Flexible-Path Human Exploration

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In the fourth quarter of 2009 an in-house, multi-center NASA study team briefly examined "Flexible Path" concepts to begin understanding characteristics, content, and roles of potential missions consistent with the strategy proposed by the Augustine Committee. We present an overview of the study findings. Three illustrative human/robotic mission concepts not requiring planet surface operations are described: assembly of very large in-space telescopes in cis-lunar space; exploration of near Earth objects (NEOs); exploration of Mars' moon Phobos. For each, a representative mission is described, technology and science objectives are outlined, and a basic mission operations concept is quantified. A fourth type of mission, using the lunar surface as preparation for Mars, is also described. Each mission's "capability legacy" is summarized. All four illustrative missions could achieve NASA's stated human space exploration objectives and advance human space flight toward Mars surface exploration. Telescope assembly missions would require the fewest new system developments. NEO missions would offer a wide range of deep-space trip times between several months and two years. Phobos exploration would retire several Mars-class risks, leaving another large remainder set (associated with entry, descent, surface operations, and ascent) for retirement by subsequent missions. And extended lunar surface operations would build confidence for Mars surface missions by addressing a complementary set of risks. Six enabling developments (robotic precursors, ISS exploration testbed, heavy-lift launch, deep-space-capable crew capsule, deep-space habitat, and reusable in-space propulsion stage) would apply across multiple program sequence options, and thus could be started even without committing to a specific mission sequence now. Flexible Path appears to be a viable strategy, with meaningful and worthy mission content.

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I. Introduction

Late in the third quarter of 2009, the Review of U.S. Human Spaceflight Plans Committee (aka Augustine Committee) recommended several alternatives to the Program of Record being used by NASA to implement the 2004 Vision for Space Exploration.[1] Among those options was "Flexible Path" (FP) defined as using near Earth object (NEO), flyby, and orbital missions as a way to extend human deep-space capabilities toward eventual planet surface exploration of the Moon and then Mars. Although the Augustine Committee reasserted Mars surface exploration to be the "ultimate goal" of U.S. human space flight, it proposed FP as a way to divide that challenge into more affordable, more achievable quanta (Fig. 1). The FP strategy is based on two principles:

1. Conducting deep-space human space missions "with no immediate plans for planet surface exploration" lowers the startup threshold by deferring the significant expense and complexity of planetary descent, surface operations, and ascent capabilities.
2. Dual-purpose missions enable stepwise demonstration of human deep-space capabilities while yielding key "beyond NASA" benefits like public engagement and inspiration, stimulation of STEM education, exercising the U.S. technically skilled workforce, and advancing technologies.

The logic of the FP strategy is seductive given the history of NASA's abortive attempts since 1989 to expand human exploration beyond LEO. But the committee's report was scant on detail about actual Flexible Path mission ideas, leaving it open to challenges regarding how useful and compelling such missions could be. A small NASA in-house study team undertook the task of articulating three potential dual-purpose FP missions to test the second principle. The authors were the principal study participants.

Our only selection criterion was that the missions successively increase distance in deep space and duration away from Earth:

1. Few weeks—Assemble Large Space Telescope at Earth-Moon L1 (example is ~8 weeks)
2. Few months—Rendezvous with a NEO (example is ~6 months)
3. Few years—Land on Phobos (example is ~2 years).

Lunar and Mars surface missions were omitted from the short study specifically because they had already been studied extensively and because the essence of Flexible Path is priority by other mission types. However, this paper includes consideration of lunar surface missions as preparation for Mars, to provide a fuller treatment.

II. Assumptions and Limitations

Because the study was quick, we quickly closed on a few axioms based on prior work: study-team members' deep background in a quarter century of analysis, multiple high-level advisory recommendations, and development work underway on early Constellation systems including Orion.

1. **Mars should be "the ultimate destination for human exploration of the inner solar system."** The Augustine Committee recommended that any path chosen advance capabilities toward humans-on-Mars.

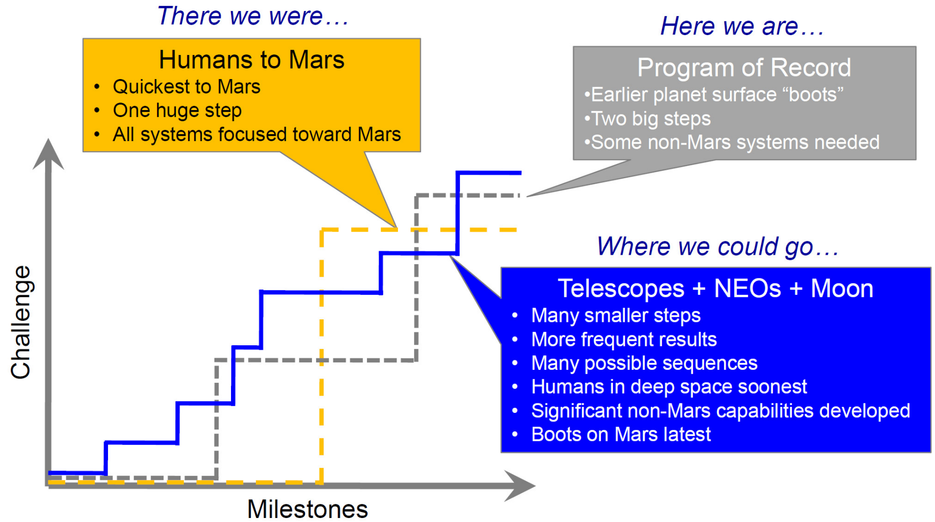

Figure 1. Since 1990, conceptual planning for human exploration has evolved from tackling Mars directly, to using lunar operations as a developmental step, to a potential Flexible Path strategy. Decomposing the challenge into more but smaller steps theoretically stretches out the final result but makes the challenge programmatically tractable.

2. **Flexible Path is not singular.** There are many pathways that can be defined. We added human missions to assemble and service large telescopes because they offer steps even more incremental, with a "lower bar," than NEO exploration and therefore could facilitate even earlier progress.
3. **ISS should be a key testbed for demonstrating and qualifying exploration systems and technologies.** ISS is a keystone programmatic destination on all reasonable paths. An international laboratory in LEO affords a peerless way to develop, validate, qualify, and showcase techniques that directly bear on future exploration missions away from Earth.
4. **Orion (with block upgrades) would provide crew launch and return for U.S. human space flight (HSF) missions.** At the time of the study, we assumed Orion as the basis for American mission-crew access to LEO, and (with block upgrades for orbital lifetime and increased entry energy) for return to Earth from deep-space missions.
5. **Heavy lift launch is essential.** Deep-space exploration architectures can be contrived to avoid heavy-lift launch capability for some destinations, but such capability is essential for eventual lunar-surface and Mars-class exploration.

The study neither engineered missions nor estimated costs. It acknowledged the Augustine Committee's finding that a Flexible Path strategy would require a significant increase in NASA's annual budget (the FY11 budget proposal requests a temporary increase of $6B over five years, about one third what the committee recommended permanently).

III. Mission Classes

Grouping potential human exploration targets of the inner solar system reveals levels of capability useful for planning a succession of FP missions (Fig. 2). The clusters are locations near Earth, locations near planets, and locations in deep space not close to planetary bodies. Venus is excluded for clarity, although human orbital missions there are possibly useful, and opposition-class Mars trajectories typically include a Venus swingby.

In the figure, color shading indicates how the clustered destinations can be used to cumulatively develop and exercise increasingly challenging human space flight HSF. Red circles highlight the destinations reached by the three illustrative mission examples described in this paper.

