By adapting ideas from robotic planetary exploration, the human space program could get astronauts to asteroids and Mars cheaply and quickly

By Damon Landau and Nathan J. Strange

Being there: An asteroid, Mars's moon Phobos and the Red Planet's surface are all on the proposed itinerary. The moons are exaggerated in this artist's fanciful conception.

Illustration by Patrick Leger

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IN OCTOBER 2009 A SMALL GROUP OF ROBOTIC SPACE EXPLORAtion geeks decided to venture out of our comfort zone and began brainstorming different approaches to flying people into space. We were spurred into action when the Augustine commission, a blue-ribbon panel that President Barack Obama set up earlier that year to review the space shuttle and its intended successor, reported that "the U.S. human spaceflight program appears to be on an unsustainable trajectory." Having worked in an exciting robotic exploration program that has extended humanity's reach from Mercury to the edge of the solar system, we wondered whether we might find technical solutions for some of NASA's political and budgetary challenges.

Ideas abounded: using ion engines to ferry up the components of a moon base; beaming power to robotic rovers on the Martian moon Phobos; attaching high-power Hall effect thrusters to the International Space Station (ISS) and putting it on a Mars cycler orbit; preplacing chemical rocket boosters along an interplanetary trajectory in advance so astronauts could pick them up along the way; using exploration pods like those in *2001: A Space Odyssey* rather than space suits; instead of sending astronauts to an asteroid, bringing a (very small) asteroid to astronauts at the space station. When we crunched the numbers, we found that electric propulsion—via an ion drive or related technologies—could dramatically reduce the launch mass required for human missions to asteroids and Mars.

It was like being back in the NASA of the 1960s, minus the cigarette smoke. We talked about what we can do and avoided getting mired in what we cannot. After our initial analysis, we put together a lunchtime seminar for our colleagues at the NASA Jet Propulsion Laboratory (JPL) that synthesized these notions and calculations. Throughout the following spring and summer we met other engineers and scientists who were interested in our approach and gave us ideas to make it better. We learned about experiments that people inside and outside NASA had been conducting: from tests of powerful electric thrusters to designs for lightweight, high-efficiency solar arrays. Our discussions have grown and become part of a larger groundswell of inventive thinking across the space agency and aerospace industry.

We have now combined the most promising proposals with tried-and-true strategies to develop a plan to send astronauts to the near-Earth asteroid 2008 EV5 as soon as 2024 as preparation for an eventual Mars landing. This approach is designed to fit within NASA's current budget and, crucially, breaks the overall task into a series of incremental milestones, giving the agency flexibility to speed up or slow down depending on funding. In a nutshell, the aim is to apply lessons from the robotic scientific exploration program to renew the human exploration one.

SMALL STEPS MAKE A GIANT LEAP

THE AUGUSTINE COMMISSION's report ignited a mighty political fight, culminating in the decision to delegate much of the task of launching astronauts into orbit to private companies [see "Jump-Starting the Orbital Economy," by David H. Freedman; SCIENTIFIC AMERICAN, December 2010]. NASA can now focus on

IN BRIEF

Space policy in the U.S. has gone through an upheaval. NASA has retired the shuttle, given up the Constellation program that was to have replaced it and outsourced orbital launches. It is supposed to return to what it does best—going where no one has gone before. But how?

The authors argue that engineers need to assume that the political process will continue to be unpredictable—and plan for it. They must design mission options that can be ramped up or down as circumstances change.

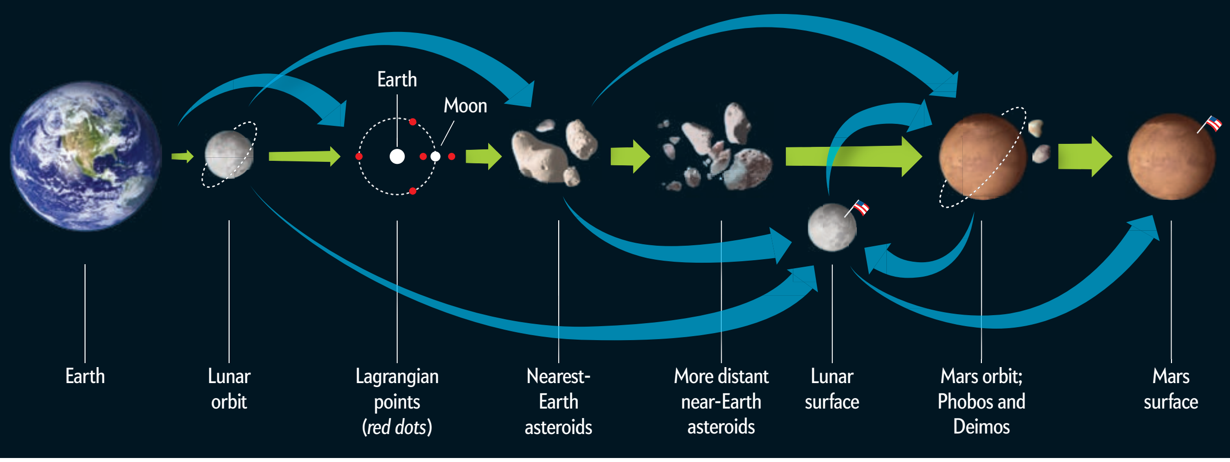
Deep-space vehicles propelled by ion drives can mount progressively more complicated expeditions to lunar orbit, near-Earth asteroids and eventually Mars.

The views expressed in this article are those of the authors, not NASA or JPL.

