The Future of Planetary Defense in the Era of Advanced Surveys

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THE FUTURE OF PLANETARY DEFENSE IN THE ERA OF ADVANCED SURVEYS: A WHITE PAPER COMMISSIONED BY SBAG FOR THE 2023-2032 PLANETARY SCIENCE AND ASTROBIOLOGY DECADAL SURVEY

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1 Executive Summary

Impacts due to near-Earth objects (NEOs) - asteroids and comets whose orbits can evolve to cross Earth's - constitute a natural hazard that can cause the extinction of humans and many other species. It is well documented that NEO impacts have already catastrophically altered Earth's evolution by rendering the dinosaurs extinct[1] and could have played a role in the four other major mass extinction events preserved in the geologic record. However, we now possess the technical means to prevent most impacts if the potential impactor is detected sufficiently far in advance. While the probability of a devastating event in our lifetimes is low, it is not negligible, and the potential consequences are so catastrophic that society is well justified in addressing the threat.

For example, in June 2020, asteroid 2020 LD, estimated to be between 50-200 m, passed inside the orbit of the Moon moving at 27 km/sec relative to the Earth. Had this asteroid impacted, the energy would have been the equivalent of ~200 megatons of TNT, producing a crater 3.5 km across and leveling buildings more than 20 km from the impact point. Ideally, we would want ample warning of such an impact – at least months and preferably years – so that we could take action to mitigate the impact. But with our current NEO survey capabilities, asteroid 2020 LD was not discovered until two days ***after*** its close approach to Earth.

The first pillar of planetary defense is thus to find and track NEOs. Plans have been formulated to carry out large-scale sky surveys to detect large numbers of objects, thus greatly reducing the impact hazard uncertainty. Yet these surveys are not adequately funded, despite public support[2], direction to NASA from Congress[3], National Academy studies[4,5], and a White House plan for NEOs.[6] The public indicates that this activity should be one of NASA's top two priorities.[2]

Objects with diameter D>1 km are capable of causing global disasters, but smaller objects with 140m < D <1 km can cause wide regional damage (i.e. of order the size of Southern California) with significant loss of life and severe political, social, and economic problems.[7,8] We have yet to find approximately 2/3 of the NEOs with D >140 m in diameter.[9,10,11] ***The first priority of planetary defense should therefore be to complete a survey of NEOs that can cause regional damage (D >140 m).*** Completing the survey is a prerequisite to averting a rare but potentially catastrophic natural disaster. Hazard mitigation has been demonstrated to be easier the farther in advance a hazardous asteroid can be found. We have the necessary technology now, so we should complete this work in the next decade and should not defer this important task to another generation. NASA is the world leader in this area by funding the surveys that have discovered >95% of all known NEOs to date.

The second pillar of planetary defense is to characterize potential threats. Ground- and space-based surveys designed to meet the D>140 m objective will provide high-quality orbits as part of their baseline cadences. The level of orbital knowledge delivered by these surveys is generally sufficient on its own to determine whether or not a particular object is of concern. But for very close predicted approaches (<<1 lunar distance), more accurate follow-up astrometry, particularly from Earth-based radar facilities, is required. We must also study NEO physical properties since they vary widely and can profoundly affect impact damage. By studying NEOs using photometry, spectroscopy, and radar, we can determine sizes, shapes, cometary activity, and composition. These properties are needed to plan a mission to intercept the body and to destroy it or change its orbit. In cases where it is difficult to observe an individual object directly, the characteristics of the NEO population will need to be used to estimate its most likely properties.

The third pillar of planetary defense is to mitigate the impact hazard by deflecting an asteroid off a predicted impact course with Earth. Efforts should be made to examine and demonstrate methods of deflecting and disrupting NEOs. A range of techniques is possible, but because the choice and scope of technique depends on what is known and the time available until impact, high priority must be placed on gathering key parameters such as orbit, diameter, density, etc.

The fourth, and final, pillar of planetary defense is coordination. Any real-world planetary defense activity is, in practice, a global exercise. Activities that test global coordination of scientific and operational readiness of planetary defense frameworks must be exercised regularly.