- Yellow shows LEO destinations including ISS. The legacy of ISS and Hubble (HST) missions is assembly and servicing of large habitable systems and telescopes, continuous occupancy, and international participation. Extended through at least 2020, ISS would be used as a developmental testbed for exploration systems, and possibly as an operational node.
- Pink (large rectangle) includes all destinations outside the geomagnetic field. The legacy of any mission in this class would be solar flare (SPE) storm-shelter capability, mitigation of galactic cosmic radiation (GCR), and a Deep Space Habitat. The risk accepted by Apollo missions (e.g., the August 1972 solar flare) would not likely be acceptable today.
- Green shows the closest destinations beyond LEO: high Earth orbits including GEO, and the Earth-Moon L1 point. Doing anything productive at such locations requires EVA and adjunct-robotics capabilities, but access and return times are short, and no special equipment is required for dealing with natural bodies.
- Purple shows deeper, free-space destinations. Sun-Earth (SE) L1 is a unique location for synoptic observations of the fully sunlit hemisphere of Earth, as well as interactions between Earth and Sun. SE L2 is a favored operational location for large astronomical telescopes. NEOs are the definitive natural-body destinations in this class. Mars Trojans (asteroids gravitationally trapped at stable Lagrange points) are known at Sun-Mars (SM) L4 and L5; Earth Trojans may exist at SE L4 and L5, but require space-based observations (e.g., from SE L1) for discovery. Destinations in this class vary widely in distance from Earth and trip time, but there are thousands. The legacy of this mission class could be solutions for deep space isolation, countermeasures for microgravity and potential immunological deconditioning, remote health care including surgery; high-reliability life support subsystems; and human-scale interplanetary propulsion.
- Blue shows locations in gravity wells of planets. Of these, Phobos is a unique destination because of its hypothesized asteroidal origin and its proximity to Mars. The legacy of this mission class would be propulsion capability to get into and back out of these gravity wells with human-class payloads and cargo. Facing this challenge opens choices: destinations beyond the "green" destinations would either require "blue" propulsive systems or "purple" deep-space human systems. Getting to Phobos requires both.
- Orange shows planet-surface destinations. The Augustine Committee recognized that planet surface missions require capabilities for entry/descent, landing, surface infrastructure, surface mobility and other operations, planetary protection (for Mars), *in situ* resource utilization (ISRU), and ascent. Targeting the other

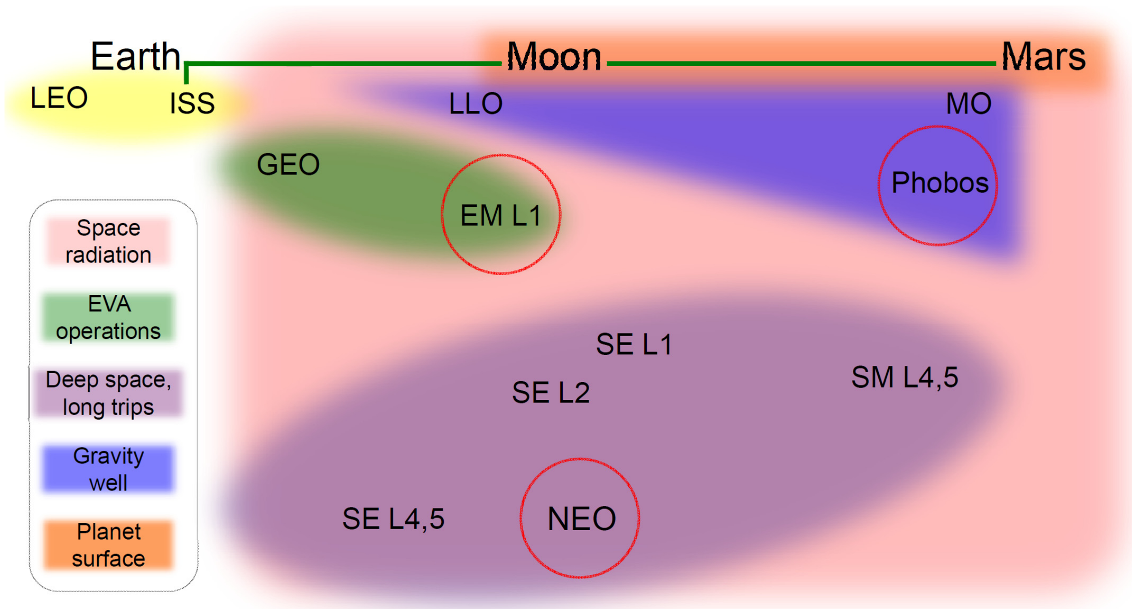

Figure 2. Destination map for human exploration of the inner solar system groups mission classes according to successively tougher challenge. LEO = low Earth orbit. GEO = geosynchronous orbit. LLO = low lunar orbit. MO = Mars orbit. NEO = near-Earth object. Lagrange points are designated by primary-body secondary-body, and L-point number using standard nomenclature: L1 is between the bodies; L2 is beyond the secondary; L3 is beyond the primary, and L4 and L5 respectively lead and follow the secondary by 60° in its orbit around the primary; S = sun; E = Earth; M = Moon or Mars.)

destination classes first would enable missions to proceed while this challenging list of capabilities is still in development.

IV. Human/Robotic Assembly of Very Large Telescopes

Human/robotic assembly and servicing of large telescopes in deep space would have dual purpose: significantly preparing for other deep-space human missions in stepwise fashion beginning at ISS; and enabling breakthrough science.

Figure 3 shows an evolutionary roadmap of in-space telescope assembly enabled by human space flight. LEO telescope assembly demonstrations would validate approaches for modular design, human/robotic interaction, on-board metrology, autonomous alignment/control, and contamination control on a "small" in-space telescope where the development environment timeline is relatively unconstrained, multiple EVAs can be conducted, and subsystem alternatives can be exchanged. The end product would be a technology toolkit and scripts for assembly of increasingly larger telescopes. Next could be a GEO Earth-Looking Observatory for applications such as: persistent intelligence, surveillance and reconnaissance; greenhouse gas monitoring, attribution & compliance; and other Earth science. Construction and servicing in the GEO environment could constitute a first step for human space flight outside the natural radiation shielding of the geomagnetosphere.

Deep Space Observatories are the "holy grail" for large-telescope science. A very large observatory at Sun-Earth L2 could deliver breakthrough science in multiple areas: visible/infrared astrophysics, Earth-like exoplanet spectra, life in the galaxy, first black holes, and event-horizon physics. Such deep-space observatories might best be assembled in the more benign, relatively close region of Earth-Moon L1, and then transported to their operational location at SE L2 by a robotic, low-thrust (ion propulsion) stage. Two options would then open for subsequent human servicing, including system replenishment and instrument upgrades: the ion stage could return the observatory to EM L1, or a human mission could even be mounted directly to SE L2. The latter mission would demonstrate the expanding deep-space capability of humans and their flight systems, and also avoid the long science down-time of relocating the observatory with a low-thrust system.

Having multiple steps on the path provides planning choices including schedule acceleration, combining of steps, or off-ramps to other types of human missions. For these reasons, and because of the unique benefits to large-

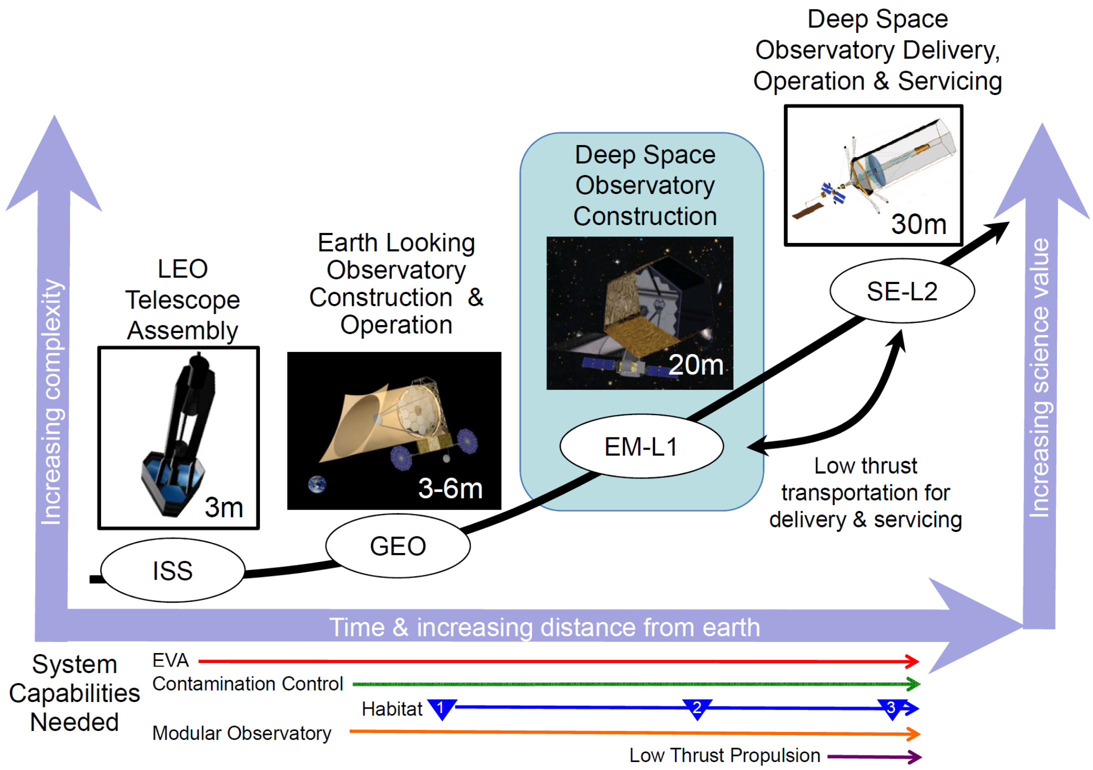

Figure 3. Stepwise progression would advance both human space flight and in-space telescope capabilities.

aperture observational science attainable only with human space flight, we recognize these mission classes as viable for an FP strategy. The illustrative mission described next would assemble a large astrophysical telescope at EM L1.

