PLANETARY SCIENCE IN THE NEXT DECADES: THE ASTROMATERIALS PERSPECTIVE. H. Y. McSween[1] and K. D. McKeegan[2], on behalf of CAPTEM[3]. [1]Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN 37996-1410, mcsween@utk.edu, [2]Department of Earth, Planetary, and Space Sciences, UCLA, Los Angeles, CA 90095-1567, mckeegan@epss.ucla.edu, [3]www.lpi.usra.edu/captem/.

Introduction: Astromaterials include samples returned to Earth by spacecraft misisons as well as those that arrive here naturally. Research on these samples creates the knowledge base needed for science-focused Solar System exploration by answering questions that no other avenue of research can. Moreover, astromaterials are the "gift that keeps on giving" – the ability to apply new technologies that did not exist when the samples were acquired or returned greatly enhances their value.

Vision for Sample Return Missions: The decades beyond 2022 offer many opportunities to significantly advance the exploration of the Solar System through sample return missions.

OSIRIS-REx will return samples of a B-class carbonaceous asteroid, and HEO's Asteroid Redirect Mission could provide additional asteroid samples. New Frontiers target missions under consideration include sample return from a comet nucleus and from the South Pole Aitken basin on the Moon. Ample motivations for these missions were provided by the NRC's Planetary Decadal Survey [1]. CAPTEM's vision includes carrying out both of these high-priority mission concepts, whether or not they are selected for flight in the current decade. Building on these missions, CAPTEM advocates additional sample returns from the Moon to understand how the Late Heavy Bombardment, as well as continued sample returns from additional asteroids and comets – the compositional diversity of these objects will never be fully understood using remote sensing and cannot be captured by the missions currently under consideration. Sampling another asteroid population, such as the Trojans, would be especially informative.

Another goal for the next decades should be a mission to return cryogenic samples from a comet, so that we can begin to understand icy/volatile materials in the outer Solar System. CAPTEM also advocates for returning samples (collected from erupting jets by an orbiting or flyby spacecraft) from "ocean worlds" like Enceledus; such a mission offers the most technically plausible and affordable way to address the goal of seeking evidence of life in subsurface oceans. Direct sampling of the methane/ethane surface lakes on Titan would be very challenging, but return of such a sample might offer the most promising opportunity to find life or understand its organic precursors. Alternatively, a returned sample of Titan's organic-rich atmosphere is less challenging and would address the same questions.

The return of samples cached by Mars 2020 ranks among the most important goals for planetary science, as noted in the NRC's Planetary Decadal Survey [1]. CAPTEM emphasizes the need for NASA and its international partners to complete the sequence of missions that will make carefully chosen martian samples available for laboratory investigations. These analyses are viewed as a prerequisite for sending humans safely to Mars [2].

Samples returned from Venus or Mercury would constitute major scientific advances but would require correspondingly major technological leaps. However, return of Venus atmospheric samples would be valueble for understanding the origin and evolution of planetary atmospheres. Likewise, obtaining samples of surface materials or subsurface oceans from satellites of the giant planets would also have great scientific value, but their collection and return probably lies beyond 2050.

Knowledge of the elemental and isotopic composition of the Sun is fundamental. Genesis provided a two-year sample of the solar wind. A future mission of this type is justified to enlarge the chemical data base for the centerpiece of the Solar System, and to improve knowledge of processes leading to the ejection of matter from the Sun. A second Genesis-type mission could be flown as an inexpensive stand-alone, or as an add-on; solar wind collection could also be part of a lunar base.

Getting the Most out of Past Missions: The 382 kg of rocks and soils collected by the Apollo astronauts are still providing fundamentally new discoveries about the geology and history of the Moon, many decades later. Other NASA-curated collections from past missions include comet dust from Stardust, solar wind from Genesis, and asteroid regolith from Hayabusa [3]. These small samples are likely to become exhausted by 2050, despite careful curation and allocation.

