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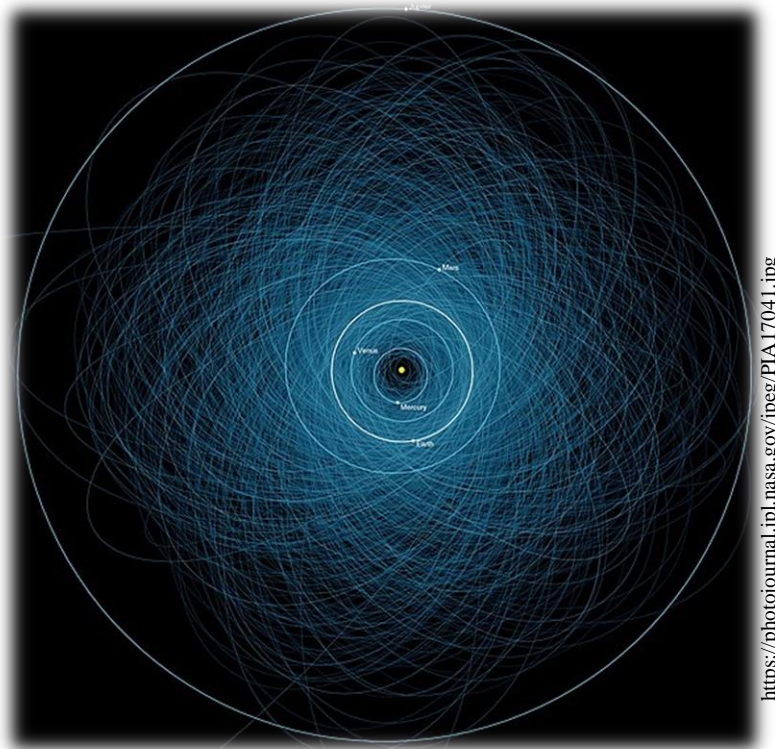
Emerging Capabilities for Detection and Characterization of Near-Earth Objects (NEOs)

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Abstract: Near-Earth objects (NEOs) are asteroids and comets that have their perihelion distance less than 1.3 au. To date, we know about ~20,000 Near-Earth Asteroids (NEAs) and just over 100 Near-Earth Comets (NEC). Potentially Hazardous Asteroids (PHAs) are NEAs that are larger than ~140 m in diameter and that have an Earth Minimum Orbit Intersection Distance (MOID) smaller than 7.5 million km. We currently know about ~2000 PHAs. The most critical questions about PHAs are: *When is the next impact likely to occur?* and *How bad will it be?* To answer the former, we must discover PHAs in large numbers and measure their orbits with sufficient precision to understand their impact probabilities on timescales of order a century or two. The answer to the latter question depends largely on kinetic energy, which scales as $\frac{1}{2} \times \text{mass} \times \text{velocity}^2$, or as ~$\text{diameter}^3 \times \text{density} \times \text{velocity}^2$. Most survey telescopes focus on discovery of PHAs in an effort to address the first question, with little effort to provide information about the objects' impact energy beyond their absolute visible magnitude. Characterization efforts are restricted to a much smaller number of objects. For example, ~10% of known NEOs have been spectrally characterized (Binzel et al. 2019) and ~10% of these NEOs are also PHAs.

1. Current NEO Capabilities

Survey. Current dedicated NEO surveys are primarily conducted by ground-based telescopes operating at visible wavelengths with 1-2 m class apertures, with the exception of the WISE/NEOWISE mission, which operates at mid-infrared (IR) wavelengths from low-Earth orbit. Survey completeness exceeds 90% for NEAs larger than 1 km in effective spherical diameter and is estimated at ~30% for NEAs larger than 140 m (Stokes et al. 2017). However, completeness is of order ≤1% for objects of the scale of the Tunguska and Chelyabinsk impactors (~20-50 m).

Another facility expected to become operational within the next year include the Space Surveillance Telescope (SST; Monet et al. 2013; Ruprecht et al., 2018). Technical specifications are restricted due to its primary funding source (DARPA), but its aperture is 3.5 m with a 6 sq deg FOV. The SST is currently being transported to Australia for recommissioning. Its primary mission objective is not NEO-related, requiring fast (≲2 sec) exposures, and negotiations for access to the NEO data with the sponsoring agency (U.S. Airforce) are underway.