A. Large In-Space Telescopes

Astrophysics is a photon-limited science. Many exciting investigations cannot be done with today's space observatories simply because the targets are extremely faint—fainter by at least an order of magnitude than even the dimmest sources ever detected by HST or Chandra. Two of the most exciting questions that future space-based telescopes could address are: "When did the first stars form?" and "Are We Alone?"

The first question may be answered by searching for black holes that the first stars left behind when they died. These black holes would have formed when the universe was a mere 100 to 200 million years old (about 1% of its current age). Ancient black holes are intrinsically very luminous, especially in x-rays, but they are so distant that they are 1000× fainter than can be seen by X-ray observatories today. An X-ray observatory with effective area of 50 m^2 could detect them and allow us, for the first time, to trace the cosmic history of stars to their ultimate origin in time.

The second question is perhaps the most fundamental facing astronomy. Are there planets around other stars where life as we know it has existed? To answer this question requires a large optical/infrared (IR) telescope. Earth-like planets even just 30 light years away would be extremely faint, so we would need a large telescope to obtain the spectra where signatures of life could be found. An "Earth twin" at a distance of 60 light years is eight times fainter than the faintest galaxy in Hubble's Ultra Deep Field Survey. And if such planets are not common, we may need to search 100 or more stars to find even a handful. The number of star systems where we could hope to obtain such spectra of Earth-sized planets in their stars' Habitable Zones increases as the cube of the telescope diameter. A 30-m telescope in space would enable an era of remote sensing of oceans, weather, land, and vegetation coverage on hundreds of habitable worlds beyond our solar system.

Space telescopes with this much collecting area can only be assembled in space.

B. Mission: Construct an Observatory at EM L1

Astronauts assisted by robotic devices could construct a large optical/IR observatory at EM L1, to demonstrate scale-up and to be transported to ES L2, the desired operational orbit for thermal and observing-efficiency reasons. For example, this might be a 20-m class wide field telescope with diffraction-limited images, detected with sensitive

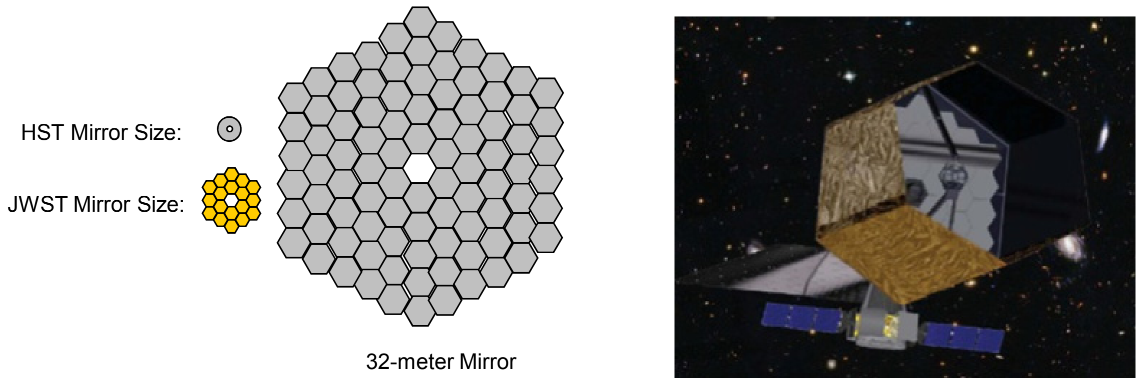

Figure 4. The light-collecting power of a human-assembled in-space telescope would dwarf prior capabilities.

visible and IR cameras and spectrometers. The scale of light-gathering power enabled by human in-space assembly would enable observational astronomers and astrophysicists to image the faintest of targets in the early universe with unprecedented resolution (Fig. 4).

The telescope design would be highly modular for ease of EVA assembly. The construction operations design would incorporate structured robotics to assist astronauts on repetitive and high-geometric-tolerance tasks. Assembly duration is a strong function of the degree of modularity employed in the design architecture. ISS and HST have dramatically demonstrated that large elements can be assembled and serviced with astronaut EVA in a manageable amount of time. Clearly the techniques and tools would have to be wrung out during prior missions and groundwork, just like with HST and ISS, to minimize risks to astronauts and hardware.

A strawman construction flow for the large aperture observatory at EM L1 would use 4–6 astronauts, performing ~20 EVAs, over a 48-day period (Fig. 5). Crew and cargo would be launched into a lunar transfer-like orbit, where assembly of pre-integrated modules proceeds as indicated in the arrowed flow. The mission duration estimate includes schedule margin, and assumes that the modularity scheme, tools, and human/robotic interfaces would be defined and validated in the ISS and GEO environments. Prior analyses leading to this notional mission description

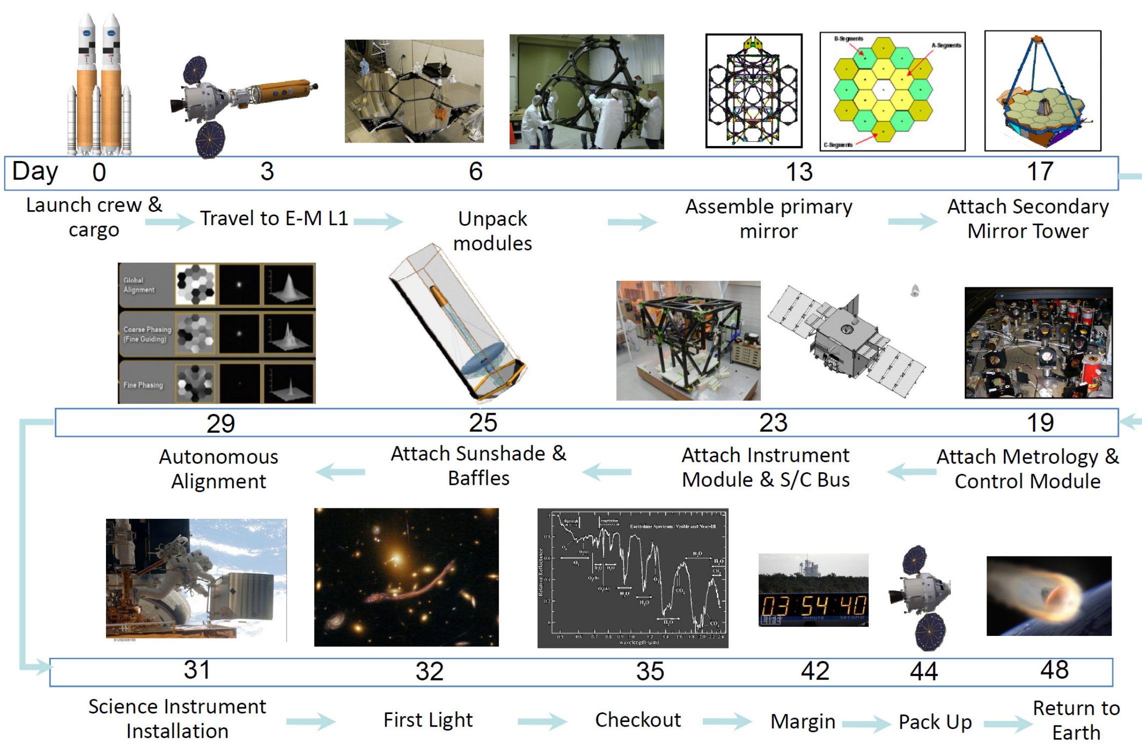

Figure 5. Construction flow of a large telescope at EM L1 would provide an exciting seven weeks of public engagement, followed by years of astounding science results.

are based on HST servicing experience, James Webb Space Telescope (JWST) and Advanced Mirror Demonstrator (AMD) development, and conceptual designs of modular observatory systems. Checkout sensors and algorithms are at high technology readiness level.

C. Mission Legacy

Virtually every stage of the mission would yield public engagement milestones, and as HST has proven, the end result would be an unprecedented science system that "keeps on giving" long after the crew has departed.

Feed-forward technologies relevant to future in-space observatories include: modular observatory instrumentation-bus interfaces; contamination control; large lightweight mirror segments; on-board metrology and autonomous control; image based wavefront sensing; expandable sunshades; and low-thrust transportation. For human space flight, the legacy would include: operations outside the geomagnetic shield, initial deep-space crew habitat, airlocks and EVA suits, and robotic toolsets.