We therefore recommend the creation of a NASA Planetary Defense Mission Program that would be adequately funded by ~$200-250M/year over the next decade, to be reassessed in the next Decadal Survey. This would enable the launch of a discrete set of missions that will complete the survey of larger NEOs and will validate reconnaissance and mitigation techniques with small- to medium-sized missions. This program is essential so that:

- Hazardous NEOs will be detected well in advance of any potential impacts that may occur;
- NEO physical properties will be characterized well enough to enable effective mitigation;
- A set of mitigation techniques will be thoroughly validated experimentally on the diversity of NEOs that may be encountered before being deployed under time-critical circumstances.

This investment will at best enable us to prevent a catastrophic natural disaster and will at a minimum rule out the anxiety caused by a poorly understood potential impact scenario, leaving us with a much greater understanding of the origins, evolution, and contents of our solar system.

This level of funding will support the current surveys, characterization facilities, international collaborations, and research programs into the effects of impacts on the biosphere (roughly $40M/year in total for all); will support the completion of DART; and will support the completion of NEOSM and the survey of D>140 m NEOs (roughly $100M/year for 5 years to launch), followed by one mid-sized characterization mission (~$70M/year for 5 years) and one mitigation demonstration mission beyond DART (~$100M/year). See the Decadal white paper by Barbee for details. The President's FY21 budget proposes to cut planetary defense from its current level of $150M/year to <$100M/year. ***In this scenario, the survey for larger NEOs is not completed for many decades, and future characterization or mitigation missions beyond DART are unlikely.***

2 Introduction

Earth resides in a region of the solar system occupied by a continuously resupplied swarm of rocky and/or icy fragments that originate from the solar system's earliest days. Small NEOs, meters across, impact Earth quite frequently and are disintegrated harmlessly in the upper atmosphere. Sizeable NEOs, kilometers in size, impact the Earth less frequently. Sixty-five million years ago, a 5-10-km object impacted Mexico, leading to the extinction of dinosaurs and ~50-75% of all species.[1] The Chesapeake Bay is marked by an 85 km-wide crater caused by an impact 35 million years ago.[12] The 1908 major fireball and subsequent 10 megaton explosion over Tunguska, Russia, likely the result of an asteroid or comet several tens of meters in diameter, leveled trees over 2000 sq km. More recently, the 2013 fireball over Chelyabinsk, Russia injured 1600 people, even though it was only ~20 m.[13,14] Such events have motivated studies of appropriate responses.

Studies[7,8] have found that while large impactors capable of causing global destruction are far less numerous than their smaller counterparts, they should nonetheless be the first objective of NEO surveys because of the tremendous damage that even a single impact could cause. Efforts have therefore focused on finding the largest objects and determining orbits with sufficient quality to ensure that no significant chance of impact exists over ~100 years.

The U.S. Congress-mandated NEO searches were initially focused on the NEOs larger than 1 km[15] because these could potentially cause the extinction of a significant fraction of all life on

Earth. To date, >90% of these have been discovered.[11] Subsequently, asteroid surveys shifted their focus to discovering >90% of NEOs with D>140 m, since that would identify 90% of the risk from sub-global impacts.[7,8] The task of reaching this goal by 2020 was codified into law in 2005 by Congress as the George E. Brown, Jr. (GEB) Act (Public Law 109-155 Sec. 321).[3]

At the present time, only roughly 1/3 of NEOs with D≥140 m has been identified. Current surveys such as the Catalina Sky Survey[16], PanSTARRS[17], NEOWISE[11], ZTF[18], and ATLAS[19] cannot reach the >90% completeness for NEOs with D>140 m required by the GEB Act for ***at least several decades*** due to their limited sensitivity and field of regard. More capable NEO survey systems are required.[5,8] This goal was reiterated in the National Near-Earth Object Preparedness Strategy and Action Plan published by the White House in 2018[6] and supported by the Small Bodies Assessment Group, a community-based forum, over the past seven years.[20]

3 The Era of Advanced Surveys

The US National Academy of Sciences concluded that a space-based IR telescope with the specifications of the NEO Surveillance Mission (NEOSM), in combination with the Rubin Observatory (formerly LSST), would meet the GEB objective in ~10 years of surveying ***provided they are fully funded***[5]. NEOSM will be NASA's dedicated space-based asset for fulfilling the Congressional mandate, whereas the Rubin Observatory is a multi-objective ground-based telescope funded by the National Science Foundation and the Department of Energy that is not required to use a traditional NEO survey cadence.[21] These advanced surveys will use wide field telescopes and very sensitive cameras to discover hundreds of thousands of new NEOs. This combination of assets is necessary for discovering >90% of NEOs with D>140 m, building upon the discoveries being made by the existing surveys. NEOSM can find 90% of NEOs with D>140 m after 10-12 years by surveying near-Sun regions of the sky, and the Rubin Observatory looks closer to opposition. Experience has shown that a network of complementary surveys is best to ensure complete and highly reliable coverage, especially in the era of megasatellite constellations. Without these new capabilities, we will not approach this level completeness for decades.

