ASTEROID STUDIES: A 35-YEAR FORECAST A. S. Rivkin[1], B. W. Denevi[1], R. L. Klima[1], C. M. Ernst[1], N. L. Chabot[1], O. S. Barnouin[1], and B. A. Cohen[2], [1]JHU/APL, [2]NASA MSFC.

Introduction: Asteroids are of central importance to space science. They are surviving witnesses to the earliest solar system history. They have been credited with delivering water and organic materials to the inner solar system, making life possible here (and elsewhere?). The microgravity of small asteroids amplifies the importance of tiny forces, allowing observations of processes that are unobservable on larger objects. Asteroids of various sizes on Earth-crossing orbits commonly rain down on us, affecting the evolution of terrestrial life and inspiring efforts to mitigate future impacts. The proximity of some asteroids has led an emerging set of asteroid mining companies to work toward making use of their resources.

Our knowledge of asteroids has undergone a revolution in the past 35 years, and practically everything we know about asteroids has been learned in that time. Forecasting forward 35 years is thus a fraught exercise, even ignoring the fits and starts in the pace of progress that are likely ahead. Nevertheless, we can look forward and discuss the likeliest or highest-priority advances before us, with the recognition that in 2050 today's undergraduates will be entering their late career and most newly-minted PhDs are still awaiting their births.

The Diversity of Asteroids: Asteroids cover a wide range of sizes, compositions, orbits, and histories. At this writing, two asteroid missions are in progress (Hayabusa-2 and OSIRIS-REx), two others are in planning (HEOMD's Asteroid Redirect Mission (ARM), and the Double Asteroid Redirection Test (DART)), and three others are finalists for the ongoing Discovery Program competition (of which zero, one, or two might be chosen). In the best case, these missions will collectively return pristine, carbonaceous material to Earth and to lunar orbit, and investigate in detail a large asteroid thought to be metallic, fly by several Trojan asteroids, and/or conduct a telescopic survey to obtain albedos and sizes for a significant number of asteroids. In addition to this set of missions, ground- and space-based facilities (including JWST and LUVOIR) will be used to make a mixture of population studies and focused investigations.

These efforts will enable significant progress on the science questions they are designed to address. However, broad and important questions of asteroid diversity will still be unaddressed without further efforts including: What is the nature of the transition from gravity-dominated to strength-dominated targets? How do the cohesive and non-gravitational forces on asteroid surfaces at small sizes interact? What were the original formation locations of the asteroid classes? *Are the handful of asteroids we know well representative of the vast population of which we know so little?*

Future Investigations: While the round of missions discussed above is still reaching its scientific prime, the thrust of the next round of missions seems reasonably clear. We will have fewer than ten objects whose properties we will know very well from spacecraft. Radar shape models will be available for a hundred or so objects, primarily NEOs. Finally, we will have tens of thousands of asteroids for which we have only disk-integrated albedo, size, and perhaps color data. *Our ultimate goal should be to understand the connections between composition, size, surface, system, and interior properties, and orbital properties such that researchers can quickly and reliably estimate properties of an unknown asteroid from a minimal set of telescopic measurements. This will have not only science benefit but also be of great benefit to the planetary science and asteroid mining communities.*

A set of missions designed to fill the middle ground between comprehensive knowledge and cursory information will be required to allow the point-source data, radar data, and rendezvous/sample return data to be best integrated. An asteroid flyby tour with current technology can provide imaging and other data on par with early rendezvous missions. If sufficient propulsion can be developed, frequent SmallSat tours could augment occasional Discovery-class tours. These tours could provide imagery and spectral data for hundreds of targets, and with particle analysis instruments like SUDA or Hyperdust compositional data can also be obtained.

In parallel, in-depth study of select targets should continue. Dawn has helped cement Ceres' place as an erstwhile ocean world and site of astrobiological interest. Similar missions to other large, low-albedo objects (some of which share Ceres' spectral properties) will be needed to establish how unusual or common Ceres-like histories were in the Solar System. Further visits to Ceres itself are certainly warranted to better understand its history and the nature of its prebiotic inventory. In-depth studies of smaller asteroids will also be necessary to further understand the connections mentioned above. Key "high leverage" targets can be identified for in-depth rendezvous/landed/sample return missions in much the same way that key locations on the Moon and Mars are identified and targeted for investigation.