The path to constructing extremely large telescopes in space would move humans progressively farther from the Earth, for longer durations in harsher environments. It involves a spectrum of progressively more complex capabilities from human EVA to locally controlled robotics, remotely controlled robotics, and autonomous robotics. Evolving capabilities would feed forward to enable larger, more capable space observatories as well as to expand humans into the solar system for other endeavors. Finally, it would produce breakthrough science to answer fundamental questions like where we come from and whether we are alone.

V. Human Exploration of Near Earth Objects

Apart from unique human-enabled science—including return of macroscopic samples and *in situ* conduct of subsurface active seismology—that could occur, human missions to near-Earth objects (NEO) offer two special benefits that support FP objectives:

- They have the lowest "price of entry" of any human exploration missions to natural bodies. Trip times range from a few months up to Mars-class, and thus can drive development and qualification of long-lived, deep-space human systems and propulsion. Yet they do not require landers, ascent vehicles, roving mobility systems, or other surface infrastructure.
- The NEO population is diverse, huge, and expected to continue growing as discovery continues. Each NEO is a small world to explore. Recent robotic exploration implies asteroids and expended comets hold many surprises in store, assuring significant scientific interest and public attention.

A. Half a Million Destinations

We now know the inner solar system has over half a million bodies to explore: in addition to the three familiar planets Mars, Venus, and Mercury, Earth's large Moon, and Mars' two small moons, it has a multitude of small bodies. The largest asteroid was discovered first (in 1801): Ceres, over 950 km in diameter and large enough to be spherical, will be orbited by the Dawn spacecraft in 2015. Figure 6 shows how rapidly our knowledge of the small-body population is growing.

By the time the discovery total reached a couple thousand, in the mid-20th century, several already were known to be "Earth-crossing" objects, now called Near Earth Objects (NEO). Arithmetically, objects are designated NEOs if they come within 45 million kilometers of Earth. In the past three years alone, about 2500 NEOs have been discovered. Ongoing and next-generation Earth-based and space-based telescope surveys expect to find many more NEOs.

Today, ~500,000 minor planets are known and tracked. Of that number, about 6600 are NEOs, and of that subtotal about 1100 are potentially hazardous objects (PHO). These last are candidates for eventual collision with Earth as their orbits propagate under the dynamic gravitational influence of other solar system bodies and momentum changes due to uneven thermal balance. They are designated PHOs if they come within 7.5 million kilometers of Earth and are large enough to cause significant regional damage in the event of an impact.

A large cohort of the NEO/PHO population is accessible by chemical and advanced propulsion technologies, with round-trip mission durations ranging from a few months up to a few years. Figure 7 shows a representative sample based on accessibility with cryogenic chemical propulsion. The upper plot shows round-trip mission duration (ranging from two to twelve months) vs. launch date. Because of synodic periodicity, multiple opportunities are available: the example highlighted, NEO 1999 AO10, could be reached with a heavy-lift based architecture launching in 2024, 2025, and 2026, and again in 2032. The same object appears in the bottom plot showing one-way robotic mission opportunities, with a one-year transfer in 2019 and additional opportunities in 2020 and 2021. In general, NEOs provide multiple target options, multiple mission opportunities to each target, and precursor mission

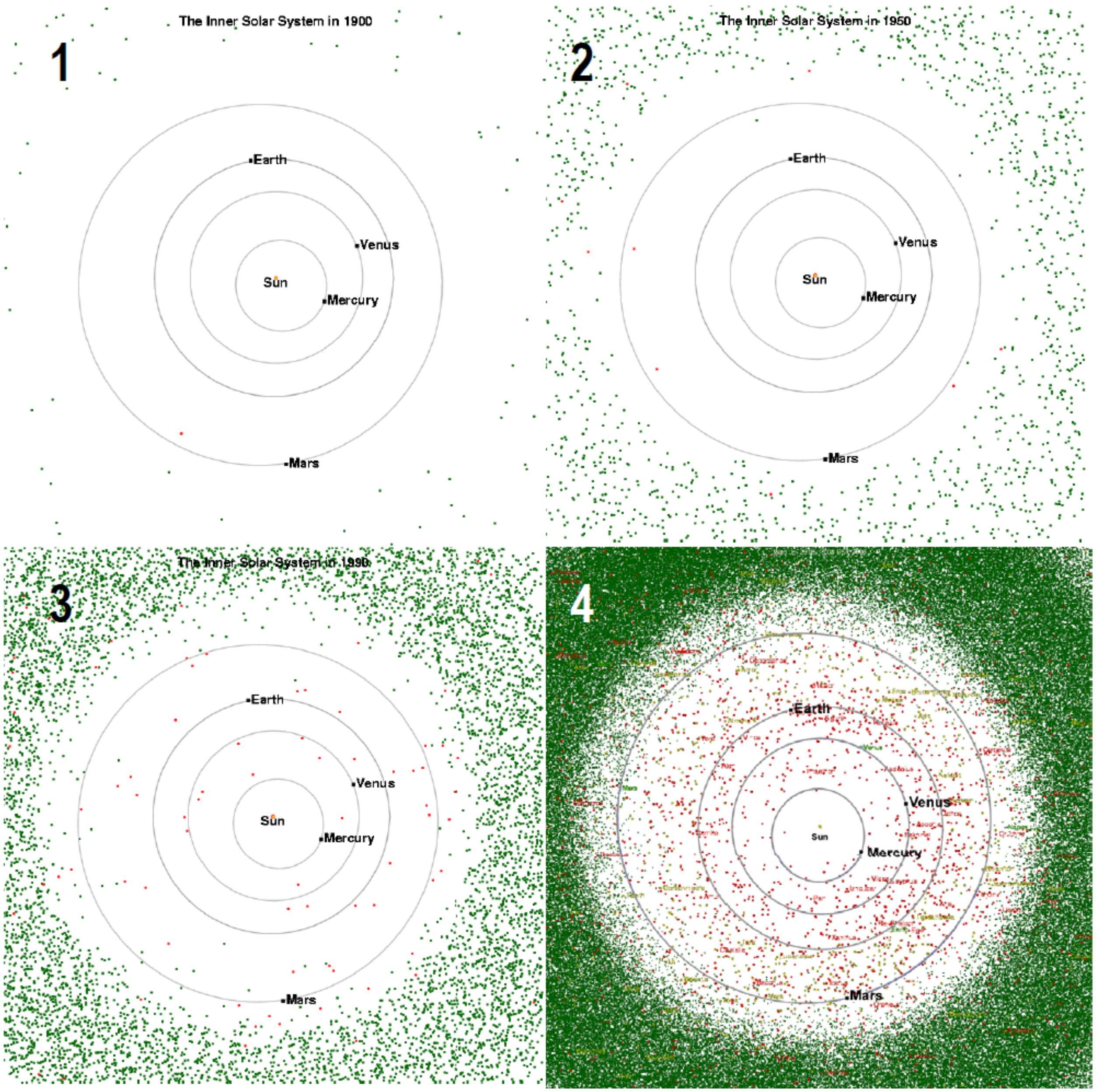

Figure 6. The known population of small bodies has grown rapidly. (1) 1900; (2) 1950; (3) 1990; (4) 2009. Green dots represent the main belt population; red dots represent "Earth-crossing" objects (NEOs).

opportunities to the same targets. Hypothetically this could allow a coherent, robust program plan that integrates robotic and human exploration and is resilient to development slips.

It requires multiple apparitions and good observations to characterize the orbit of a small body well enough to plan a human mission. Figure 8 shows recent work based on human accessibility using high-power electric propulsion (EP). The plot shows orbit quality confidence (small numbers are good) vs. launch date for a human mission. Even with current knowledge, five large NEOs of various spectral types are prime candidates in the timeframe of interest to meet President Obama's "NEO 2025" challenge.