Once a NEO has been discovered, the hazard it poses must be quantified. If an object has a potential Earth impact, two immediate questions arise: 1) When will the impact occur, and 2) How much damage will it cause? The former requires extending the observational arc so that the orbit is well-constrained.[22] The latter depends on impact energy, which scales as kinetic energy $KE = \frac{1}{2}m \cdot v^2 \propto \rho \cdot D^3 \cdot v^2$, where m is mass, v is impact velocity, ρ is density, and D is diameter. Determining D and v is therefore critical; v is determined from the orbit. Mass m can either be determined directly in rare cases[23] or derived from a combination of D and ρ. The thermal IR capability provided by NEOSM allows diameters to be determined for hundreds of thousands of objects.[24] Roughly 1/3 of NEOs are extremely dark,[9,11] so achieving >90% completeness for asteroids with D >140 m (corresponding to absolute magnitude H<23 mag – as opposed to the previously used H<22 mag) requires finding the dark objects[25]; NEOSM, with its IR camera, is well-suited to this task. The density of a potential impactor could be anywhere between that of water and metal, so measuring density is also key for assessing impact energy. Where optical and thermal IR data are available, albedo can also be determined, which helps constrain composition. Visible and near-IR colors can also provide links to albedo if detections in multiple filters are available with a cadence suitable for resolving rotational and shape degeneracies. The Rubin will return mostly visible and near-IR color photometry for larger NEOs that are observed repeatedly over the survey.[26] ***The combined capability offered by both NEOSM and the Rubin Observatory will provide an unparalleled dataset*** for finding NEOs and characterizing the population.

4 What Remains to Be Learned About NEOs & Comets in the Era of Advanced Surveys?

Once the GEB congressional mandate has been achieved, the remaining unknown risk lies with asteroids with diameters <140 m and with the long-period comets (LPCs)[8]. When survey completeness for NEOs >140 m is nearing 90%, another study similar to [7,8] should be undertaken to determine the appropriate next steps to address remaining impact risks.

4.1 Future Survey and Warning Strategies

The next surveys that might be undertaken would depend on the statistics revealed by the Rubin and NEOSM. These surveys will quantify the slope of the size-frequency distribution (SFD) down to tens of meters, including any breaks, allowing for robust comparison with bolide data in the ~1 m range[27,28,29] and studies of lunar cratering. The SFD slope is very uncertain in the range 10 m < D < 100 m, leading to large (factor of ~30) uncertainty in the total number of objects in this size range.[9,30] NEOSM and Rubin will also reduce the uncertainty in comet SFD measurements; present-day knowledge comes from studies of dozens of objects to ~150 objects.[31,32,33]

Should small NEOs turn out to be more numerous than expected, surveys focused on providing short-term warning on timescales of hours or days (e.g. ATLAS[34], Flyeye[35]) may need to be augmented to provide warning for objects approaching from the daytime sky. For such small objects, longer warning times allowing for deflection may not be feasible but days of warning may be sufficient to carry out civil evacuation. Backyard astronomers will have a role to play in follow-up of new discoveries through small, networked, automated digital telescopes.[36]

4.2 Astrometric Follow-Up

NEOSM and Rubin are designed with self-follow-up cadences suitable for ensuring that most NEOs can be recovered on subsequent apparitions (and NEOSM can be pointed at specific targets of interest). However, follow-up will remain a high priority even after 90% of NEOs with D>140 m are discovered to ensure that uncertainties in the timing and location of any potential impacts are thoroughly understood. As NEOs like Apophis, Bennu, and 1950 DA demonstrate, there will always be objects where the uncertainty region of the asteroid's position crosses the Earth or passes through dangerous orbit-changing near-Earth gravitational "keyholes", requiring careful follow-up to verify the timing and location of impacts. Telescopes dedicated to astrometric follow-up and ranging in aperture size and geographic distribution will be needed, building on the capabilities provided by e.g. Spacewatch[37], LGOCT, and others, but expanding capability to track objects with an average visual magnitude of V~24 mag. See white papers by Seaman, Taylor, and Virkki.