The Cheapest Sample Return Missions: The Antarctic Search for Meteorites (ANSMET) program has provided >20,000 meteorites from at least 80 parent asteroids plus the Moon and Mars [3]. The continuation of meteorite collection programs will provide samples of a much greater diversity of Solar System bodies than can be visited by 2050. Cosmic dust, collected in the stratosphere by U2 aircraft, retrieved from melted Antarctic ice, and vacuumed onto soon-to-be installed atmospheric filters at the South Pole, provide samples of cometary solids (sometimes from specific comets through targeted meteor showers). Although meteorites and cosmic dust, however valuable, are samples without provenance or geologic context, they allow fundamental questions about processes and conditions in the solar nebula and on primitive and differentiated bodies to be addressed in a quantitative way.

Challenges: The Decadal Survey [1] stated that "The most important instruments for any sample return mission are the ones in the laboratories on Earth." Without adequate support through the next decades, NASA's ability to analyze extraterrestrial samples, develop new microanalytical techniques, and provide the experienced workforce needed to maximize the scientific results of future missions will wither. This community of scientists also is engaged in developing capable instruments to be flown on spacecraft. In the future, coordination of analytical capabilities and facilities with international partners will likely be desirable.

The sample return missions (beyond those already in the current prioritized New Frontiers list, for which challenges have already been noted [1]) that CAPTEM advocates and some of their technological challenges are reiterated below; these are not prioritized or chronologically sequenced, as that requires in-depth study and advice from the broader science community.

- ***Mars sample return***: The mechanics of the multiple missions that retrieve samples from the planet's surface and launch them towards Earth are already under study. The requirements for sample curation, including issues related to planetary protection, and the necessary funding are not.
- ***Sampling the Moon*** and ***additional asteroid sample returns*****:** Autonomous approach and sampling when out of communications with Earth is part of the OSIRIS-REx mission, but that technology is primitive and applies only to unconsolidated regolith. It seems possible that some sample return missions from small bodies might be flown within the costs of the Discovery program, and that capability should be explored.
- ***Cryogenic comet sample return***: The ability to take a core on a comet, reaching beneath the dusty mantle to collect ices and retain stratigraphic context, is very challenging. The sample must be collected and returned to the Earth's surface in a frozen state.
- ***Sampling jets of volatile materials from an ocean world***: Cassini has already flown through and remotely analyzed jets from Enceledus, but detecting life likely requires study in a terrestrial laboratory; the challenge may lie in collecting enough material to make its return to Earth worthwhile.
- ***Sampling Titan's lakes or atmosphere***: Huygens has successfully transited (one way) Titan's atmosphere, but traveling in the other direction is harder. How to land on and sample a lake, and then launch from a liquid surface is problematic. Luckily, the lakes are smooth, but their properties are unknown. Sampling the upper atmosphere of titan is a more tractable problem, as it does not require landing.
- ***Venus sample return***: The problems encountered in sampling Venus rocks before being incapacitated by the searing heat or crushed by the dense atmosphere, and of escaping through the atmosphere and from a gravity field like that of Earth's, are legion. However, return of atmospheric samples would be more tractable.
- ***Mercury sample return***: The orbital problems in landing a spacecraft on Mercury may preclude serious consideration of sample return in the next few decades.
- ***Genesis-type solar wind return:*** Building on Genesis technology, this sample return would be straightforward, although advances in analysis technology are needed.

Summary: Samples studied in laboratories on the Earth provide otherwise unobtainable information about extraterrestrial bodies that motivates and enables future spacecraft missions. The next decades offer many opportunities to conduct missions that will return samples, significantly increasing our understanding of Mars, the farside of the Moon, asteroids, comets (including ices), jetted or surface volatiles on an ocean world, and possibly Venus and Mercury. The analyses of samples collected and returned by spacecraft is complemented by continued investigations of meteorites and cosmic dust that arrive on Earth naturally (the cheapest missions). NASA should sieze this vision.

References: [1] National Research Council (2012) *Vision and Voyages for Planetary Science in the Decade 2013-2022,* Nat. Acad. Press. [2] National Research Council Space Studies Board (2002) *Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface*, Nat. Acad. Press. [3] Allen C. et al. (2013) *EOS* 94, 253-260.