 days running on a typical Linux desktop Intel(R) Core(TM) i7-2600K CPU 3.40GHz, followed by manual check using $Find\_Orb$ of about 100 possible pairs (defined as generating small orbital RMS - few arcsec after fitting a given VI and Subaru pair using FO), no link between any known VI and our Subaru NEA candidates could be found.

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