Characterization. Impact energy scales as $\text{diameter}^3 \times \text{density} \times \text{velocity}^2$. While velocity comes from knowledge of orbit, impact energy depends strongly on diameter and less so on density. Thus, knowledge of diameter is critically important to determining impact energy; a factor of 2 diameter uncertainty translates to nearly an order of magnitude uncertainty in impact energy. However, efforts to understand anything beyond an object's orbit and absolute visible magnitude, H, are restricted to a much smaller sample: of the ~20,000 NEOs known, only a few thousand have been characterized. Other parameters such as rotational period, spin pole orientation, bulk density, surface properties, shape, and potential satellites will also influence mitigation strategies should an object with a high impact probability be discovered. Different observational methods yield differing parameters, summarized in Table 1.

Effective spherical diameters are most directly determined using radar or IR radiometry and can be measured to within ~10-20% with good quality data (Wright et al. 2018, Mainzer et al. 2011, Nolan et al. 2013, Tedesco et al. 2002); stellar occultations also obtain diameters, but these observations tend to be limited for NEOs (Herald et al. 2018). Direct measurements of density are known for a handful of NEOs. These are derived from *in situ* spacecraft visits (e.g. Itokawa; Yoshikawa et al. 2007), from radar and optical observations of the Yarkovsky effect candidates (Chesley et al., 2003; Chesley et al., 2014), and from radar observations of binary NEAs (Margot et al., 2002; Ostro et al., 2006; Fang et al., 2011). To date, radar observed 57 out of 64 known binaries in the NEA population, and at least 50% of the observed objects have data suitable for density estimates. Similar to albedo and colors, density is broadly correlated with taxonomic class.

2. Summary of Emerging Asset Capabilities

NEO Searches. While the current surveys cannot reach 90% completeness for potentially hazardous asteroids (PHAs) ≥140 m within the next few decades, emerging assets will provide some capability. It has been assumed that absolute visible magnitude H<22 mag is an accuracy proxy for objects that are ≥140 m; this assumes that all NEOs have albedos of 14%. However, Wright et al. (2017) showed that ~25% of NEOs have extremely low albedos, around 3%, and the remaining two-thirds are in a moderately dark population, around 17%. Using the size distribution of NEOs from Ivezic et al. (2002), Wright et al. (2017) demonstrated that a survey that aims to be 90% complete in H must reach that completeness for H<23 mag to ensure that 90% of the objects ≥140 m are detected.

Depending on its observing cadence, the predicted LSST completeness during its lifetime (2022-2032) is 80% for PHAs with H<22 mag (Chesley et al. 2017, Jones et al. 2018) and 71% for the PHAs ≥140m (Grav et al. 2016). NEOCam is a dedicated NEO survey optimized for high

survey completeness for PHAs ≥140 m that will also detect hundreds of thousands of smaller objects. NEOCam's expected completeness is 78% for PHAs ≥140m during its 5-year baseline mission, increasing to 88% if a 5-year extended mission is included (Mainzer et al. 2015). These numbers were reproduced in the NASA Report of the Near-Earth Object Science Definition Team (Stokes et al. 2017). This report reaffirmed that the goal of the search system should be to produce a catalog that is 90% complete for PHAs ≥140 m, and found that the ideal way to achieve this goal is using a half-meter IR space-based system or a combined VIS and IR system located at the L1 Sun-Earth Lagrange point.

Other current or emerging assets, such as the Transiting Exoplanet Survey Satellite (TESS), the James Webb Space Telescope (JWST), and the Wide Field Infrared Survey Telescope (WFIRST), will make negligible contributions to the search effort. JWST has a limited field of view (FOV), which makes searching for PHAs nearly impossible for JWST and limited with WFIRST in the larger FOV. While TESS has a very large FOV, its limited sensitivity and very large pixel sizes (21" per pixel) makes searching for PHAs nearly impossible.

NEO Characterization. The emerging assets offer some capability to characterize PHAs. TESS monitors the same 96×24 deg^2 FOV for 27 days, providing postage stamps of 200,000 preselected stars every 2 minutes and full frame images at 30-minute cadence. TESS will provide well-sampled rotational light curves for most of the brighter main belt asteroids and a much smaller number of PHAs, as these rarely are bright enough for TESS to detect. TESS will also provide information on thousands of stellar occultation events (Pal et al. 2018), but PHA occultations will be limited.

LSST will provide a catalog of observations of PHAs from ~0.3-1.1 μm (*ugriz*), allowing for colors to be determined for some objects. This can allow for crude determination of taxonomic classification of many PHAs using the taxonomic system of e.g. Carvano et al. (2010). However, this effort will be made significantly harder by the cadence, which results in different filters being taken days, months, or years apart, which means that effects such as rotation and phase curves can significantly affect the resulting colors and classifications. For some objects, rotation state and phase curves may be solvable.