4.3 Characterization

4.3.1 Remote Sensing in the Visible and Infrared

Remote sensing is the most effective method to rapidly characterize of NEOs, allowing researchers to sift through large numbers of objects quickly to identify the most hazardous objects. The combination of thermal IR data from NEOSM and optical colors from the Rubin will provide basic characterization for most detected NEOs. NEOSM will produce highly reliable NEO detections and robust diameters and constraints on shape and spin state within days or weeks of a discovery. From thermal IR observations in two bands, it is sometimes possible to infer a metallic composition and/or derive an estimate of thermal inertia.[38,39] As discussed in Section 3, when visible light observations are available for a NEOSM-detected object, the albedo can be determined as well, which loosely correlates with taxonomic type.[40] Rubin ultraviolet to near-IR detections will provide sparse colors (i.e. colors assembled from observations spanning ~months to years), which link to asteroid taxonomy.

However, it is vital to understand the range of parameters among the NEOs and their source populations for cases where observational opportunities are limited.[41,42,43] Follow-up using ground-based large aperture visible, near-IR, and radar telescopes are essential for determining taxonomy, mineralogy, porosity and internal strength, the presence of satellites, refinement of spin state and shape models, etc.[43,44,45] See white papers by Raymond, Milam, Taylor, and Virkki.

4.3.2 Characterization and Follow-up with Radar Assets

Accurate astrometry of close-approaching NEOs from NEOSM and Rubin will significantly increase the targets that can be studied in detail with radar. Radar observations are pinpoint-targeted and require advance knowledge of an object's sky position. Because radar observations provide high precision line-of-sight distance and velocity measurements, they significantly improve the astrometry of objects; however, due to the $1/r^4$ decrease in received echo power with distance r, objects must be correspondingly closer relative to an optical/IR telescope to be detected. Radar measurements can improve knowledge of asteroid orbits, prevent loss of newly discovered objects, and increase the window of reliable predictions of trajectories by decades to centuries.[46] Radar can also provide measurements of spin state, radar albedo, porosity, and satellites. Sometimes, radar can resolve objects well enough to detect boulders and craters. Repeated radar ranging observations over years to decades enables measurement of the orbit-altering Yarkovsky effect[47]. When combined with thermal data obtained from an IR telescope such as NEOSM, these data can constrain the mass of an asteroid.[22,48] The advanced surveys will provide a wealth of targets for future examination with radar. ***Maintaining the funding of the only two key radar facilities, Arecibo Observatory and Goldstone Solar System Radar, is crucial for planetary defense.*** See white papers by Rivera-Valentín, Virkki, Taylor, and Lazio.

4.3.3 Research and Modeling Program

A strong research and analysis program is an essential part of NASA's planetary defense efforts. The geophysical properties of NEOs (density, internal structure, cohesion, regolith, shock propagation, shape, etc.) affect both potential hazard (e.g., atmospheric breakup vs. intact ground impact) and potential mitigation. Given the extremely limited data on the outcome of NEO impacts on Earth, one of the best means we have to understand potential impact threats and develop effective planetary defense techniques is computational modeling. Modeling tools to properly interpret the effects of impacts from different types of objects should be validated against laboratory measurements; see white papers by Fayolle, Ishii, Jacobson, and Stickle for details.

4.3.4 In-Situ Missions

Remote sensing can provide a robust set of basic parameters for a great many objects, but should an individual NEO be detected with a significant probability of impact, plans for in-situ reconnaissance missions must be mature with flight-proven instruments ready for potentially very rapid deployment. NASA and other international space agencies have gained considerable expertise from missions to small bodies such as NEAR-Shoemaker[49], Dawn[50], Hayabusa[51], Hayabusa2[52], OSIRIS-REx[53], and Chang'e-2[54]. Missions currently in development such as DART[55], Near-Earth Asteroid Scout[56], Hera[57], and the Comet Interceptor mission[58] will provide further experience. Development of small spacecraft and high-fidelity miniaturized science payloads that can be quickly deployed in flyby or rendezvous missions to gather an expanded set of NEO physical properties and detailed maps is essential. Missions that demonstrate these capabilities should be considered options for a planetary defense mission line. NASA should take advantage of upcoming frequent potential low-delta-V encounters with NEOs discovered by NEOSM and Rubin to refine lower cost, rapid missions and instrument suites (see white papers by Barbee, Binzel, Castillo-Rogez, Raymond, and Haynes).