Ceres and the icy asteroids of the outer belt also appear to be indispensible waypoints to the icy satellites. The technology needed for ambitious missions like drills through Europa's ice shell can be tested on an icy asteroid without long travel times to the outer solar system or the complicating challenges of Jupiter's radiation. Similarly, when humankind has walked on Mars and begins to look for additional challenges, Ceres provides an obvious next outpost with its abundant water.

Future Capabilities: We can already imagine the capabilities that will be available for asteroid studies by the end of the 2020s if current and planned missions move forward. Multiple sample return techniques will be available for "particle sizes" varying from typical regolith (OSIRIS-REx and Hayabusa) to multi-meter blocks (ARM). The studies for ARM and DART show how asteroids can be manipulated and orbits changed with current or near-term technology. The following decades could see such capability expanded, perhaps by allowing larger masses to be moved or by allowing more precise placement of perturbed asteroids. For instance, a mission to divert a PHA to cause a lunar impact could simultaneously provide data for a future lunar seismic network, asteroid samples for geochemical study, and a large-scale test of impact models, as well as remove the asteroid as a threat to future generations.

As instruments become more miniaturized and capable, as communications become better, and as AI and telerobotics mature, we might also expect a flowering of *in situ* asteroid studies. Indeed, combining the above points to the utility of a robotic science facility orbiting in the main asteroid belt, with a fleet of reusable probes visiting targets and returning samples of interest to the central facility, where sample analysis is done telerobotically.

We can expect surveys for PHAs larger than 140 m to be completed before 2030, with some fraction of smaller objects also discovered during the process. Surveys designed to provide days-to-weeks warning of impending impacts will likely be in place, potentially turning bolides and fireballs into predictable events. Those PHAs that are most dangerous can be targeted by flyby tours of the sort mentioned above in order to obtain first-order physical characteristics to provide a head start in case future mitigation is ever deemed necessary. The technology used to extract blocks from asteroid surfaces could also plausibly be put to use emplacing long-lived transponders to allow precise tracking of PHAs, as warranted.

Astronomical facilities will also become more capable in coming decades. Observing time on 30-m-class telescopes will be difficult to obtain, but will be enabling for studies of objects too dynamically difficult to reach conveniently with missions. Asteroid studies will continue to benefit from the need to identify moving targets in all-sky astrophysical surveys, as they have benefitted from the massive databases created by the Sloan Digital Sky Survey, IRAS, WISE, Gaia etc.

Commercial and International Aspects: In addition to science-driven and hazard-driven investigations, asteroids have been identified as sites for economic development. The United States has been enacting laws to make asteroid mining more economically feasible, and the nations of Luxembourg and the United Arab Emirates have followed suit or are planning to do the same. Multiple asteroid mining companies have formed, and aim to begin operations well within the time frame considered here. Asteroidal resources have been touted as potentially enabling for human exploration and outpost creation on the Moon and beyond. As a result, asteroid studies will have aspects of basic science, trade secrets, and applied engineering.

There will potentially be a lot of overlap between the data desired by mining companies and asteroid scientists in the 2020s and beyond, even if the goals of the data analyses differ. This raises opportunities for public/private partnerships, but also the need for clear expectations from each side as to what is being paid for in terms of public vs. proprietary data. The USGS is in the process of an exercise as to how they might go about assessing asteroidal resources, and the government should play a role in ensuring all Americans benefit from use of space resources.

In addition to Americans, the asteroids provide potential targets for many other nations. The Europeans, Chinese, and Japanese have all had successful asteroid encounters, as the Russians and Indians presumably could if so moved. Other nations could support asteroid missions in this timeframe as well. Their interest will likely increase if asteroid mining companies establish themselves. Again, this offers both opportunity and peril, depending on how the legal framework for asteroid mining is established and enforced: if expansion of humanity off of the Earth is seen as benefiting only a few wealthy nations (or individuals), it will inevitably run into opposition. Similarly, if perhaps beyond the scope of this report, the United States will be very different demographically over the next few decades compared to the last few. For American space studies to succeed, its participants must be seen as reflecting and representing our nation. It is not too soon to take steps to help the science community of 2050 look like the United States of 2050.