NEOCam will provide observations in thermal IR wavelengths for most PHAs ≥140m. IR observations allow for determination of diameter (Usui et al. 2014, Mainzer et al. 2011, Tedesco et al. 2002), a key physical parameter in the impact hazard, since impact energy scales as diameter^3. While diameter can be determined using IR photometry alone, if visible photometry is also available, the combination of visible and IR measurements allows albedo to be determined. The combination of optical photometry from LSST and thermal IR from NEOCam provides a powerful dataset that will yield accurate diameters and albedos for the majority of PHAs ≥140m. NEOCam also includes support for a targeted mode that allows high SNR observations in two channels to be obtained, along with densely sampled lightcurves.

JWST can potentially characterize surface composition, surface alteration, and physical properties of individual PHAs using visible and near-IR (NIR; 0.7-2.5 μm) wavelengths (Thomas et al. 2016). While JWST should be able to perform sidereal tracking of a large fraction of NEOs, it is unclear how much of the observing time will be available devoted to NEOs. Additionally, observing overheads are expected to be large (~45 min) compared to the exposure time required for most NEOs (~few min). Thus, JWST will be of tremendous value for study of individual PHAs of particular interest, but will see limited usefulness in the characterization of more than a small number of objects.

3. Gaps in Capabilities

Future Surveys. The exact LSST cadence and survey region are not yet determined, but there is some chance it will extend to +10 deg ecliptic latitude (LSST Science Collaboration, 2017). LSST is in the southern hemisphere, so image quality will suffer at moderate northern ecliptic latitudes. High northern ecliptic latitudes will be entirely unobservable at faint (V>23) magnitudes. This uncovered area will reduce NEO completeness for ≥140 m, and will also decrease the ability to warn of imminent impacts from small (<100m) NEOs appearing on their last approach in the northern hemisphere. No future survey currently planned will achieve high survey completeness in this smaller size scale because there are so many objects; however, enough objects will be discovered by LSST and NEOCam to enable robust statistics on the population's characteristics.

Future Characterization. Table 2 summarizes emerging assets that could be used for NEO characterization. Outside of the diameters provided by NEOCam and broad band colors from LSST, there is currently no guarantee of any other large-scale characterization work. In the absence of observations by an IR system, all albedos and diameters are speculative. Radar observations can obtain high-quality sizes of a few dozen objects each year, as well as put size constraints to at least several dozen more. The increasing faintness of the average NEO discovery will also result in a drop in objects characterized at optical wavelengths (e.g. colors, lightcurves, and spectra), although at least some of these objects will have future observing opportunities.

Given the limitations on rate of motion and solar elongation of both JWST and WFIRST (see Thomas et al. 2016; Holler et al. 2018), there will always be objects that cannot be observed by either telescope. Further, time is not guaranteed on either facility for this work. NEOs frequently require immediate characterization observations, and this may not be possible given scheduling and observing constraints on both solar elongation and rate of motion.

Rotation state determination requires observations across many geometries and timescales, or radar. These observations are possible for a few hundred objects per year, but extending this to a larger study of hundreds or thousands of NEOs will not be possible given the available observing time. While TESS covers large areas of sky over long (~27 day) timeframes, its limiting sensitivity of V~19 means that few additional light curves beyond those currently available are likely to be obtained. Likewise, visible and near-IR (VNIR) spectroscopy for many thousands of objects will also be unlikely to occur given the competitive nature of observing proposals and the amount of time available.

NIR is essential for constraining composition, density and meteorite analogs of PHAs. While taxonomic classification is possible with broadband colors and visible spectra, it is not diagnostic of surface composition (Gaffey et al. 2002). At present, taxonomic classification using colors is limited to objects brighter than V~21 and V~19.5 for detailed surface characterization using NIR spectroscopy. NIR characterization is limited to objects whose positional uncertainties are <1 arcminute due to the limited FOV of the guide camera on the most prolific instrument used for this task (NASA IRTF). As LSST and NEOCam come online, the number of targets available for characterization each night is expected to increase exponentially, making it challenging to maintain this effort for a significant fraction of small PHAs. Additional ground- and space-based assets for characterization of NEOs would help keep characterization in pace with discovery.

The Goldstone and Canberra radar antennas are primarily dedicated to spacecraft tracking, and time to observe NEOs is negotiated with spaceflight projects. Currently, Goldstone devotes about 6% of its time to NEA radar observations. Demands on the 70 m antenna for spacecraft tracking have been shrinking, so more time is likely to become available in the future. At Arecibo, the Environmental Protection Agency (EPA) limits radar use to ~1000 hours/year, and any increase beyond that would need to be renegotiated.

Table 1: Characterization of NEOs is currently performed by a variety of facilities and wavelengths; however, for the vast majority of the ~19,000 NEOs known, little is known about them other than orbit and H.