B. Mission: Explore a NEO

Apart from the ways human missions to NEOs would help prepare for missions to Mars, human presence *in situ* at NEOs could accomplish key science objectives to advance understanding of primitive-body and solar-system formation as described by the NRC: geochemistry, impact history, thermal history, isotope analysis, morphology,

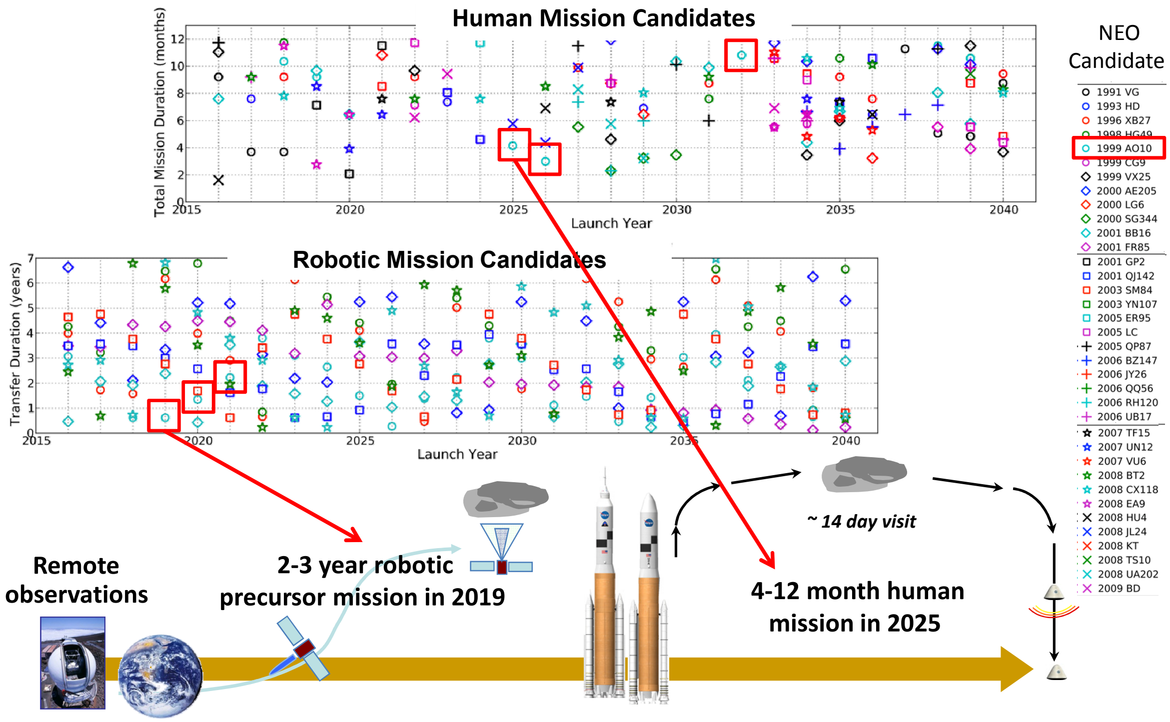

Figure 7. Many NEO targets could be accessible by human missions on multiple opportunities, preceded by robotic precursor opportunities to learn about their unique local conditions and properties.

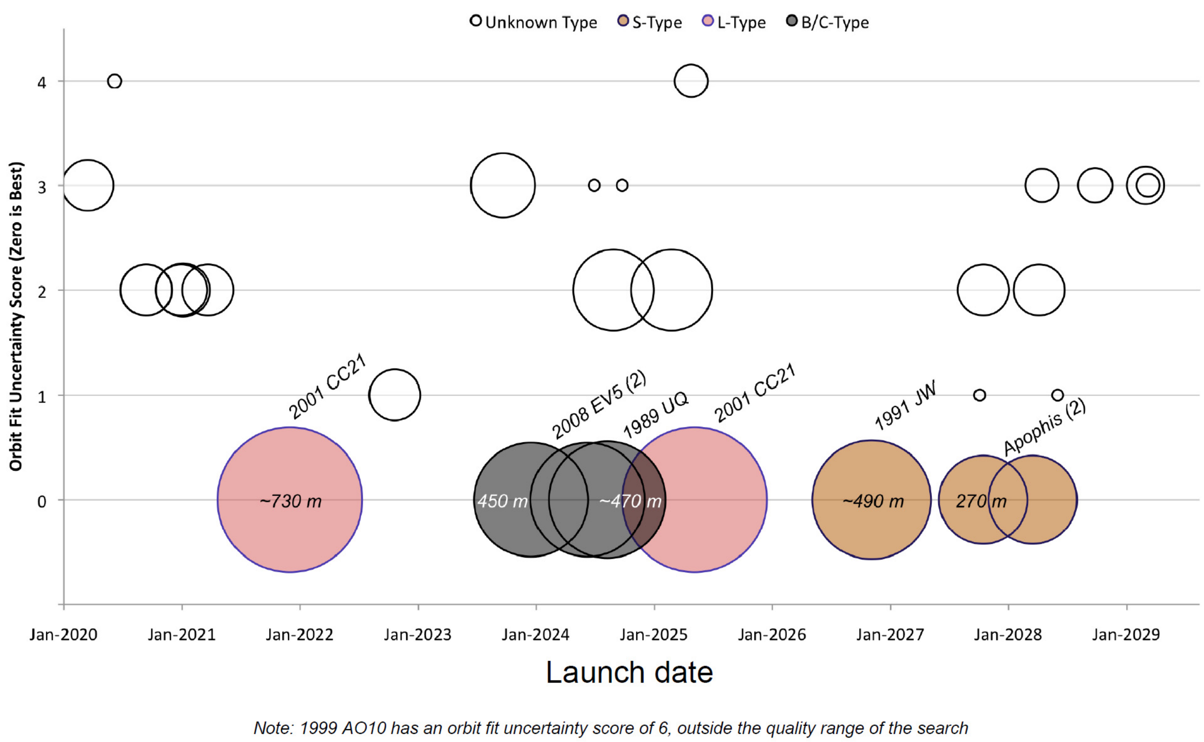

Figure 8. Some NEOs are large enough and have orbits already well-characterized enough to be known now as worthy candidates for human missions around 2025. Circles scaled to NEO diameters.

mineralogy, space weathering, formation ages, thermal inertias, volatile content and interior structure. Acquisition and adaptive interpretation of complex data, and real-time replanning, enable human crews to explore NEOs more thoroughly than remote robotic systems can. Figure 9 shows the NEO Itokawa, from which the Japanese mission Hayabusa returned particle samples this year.

A first round of robotic precursors would conduct initial comparative surveys to help select the best human-mission target. A more sophisticated precursor would perform detailed “site mapping’ of the selected target(s) in time to inform the Phase B preliminary design of tools, systems, and operations for the corresponding human mission(s). Important robotic precursor/adjunct functions include:

- Preliminary determination of target characteristics: surface morphology and properties (i.e., boulders vs. pebbles), gravitational field structure, rotation rate and pole orientation, mass/density estimates, general mineral composition.
- Assessment of potential hazards that may pose a risk to flight systems or crew (Rangers, Lunar Orbiters, and Surveyors performed this function for Apollo), such as binary or ternary objects, potentially active surfaces, and non-benign surface morphologies.
- Surface assessment to efficiently plan activities the human mission will conduct: proximity operations, surface operations, and sample collection.
- Aid navigation of human mission vehicle to the target NEO; provide additional data coverage during operations; obtain “third viewpoint” images of interactions of the crew and other assets at the NEO.
- Monitor the NEO after crew departure, including excavations from kinetic or explosive experiments; precise orbital measurements over long time scales to observe the Yarkovsky effect (evolution of the NEO’s orbit due to momentum transfer from diurnal differences in infrared photon emission).
- Orbital relay to maintain continuous contact with science equipment left behind on the NEO by the crew.

Figure 9. NEO Itokawa, over half a kilometer across, may be indicative of what human explorers will find at some of the candidate targets identified in Figure 8. ISS is shown for scale.

A typical human mission profile would include 2–6 weeks at the asteroid. Mission activities would likely include:

- Initial fly-around reconnaissance of the entire body
- “Docking” and ultra-low-g EVA exploration for comprehensive observations, including exposed subsurface strata and correlation of *in situ* observations with robotic-precursor findings
- Deployment and teleoperation of robotic explorers to supplement EVA collection of macroscopic solid and volatile samples in geologic context from various locations
- Preliminary analysis of collected samples, which could continue on the multi-month trip home
- Well-characterized deployment of a seismic network and explosive charges, for seismic study of the interior
- Preparation of post-departure kinetic energy experiments, to measure momentum transfer that could change orbital motion.

The human crew would provide “hands-on” adaptability to deal with emergent complex issues; direct interaction with the surface via a variety of methods; and wide-ranging education and public-outreach activities including high-definition video of humans at another world.

C. Mission Legacy

NEO exploration requires trans-lunar, genuinely deep-space mission capabilities. Sprinting home in the event of trouble is not an option, so solutions must be carried onboard for mitigating space radiation and emergent medical needs (e.g., surgery and dental care). Life-support systems must be either robust or repairable with adequate spares. These solutions must be integrated into a Deep Space Habitat system. The FP strategy opens options for such a NEO hab system to prototype—or even protoflight a subscale module of—a Mars-class habitat system.

An interplanetary-class propulsion system is also required to push the human-scale systems onto Earth escape and Earth return trajectories. Advanced cryogenic chemical (with zero-boiloff hydrogen storage), high-power electric, or both technologies are needed, so these leave the second major legacy for subsequent, longer NEO missions or Mars-class missions.

Finally, small-body EVA and proximity operations technologies are required; this is unique to small-body exploration, and precursor information about the targets of interest is required in turn to inform detailed design. The major legacy is capability to explore multiple NEOs, recognizing that targets can be selected to advance deep-space mission-duration confidence incrementally from a few months to a few years.