4.4 Infrastructure and International Collaboration

NASA has responded to the issue of NEOs by creating the Planetary Defense Coordination Office (PDCO) in 2017, serving as the lead U.S. agency for this topic. Systems for automatically computing orbits and impact probabilities have also been put into place.[59] Links to other U.S. agencies and international partners are being strengthened due to the issue's global nature. The White House's NEO Preparedness Plan is an important planning document that makes similar recommendations to this white paper, and NASA's PDCO has engaged with the international community: The PDCO participates in the United Nations Committee for the Peaceful Uses of Outer Space[60] and communicates with voluntary members of the International Asteroid Warning Network[61] for remote sensing of NEOs. The Space Mission Planning Advisory Group[62], chaired by ESA's Planetary Defence Office, brings nations together to study potential mitigation missions. These efforts ensure that a global plan exists for NEOs among scientists, policy makers, and communications experts. NASA's PDCO has led both tabletop and observational campaigns to exercise global planetary defense assets and should continue conducting regularly.[45]

ESA's planetary defense activities center on follow-up, performing independent orbit determination, and providing an observer spacecraft for NASA's DART mission. Arriving a few years after the DART impact, it will determine surface properties of the impacted object. ESA is also developing the 1.2 m Flyeye telescope to observe mostly small NEOs.

Given the international nature of the potential hazard from NEOs, the political, cultural, and sociological differences around the world, and the fact that natural disasters can disproportionately affect marginalized communities, effective planetary defense requires trained experts from a broad range of backgrounds, experiences, and contexts. Thus, ***a commensurately diverse, representative, and equitable planetary defense workforce is essential***. Plans to create this workforce must be made to ensure that trained experts from different communities are included and take the lead in making decisions that can affect them. See white papers by Rivera-Valentín and Ritchey.

5 What Would We Do If a High-Probability Potential Impactor Were Discovered?

In the event that an object with a significant chance of a major impact is discovered, the next steps will depend critically on what is known about it, and when these data becomes available. The most appropriate mitigation option depends on the lead time and asteroid mass/size.[4] NEOSM is specifically designed to discover and characterize NEOs years to decades in advance of a potential impact, facilitating a range of possible mitigation strategies assuming it is funded. For kinetic impactors, NASA's Deep Impact mission[63] probed impact processes on a comet, and the upcoming DART technology demonstration mission, coupled with Europe's Hera reconnaissance mission, will shed light on the effects of kinetic impacts on ~100-m sized S-complex asteroids. JAXA's Hayabusa2 mission has successfully excavated a 10-m crater on the primitive asteroid Ryugu.[64]

As surveys fill in our knowledge of the potential impactors, additional mitigation tests should be carried out, including e.g. using gravity tractors or laser ablation to perturb orbits. Kinetic impacts on a larger scale and on different targets (varied spectral classes, porosities, sizes) could also be undertaken; see white papers by Barbee. However, mitigation experiments should not be prioritized ahead of the basic task of finding, cataloging, and characterizing NEOs. Unless we find the impactors, we cannot deflect them. Without knowledge of a potential impactor's likely physical properties, the outcome of a deflection attempt would be very uncertain. T***he best course of action is to adequately fund both surveying and mitigation testing*** at the level of ~$200-250M/year.

6 What Can Be Learned About the Solar System in the Era of Advanced Surveys?

NEOSM and Rubin will deliver a wealth of data informing us about the origins and evolution of our solar system. In addition to delivering data on hundreds of thousands of NEOs and thousands of comets, these surveys will discover millions of more distant small bodies. Populations of rare objects such as Earth Trojans and interior-to-Earth-orbit objects can be studied in detail.

By finding the most hazardous population of asteroids the advanced surveys will identify a much larger set of accessible asteroids. The OSIRIS-REx and Hayabusa2 missions have revealed in exquisite detail the strange top-shapes and rugged, boulder-rich surfaces of primitive asteroids Bennu and Ryugu (both of which were discovered by NEO surveys), and pristine samples returned from them will yield new insight into their compositions. The ability to return pristine samples from a larger and compositionally diverse set of objects will help to fill out our understanding of volatile-rich objects, possibly supporting in-situ resource utilization (see white paper by Milam).