Method & Facilities	Parameters Determined	Aperture	Approx. # of Objects	Approx. Sensitivity	Notes
Radar: Arecibo & Goldstone	Orbit refinement, diameter, shape, surface features, rotational state, multiplicity, radar scattering properties, masses for Yarkovsky effect, constraint optical albedo and composition; binaries: mass and bulk density estimates.	305 m & 70 m	Total unique objects between Arecibo & Goldstone is ~80-110 per yr	Can get shape model for 140 m NEO at @0.06 au (Arecibo) & @0.03 au (Goldstone)	Radar detectability scales as 1/distance[4]. Full shape/rotational state modeling only possible for ~30% of detected NEOs (e.g. Nolan et al. 2013)
Visible & near-IR (VNIR) colors: Palomar, Mayall, Blanco, SOAR	Rough taxonomic class	4-5m	~500	23 V mag	Colors can provide rough taxonomic classification w enough wavelengths & high SNR (Carvano et al. 2010).
VNIR spectroscopy: Palomar, Mayall, Blanco, SOAR, IRTF, Gemini	Taxonomic class	3-8m	~2000 total (including IRTF)	21 V mag (19.5 V for IRTF)	See e.g. Magnuson et al. (2018).
Visible lightcurves: Modestly sized telescopes	Rotational states, shapes	<1 to 2m	~1500	20 V mag	Rotational state & shape from lightcurve inversion (e.g. Warner et al. 2018).
Space- based thermal IR: Spitzer & WISE/ NEOWISE	Diameters, albedos, rotational states, shapes, thermal inertia	0.4- 0.85m	~3000	Approx. equivalent to ~22-23 V mag	Albedo requires IR + visible; thermal inertia usually requires multiple viewing geometries and/or shape information.

Note: "Diameter" refers to effective spherical diameter. Both Spitzer and NEOWISE are likely to be decommissioned in the next year.

Table 2: Future facilities that could contribute to NEA characterization.

Asset	TESS	JWST	WFIRST	NEOCam	LSST	DSN
	4x10 cm lenses	6.5 m mirror	2.4 m mirror	0.5 m mirror	8.4 m mirror	Canberra radar 70 m antenna
	Low-Earth Orbit (2018-2020)[b]	*L2*[a] (2021-2031)[b]	*L2*[a] (2025-2030)[b]	*L1*[a] (2024-2029)[b]	*Ground* (2022-??)	*Ground* (2021-??)
Operational Mode	Pre-determined survey pattern	Queue scheduled	Pre-determined survey pattern	Pre-determined survey pattern & targeted	Pre-determined survey pattern	Queue scheduled, targeted
FOR[c]	All-sky	85-135°	55-126°	45-120°	~60° [d]	N/A
Wavelength	0.6 – 1 μm	0.6-28 μm	0.6 -2 μm	4.6 & 8 μm	0.3-1 μm	4.2 cm
FOV[e]	96°x24°	<0.1°x0.1°	0.79°x0.43°	1.7°x7.1°	3.5°x3.5°	0.04°x0.04°
Distance to 140m NEO w/ SNR=5	Max 0.1 au [f]	Variable	Variable	~1.1 au at 90 deg solar elongation [g]	~0.7-1.2 au depending on albedo [f]	<0.03 au; can detect 500 m NEA at <0.05 au
Exposure Time	2m and 30m exposures	Variable	Variable	3m & 30 sec exposures	~30 s exposures	Exposures: N/A
NEA observing time	Serendipitous observations	GO proposal opportunities	Serendipitous observations; GO program?	~22-23 hrs/day	~9 hrs/day	~100 hrs/year
What it means for NEAs?	Chance follow up of bright (or close) NEAs	Occasional targeted observations	Occasional targeted observations	Systematic discovery, self-follow up	Systematic discovery, follow up	Occasional targeted observations
Data products	Astrometry	Astrometry, spectra, lightcurves, plane-of-sky images	Astrometry, spectra, lightcurves, plane-of-sky images	Astrometry, diameters, albedos, thermal inertia, IR lightcurves	Astrometry, colors, sparse lightcurves	Astrometry, diameters, echo power spectra, delay-Doppler images

NOTE: "Follow up" means that a telescope will sweep NEAs discovered by other telescopes just as a part of the regular operating routine and "self-follow up" means that a telescope will do targeted observations of the objects that it discovered. [a] Sun-Earth L1/L2 Lagrange point. [b] Primary Mission. [c] Field of Regard (Solar Avoidance). [d] Low elongation regions are accessible, with degradation in sensitivity. [e] Field of View. [f] Object at opposition. [g] Little variation based on albedo (Grav et al. 2016; Mainzer et al. 2015).

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