VI. Human Exploration of Phobos

Phobos is a unique destination: like the largest NEOs, but in Mars orbit (Fig. 10). This "Far-O" exemplifies the culmination of a stepwise progression that could use NEOs to bootstrap human systems and mission confidence toward Mars: exploration activities akin to NEOs, but requiring capture/departure in Mars orbit, and Mars-class mission duration. A human mission to Mars orbit, including Phobos exploration, would therefore represent an intermediate step between exploration missions in near-Earth space and missions to the surface of Mars. It could demonstrate in-space hardware elements designed for Mars missions (e.g., as described in Mars Design Reference Architecture 5.0[2]) while accomplishing scientific and exploration objectives both at Mars and on Phobos.

A. Why Would Humans Go to Phobos?

Phobos is a large body (over 27 km long) that shows evidence of a dramatic physical history (Fig. 11). It orbits closer to Mars than any other satellite to its primary, and rotates synchronously. Its gravity varies by more than a factor of four across its surface, and albeit weak is still enough to prevent humans from reaching escape velocity by jumping. One of the darkest bodies known, it may be a D-type asteroid (organics-rich with possible interior ice) captured by Mars in the distant past.

The mystery of the origin of Phobos could be resolved, and its evolution since formation investigated, by *in situ* field geologists working with Earth-based teams. As a possible D-type asteroid, it offers science beyond what is readily available in the NEO population, and can shed light on objects that delivered the initial inventory of water and organics to the surfaces of Earth and Mars. Returned samples would contain a record frozen very early in the formation of the solar system.

Phobos has been a collector of ejected Martian surface material for billions of years. That material is a record of the history of early Mars that may not even be preserved on Mars itself due to weathering. Martian material should be readily recognizable by color for collection. These samples would be an important supplement to samples collected directly from the surface of Mars.

Operation of Mars rovers from Earth is limited by the light time and communication opportunities to once-per-sol driving and articulation commands. From Phobos, a landing site would be visible about twice per

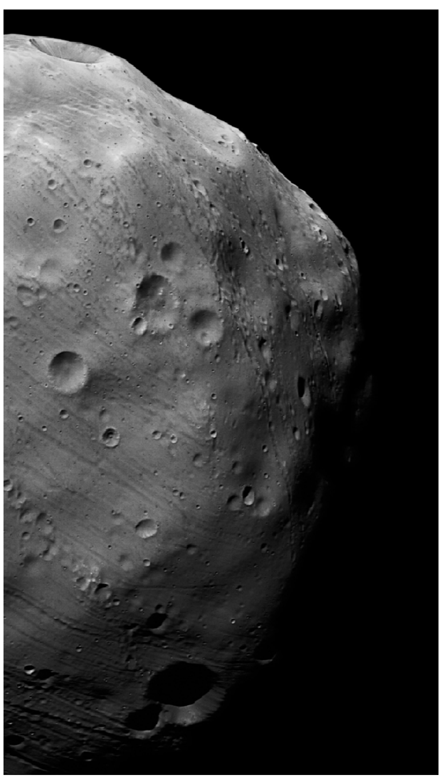

Figure 10. Mars Express took this image of Phobos in 2010.

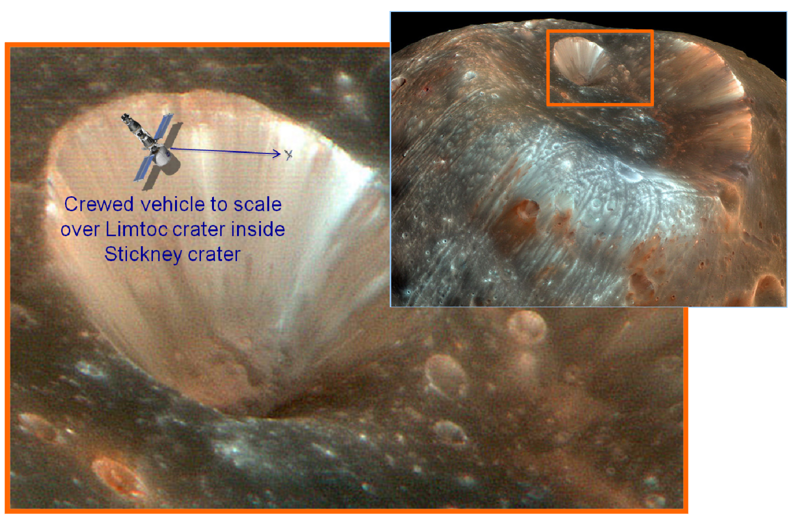

Figure 11. Phobos rotates synchronously; Stickney crater, on the Mars-facing side, is vast compared to the scale of a human vehicle.

sol for four hours each time, thus about four hours per sol during daylight. Two rovers with sufficient longitudinal separation could be operated by a single astronaut during a reasonable workday. The almost zero latency would permit vastly more efficient field work and sample collection on Mars than possible if they are operated from Earth. Even joystick driving would be feasible, allowing the rovers to cover much greater distances. The ability to interact with the environment in real time would significantly improve our understanding of the geology and our ability to select samples that best reveal the physical and biological history of Mars. Samples could be launched into orbit for pickup by the crew, or for later pickup by robotic return orbiters.

The low density of Phobos and its D-type spectrum suggest the possibility of large amounts of interior ice. Accessible ice would be a tremendous boon to subsequent, and especially repeated, crewed Mars missions if it enabled refueling in Mars orbit.

B. Mission: Explore Phobos

For chemical or nuclear-thermal propulsion, two classes of mission are feasible: opposition-class (sometimes called "short stay"), and conjunction-class ("long stay"). Key characteristics of opposition-class missions are: (1) propulsive requirement that varies greatly from opportunity to opportunity; (2) mission duration less than two years, that also varies with opportunity, ranging from 550-650 days; (3) a short (~190 days) and a long (~400 days) transit leg; (4) the long transit leg passing inside the orbit of Venus and typically using a Venus swingby; (5) 95% of the total mission time spent in the deep-space interplanetary environment, leaving only 30–40 days in the vicinity of Mars. By comparison, conjunction-class missions are: (1) more consistent across opportunities; (2) about 2.5 years overall; (3) symmetrical transit legs about 210 days long; (4) about 500 days in the Mars vicinity, roughly 12 times as long as the opposition-class type.

The example in Fig. 12 depicts a short-stay type mission, using cryogenic chemical main propulsion. It begins with the launch of the mission flight system. Propulsive stages for the major in-space maneuvers are launched next. Between 10 and 15 heavy-lift rocket launches are required to assemble the fully-fueled system in low Earth orbit. Finally the crew launches in an ascent/re-entry capsule, docks with the flight system and departs for Mars. Upon arrival at Mars the crew propulsively captures into orbit and maneuvers to Phobos rendezvous.