7 Conclusions

Preparation for disaster will save lives. We can ensure that we are not caught by surprise by an asteroid or comet impact, and we have the technology today to greatly reduce the hazard. The resources required are reasonable by the standards of the U.S. Government. ***Sufficient funding to complete the survey of large NEOs within a decade needs to be made available.*** A planetary defense program funded at the level of approximately $200-250M/year will enable discovery of >90% of asteroids large enough to cause significant destruction; allow us to keep watch for long-period comets; develop a deep understanding of Earth-crossing objects; and mature the tools and techniques so that we have the best chance to ensure that a dangerous impact does not occur.

REFERENCES

[1] Alvarez et al. 1980 Sci 208, 1095 [2] Pew Research [3] GEB law [4] National Research Council 2010 [5] National Academies 2019 [6] White House NEO Plan [7] Stokes et al. 2003 [8] Stokes et al 2017 [9] Morbidelli et al. 2020 Icarus 340, 113631 [10] Granvik et al. 2018 Icarus 312, 181 [11] Mainzer et al. 2011 ApJ 743, 156 [12] Koeberl et al. 1996 Sci 271, 1263 [13] Popova et al. 2013 Sci 342, 1069 [14] House hearing [15] Morrison et al. 1992 [16] Larson et al. 1998 BAAS 30, 1037 [17] Kaiser et al. 2002 SPIE 4836, 154 [18] Bellm et al. 2019 PASP 131, 018002 [19]Tonry et al. 2018 PASP 130, 064505 [20] SBAG 2020 Goals Document [21] Ivezić et al. 2019 ApJ 873, 111 [22] Chesley et al. 2002 Icarus 159, 2002 [23] Chesley et al. 2014 Icarus 235, 5 [24] Mainzer et al. 2015 AJ 149, 172 [25] Wright et al. 2016 AJ 152, 79 [26] Jones et al. 2018 Icarus 303, 181 [27] Brown et al. 2002 Nat 420, 294 [28] Gi et al. 2018 M&PS 53, 1413 [29] Rumpf et al. 2019 Sensors 19, 5 [30] Trilling et al. 2017 AJ 154, 170 [31] Meech et al. 2004 Icarus 170, 463 [32] Fernandez et al. 2013 Icarus, 226, 1138 [33] Bauer et al. 2017 AJ 154, 53 [34] Tonry et al. 2018 PASP 130, 064505 [35] Cibin et al. 2016 MmSAI 87, 197 [36] Marchis et al. 2020 Acta Astro 166, 23 [37] McMillan 2007 IAU Symp. 236, 329 [38] Harris & Drube 2014 ApJL 785, 4 [39] Harris & Drube 2016 ApJ 832, 127 [40] Mainzer et al. 2012 ApJ 745, 7 [41] Rivkin et al. 2005 Icarus 175, 175 [42] Moskovitz et al. 2014 ACM 366 [43] Binzel et al. 2019 Icarus 324, 41 [44] Thirouin et al. 2016 AJ 152, 163 [45] Reddy et al. 2019 Icarus 326, 133 [46] Naidu et al. 2016 AJ 152, 99 [47] Bottke et al. 2006 Ann. Rev. Earth Plan. Sci. 34, 157 [48] Lauretta et al. 2019 Nat 568.7750, 55 [49] Cheng 2002 *Asteroids III* p351 [50] Russell et al. 2015 *Asteroids IV* p419 [51] Yoshikawa et al. 2015 *Asteroids IV* p397 [52] Watanabe et al. 2017 SSR 208, 3 [53] Lauretta et al. 2017 SSR 212, 925 [54] Jiang et al. 2015 SR 5, 16029 [55] Cheng et al. 2016 P&SS 121, 27 [56] Lockett et al. 2019 IEEE AESM 35, 20 [57] Michel et al. 2020 LPI 51, 1441 [58] Snodgrass & Jones 2019 Nat Comm 10**,** 5418 [59] MPC; CNEOS; NEODyS [60] UN COPUOUS [61] IAWN [62] SMPAG [63] A'Hearn et al 2005 Sci 310, 258 [64] Arakawa et al. 2020 AGUFM #U54A-04