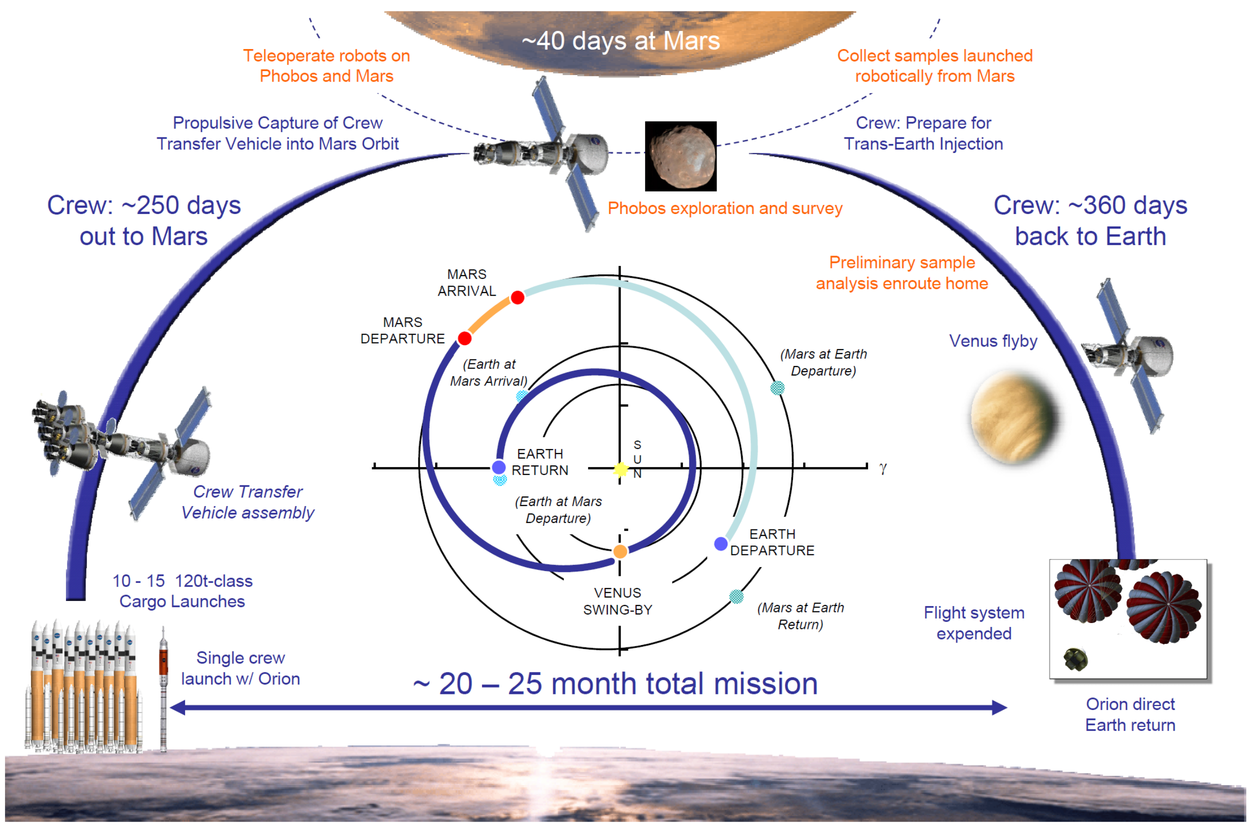

Figure 12. Illustrative opposition-class Phobos mission profile allows 40-day exploration within a 2-year total mission duration.

Mars DRA 5.0 challenges accomplished

- \+ Exceeds Mars requirement
- ✓ Solves or uses
- ⦿ Partially solves
- ○ Not retired by Phobos

Ground Operations
- \+ 7+ launches per mission (option)
- ✓ 30 day launch centers (300 day launch campaign)
- ○ Processing of nuclear surface systems
- ✓ Heavy lift launch vehicle configuration
- ✓ Production and storage of cryogenics and helium

Heavy Lift Launch
- ✓ 10-m dia x 30 m total length launch shroud
- ○ Dual use shroud (EDL)
- ✓ 125+ t to LEO
- ⦿ Launch to higher inclinations
- ⦿ EDS evolution to long-duration (option)

Cross-cutting
- ✓ Automated Rendezvous & Docking (in Earth orbit)
- ✓ Cryogenic fluid management (H_2, O_2, CH_4)
- ✓ Commonality & lowest level maintenance & repair
- ✓ Long-term system operation (300-1200 days)
- ✓ Low-Earth Orbit loiter for 300+ days
- ⦿ Planetary protection
- ⦿ Dust mitigation

Mobility and Exploration
- ○ 100+ km roving range
- ⦿ 10+ m depth access
- ⦿ Lightweight, dexterous, maintainable EVA
- ⦿ *In situ* laboratory analysis capabilities

Human Health & Support
- ⦿ Support humans in space for 900 days (option)
- \+ Radiation protection & forecasting
- \+ Zero-g countermeasures
- ✓ Closed-loop life support (air & water)

In-Space Transportation
- ⦿ ~50 t roundtrip (LEO to Mars orbit return)
- ✓ 110 – 125 t to Trans_Mars Injection
- ✓ Assembly via docking only
- ○ ISRU compatible lander propulsion (oxygen)
- ✓ Integrated transportation flight experience
- ⦿ Advanced interplanetary propulsion

Aeroassist
- ⦿ Aerocapture
- ○ 40-50 t payload to the surface
- ○ Abort-to-Mars-surface
- \+ 12 km/s Earth return speed (option)

Surface Related
- ○ Auto-deployment and checkout of systems
- ○ 30+ kWe continuous power with reliable backup

ISRU
- ○ Consumables from Martian atmosphere
- ○ Production of 24 t of oxygen for ascent
- ○ Production of life support oxygen (2 t) and water (3.5 t)

Figure 13. Phobos mission would retire many Mars-surface-class mission risks, leaving those associated with descent, surface operations, and ascent as the remaining challenges.

After 40 days in Mars space, the crew departs for Earth return. The return leg includes a Venus swingby and the closest approach to the sun by a human crew. Flyby opportunities of small asteroids may also exist on such trajectories. The flight system targets an Earth flyby and is expended in deep space, while the crew returns via direct entry in the ascent/re-entry capsule.

C. Mission Legacy

A mission to explore Phobos would yield two key legacies: dramatic improvement in our understanding of Mars and Phobos; and establishment of a technical foundation for subsequent human Mars surface missions. Samples from both Mars and Phobos—including from candidate landing sites for future human crews—would be gathered and analyzed. And design and demonstration of in-space hardware elements needed for Mars surface missions would have been accomplished.

Figure 13 lists driving technologies and challenges identified via DRA 5.0 for eventual human missions to the surface of Mars. Finding and demonstrating technical and operational solutions to these items is a significant undertaking, particularly if they must all be solved to enable even a first mission. One of the significant advantages of a Phobos mission would be to demonstrate a large subset of the technical and operational approaches needed for Mars missions and without committing a crew to the surface on a first Mars-distance mission. In the figure, icons indicate a preliminary assessment of the degree to which the example Phobos mission described above could drive and demonstrate solutions to these challenges. Yellow shading highlights the DRA 5.0 challenges that would remain for Mars surface missions; red shading highlights challenges unique to opposition-class missions (i.e., radiation and microgravity mitigation for opposition-class flight times; vehicle thermal control for cis-Venus perihelion passage; larger and more variable heavy-lift launch campaigns). The yellow-shaded items comprise a major set of challenges. A FP strategy that enables humans to do productive exploration at Mars before those challenges are met may have benefits for phasing investments and sustaining public attention.

VII. Human Exploration of the Moon

While the 2009 NASA-internal Flexible Path study did not address the Moon, many prior NASA and blue-ribbon studies consider human lunar surface operations as a stepping-stone into the solar system, leading eventually to Mars.[1-10] Essentially a dwarf planet with 1/6 Earth gravity and surface area roughly equivalent to Africa, the

Moon is a nearby natural research laboratory. Return takes just a few days and is available essentially any time, offering a significant risk-management benefit compared to exploration of deep-space targets like NEOs or Mars.

A primary "Mars forward" purpose of human lunar exploration could be to use the lunar topography and environment to simulate some Mars-exploration operations. This would call for testing and operating prototype or actual Mars systems on the Moon, where life-testing could be conducted and remote servicing could be rehearsed in an analogue environment that still allows contingency return to Earth.

A. Science of, on, and from the Moon

Between 2004 and 2010, NASA and many other spacefaring nations began earnest discussions regarding how to combine resources and work together for joint advantage in exploring the Moon. Several robotic scientific precursor missions emerged from these international collaborations and have flown, a harbinger of the collaboration likely needed to sustain human exploration.

Lunar science is key to understanding the formation of the solar system and Earth, because without weather the lunar surface is changed only gradually by space radiation, the solar wind, and meteorite impacts. The native surface thus preserves a record of the Moon's entire geological history, the inner solar system's impact history, and the history of solar variation.

The Moon provides a key research environment for biological adaptation to non-Earth gravity. All long-term space flight adaptation experience has been in microgravity; since empirical biological data exist only at gravity levels of unity and zero, we have no understanding of the shape of the response curve or the need for or effectiveness of countermeasures along it. The Moon can illuminate the bottom half of this range; Mars will someday illuminate the upper half to complete our understanding of how biological systems behave and adapt to the fundamental parameter of gravity. Countermeasures that may be applicable to Mars surface missions can be developed and tested for long durations on the Moon.

The lunar surface provides a unique observational vantage point. Earth observation from nearside non-polar locations, albeit enabling lower-resolution than from GEO with comparable optics, would be synoptic and non-synchronous. Given human presence, some optical astronomy (e.g., with serviceable segmented optics) could take advantage of the stable, airless conditions. Most interesting would be radio astronomy conducted from farside locations that are permanently shielded from terrestrial radio transmissions. In particular, low-frequency radio is a virtually unexplored region of the electromagnetic spectrum because it is attenuated by Earth's atmosphere and requires simple but very large antenna arrays.

B. Using the Moon to Manage Risk

Missions to NEOs, or the vicinity or surface of Mars, would impose quite long durations—one to three years—far from Earth with no option for contingency return, and with severely limited opportunities for resupply of spares and other logistics for maintenance and repair. Understanding beforehand how human-support, spacecraft, and propulsion systems will perform on such missions is problematic, yet also key to achieving a balance among risk, performance, and cost. Lunar surface missions could be used to build confidence in human and system performance for long-duration deep-space missions, and particularly for surface operations.

Extended-duration lunar surface mission experience could provide data vital for reducing Mars mission risk compared to scenarios lacking the lunar step. Each stage of human expansion into the solar system will include rigorous testing before committing human crews to deep space. But such tests are always compromised by conditions different from actual use, including partial integration, shorter duration, and non-identical environments. No exploration system test plan could anticipate or accurately replicate the full complexity of the actual mission, so the risk of "unknown-unknowns" will remain. While the Moon is not the same as Mars, it is a far better analogue than Antarctica, and a lot closer than Mars. Lunar mission capability could be a key confidence builder enroute to Mars.

C. Lunar Mission Legacy

Viewed strategically, many lunar systems could be analogues, prototypes, or even subscale implementations of Mars-class flight systems. This would not only help manage the risk of future missions but also help manage their cost by reducing costly duplication or late surprises. Areas with the best Mars-forward synergy include: (1) crew health and performance including radiation protection techniques; long-duration reduced-gravity crew performance; advanced, highly reliable, and maintainable life support; extra-vehicular activity; and advanced habitation systems; (2) surface mobility and regolith handling; (3) terminal descent and landing including deep-throttling chemical propulsion, precision landing, hazard avoidance, and exhaust plume cratering; (4) advanced surface power including fission power generation, setup, and shielding; and efficient power management and distribution including transmission; (5) infrastructure and integrated systems including high-data-rate and delay-tolerant communications; dust mitigation; ascent propulsion including use of locally-produced oxygen; and supportability and maintenance approaches. In the extreme, lunar surface missions could include Mars mission "dry runs" to test systems embedded into integrated concepts of operation (i.e., autonomy, maintenance, repair, scientific investigations, protocols, timelines, and contingencies) for the extended operations needed for Mars surface exploration. Whatever degree of extended lunar surface operations we may choose to afford and conduct would "burn down" risk for our horizon destination Mars.

VIII. Assembling a Program

The illustrative missions outlined above demonstrate that missions other than traditionally-envisioned surface exploration of the Moon and Mars might also be inspiring, worthy, and useful. A Flexible Path program strategy would divide the enormous challenge of humans-to-Mars into stepwise achievements, using a series of fascinating, productive missions to cumulatively build up systems, experience, and confidence. Major milestones would occur both in the near term and continually along the way, helping to sustain public interest and political support.

More than one program plan can be developed using these mission classes. Indeed multiple pathways can "connect the dots" in an FP strategy, providing decision flexibility deep into the future. Figure 14 shows a representative program map to illustrate these principles. The main conceptual path is shown in blue in the center, beginning with ISS operations and leading to Mars. Alternative missions supporting and supported by these capability levels are shown below the main path, indicating a rich set of mission objectives for future Administrations to choose from and "own" during their tenure, but all of which move forward to Mars. Across the top are stepwise increments in technologies and systems required to enable each capability level. Dotted lines show flexibility in the timing of individual elements. For example, a one-year-capable Deep-Space Habitat system is not needed for EM L1-class missions, but could be tested on them. Similarly, a Heavy Lift Launch vehicle is not needed to enable EM L1-class missions or even NEO missions, so it could be deferred. Finally, notable "headline" achievements that could measure the cadence of advancement toward Mars exploration are indicated at the bottom.

Other maps are possible; the complete set of possibilities and interconnections is large. Comparing and selecting among them hinges on many factors, only some of which are technical-performance or cost-budgeting factors

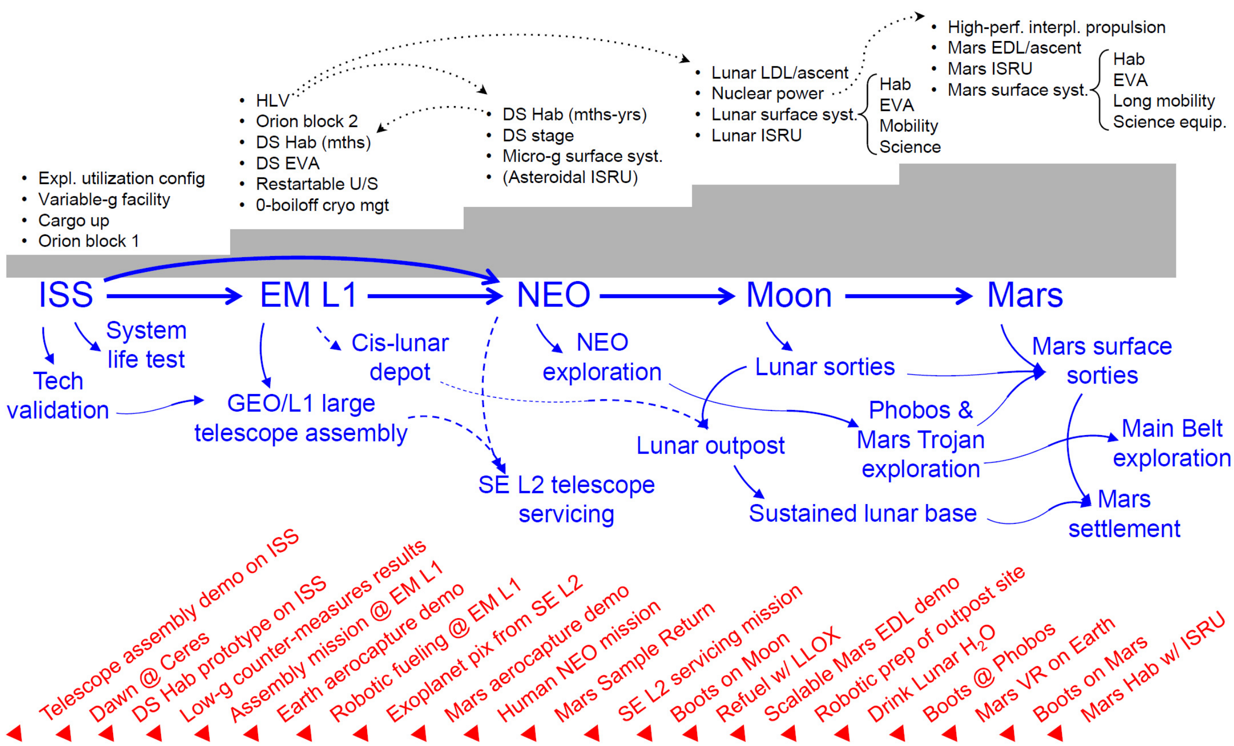

Figure 14. Candidate NEO-precedence roadmap shows how a series of destination classes opens many types of mission (blue), requires cumulative investments (black), and yields notable achievements (red). Dotted lines indicate flexibility of specific mission, precedence, and timing choices within the overall strategy.

historically used in NASA exploration architecture development. For example, consider the following candidates for measurable program characteristics:

1. **Clarity of a multi-generational, multi-stakeholder "grand strategy"—**A comprehensive roadmap of destinations, paths, and needs would help explain how decisions are made and how each project fits into the big picture.
2. **Frequent "firsts" and few "thirds"—**Unprecedented, breakthrough achievements make participating nations proud and demonstrate forward progress; too many "repeats" lose public attention.
3. **Frequent project onramps so inspired kids join the space workforce later**—Smaller, more frequent projects provide a succession of opportunities so inspired children can follow their dreams by entering our professional workforce.
4. **Constant new technology development to exercise NASA workforce**—Challenging NASA and industry workers with a steady pace of hard, new problems.
5. **Visible achievements for each Administration**—Pace of decisions, and pace of accomplishments, rapid enough to be visible on timescales of four years.
6. **Reset-tolerance via multiple paths**—Ability to make progress on the grand strategy even as individual projects are reoriented or canceled by contemporary policymakers.
7. **Diverse international and commercial opportunities**—"Hooks" for meaningful participation and contribution by non-NASA entities including other space agencies, other government agencies, and for-profit entrepreneurs.
8. **New industries created**—Enablement of brand new industries as a result of government investment clearing the way or establishing proof of capability, e.g., satellite servicing; LEO fueling, servicing, and hospitality; lunar mining.

Considering such "extrinsic" metrics can help shape a multi-decade program that works and that lasts. A Flexible Path strategy asks stakeholders to subsume their enthusiasm for any given technology, system project, or mission into a sustained, overall support for the "bigger picture."

Out of a rich discussion of FP possibilities can arise consensus on investments that could be started soon because they share relevance across many path options. Fundamental capabilities—like the use of ISS as an exploration systems testbed, robotic precursors to answer key unknowns about deep-space destinations, a deep-space habitat system, a way to get crews up from Earth and back down, a heavy-lift rocket optimized for cost, and a reusable in-space propulsion stage—may be common enough to warrant near-term development priority even as the overall plan is formulated.

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