FLEXIBLE PATH

More Than One Way to Reach into Space

In the past the U.S. human space program took an all-eggs-in-one-basket approach: it focused on a specific target and a single system to get there. As of last year, it does things differently. It now has the broad goal of venturing into interplanetary space in progressively more complicated missions, such as the authors' proposed program (*green arrows*) and variants (*blue arrows*). The destinations are listed here in rough order of difficulty. Vehicles can be repurposed to reach different destinations, follow different sequences or use different technologies if technical problems arise or politicians fail to come through with the required funding.



transformative technology and push human exploration on to new frontiers. But how can the agency move forward without the political support and resources it enjoyed during the glory days of the Apollo moon landings?

The established approach in robotic exploration is incremental: develop a technology portfolio that enables increasingly ambitious missions to take place. Rather than relying on an all-or-nothing development path to a single target, the robotic exploration program makes use of novel combinations of technology to reach a variety of targets. To be sure, the robotic program has suffered its own mistakes and inefficiencies; nothing is perfect. At least it does not grind to a halt when the political winds change or when technological innovation lags. The human program can borrow from this strategy. It need not commence with "one giant leap" as with Apollo. It can embark on a series of modest steps, each building on the one before.

For some, the real lesson of robotic exploration might be that we should not send people at all. If NASA's only goal was scientific discovery, robotic probes would certainly be cheaper and lower risk. Yet NASA is tasked with more than just science; science is only one aspect of a broader human impulse to explore. Space exploration has wide appeal because of a desire for ordinary people to experience it firsthand someday. Robotic probes are just the first wave of solar system exploration. Government-funded human missions will be the second wave, and the third will be private citizens seeking their fortune and adventure in space. NASA's past investments developed the technology that is fueling today's commercial space race, with capsules launching to the space station and space planes jetting over the Mojave Desert [see "Blastoffs on a Budget," by Joan C. Horvath; Scientific American, April 2004]. NASA can now develop the technology that we will need to push deeper into the beyond.

FLEXIBILITY IS THE WATCHWORD

THREE BASIC PRINCIPLES govern the course we recommend. The first is the "flexible path" approach that the Augustine commission advocated and that President Obama and Congress accepted. This strategy replaces the old insistence on a fixed path from Earth to moon to Mars with an extensive selection of possible destinations. We would begin with nearby ones, such as the Lagrangian points (locations in space where an object's motion is balanced by gravitational forces) and near-Earth asteroids.

The flexible path calls for new vehicle technologies, notably electric propulsion. We propose using Hall effect thrusters (a type of ion drive) powered by solar panels. A similar system propelled the Dawn spacecraft to the giant asteroid Vesta and will, by 2015, carry it onward to the dwarf planet Ceres [see "New Dawn for Electric Rockets," by Edgar Y. Choueiri; Scientific American, February 2009]. Whereas traditional chemical rockets produce a powerful but brief blast of gas, electric engines fire a gentle but steady stream of particles. Electric power makes the engines more efficient, so they use less fuel. (Think space Prius.) Because the price of this greater efficiency is lower thrust, some missions can take longer. A common misperception is that electric propulsion is too slow for crewed spaceflight, but there are ways around that. The idea that emerged at our first brainstorming session was to use robotic electric propulsion tugs to place chemical boosters at key points in a trajectory like a trail of bread crumbs; once the trail is laid, astronauts can set out and pick up the boosters as they go along. In this way, missions get the fuel efficiency of electric propulsion while keeping the speed advantage of chemical propulsion.

Crucially, electric propulsion saves money. Because the ship does not need to lug around as much propellant, its total launch mass drops by 40 to 60 percent. To first order, the price tag of

MODIFIED FROM NASA'S REVIEW OF U.S. HUMAN SPACE FLIGHT PLANS COMMITTEE; NASA (*Earth, moon and Mars*)

Illustration by Pitch Interactive

space missions scales linearly with the launch mass. Thus, slimming the mass by half could cut the cost by a similar fraction.

Many space enthusiasts wonder why we would bother visiting an asteroid when Mars is everyone's favorite destination. Actually asteroids are the perfect targets for an incremental approach toward reaching Mars. Thousands are sprinkled through the gap between Earth and Mars, providing literal steppingstones into deep space. Because asteroids' gravity is so weak, landing on one takes less energy than reaching the surface of the moon or Mars. It is hard enough to mount a long interplanetary expedition—six to 18 months—without also having to develop elaborate vehicles to touch down and blast off again. Asteroid missions let us focus on what, in our estimation, is the most complex (and still unsolved) problem for humans ever to venture far from Earth: learning how to protect astronauts from the deleterious effects of zero gravity and space radiation [see "Shielding Space Travelers," by Eugene N. Parker; Scientific American, March 2006]. As NASA gains experience dealing with the hazards of deep space, it will be in a better position to design vehicles for Mars surface missions.

Several scientifically interesting asteroids could be visited by astronauts with flight times ranging from six months to a year and a half using a 200-kilowatt (kW) electric propulsion system, which is a reasonable advance over our present capability; the ISS currently has 260 kW of solar arrays installed. Such a mission would break the deep-space barrier, while taking a crucial step toward the two- to three-year flight times and 600-kW systems that would be needed for Mars exploration.

To get to an asteroid, NASA does not have to invent completely new systems for everything, as it did in the 1960s.

The second governing principle of our plan is that NASA does not have to invent completely new systems for everything as it did in the 1960s. Some systems, most notably zero-g and deep-space radiation protection, will require new research. Everything else can derive from existing spacefaring assets. The deep-space vehicle can be assembled by combining a few specialized elements. For instance, the structure, solar arrays and life-support systems could be adapted from designs that have been implemented on the space station. And many private companies and other nations' space agencies have expertise in these areas that NASA could tap.

The third principle is to design a program that can maintain forward momentum even if one component runs into problems or delays. This principle should be applied to the most debated component of the space policy adopted by Congress: the launch vehicle that will ferry the crew and exploration vehicles from the surface of Earth into orbit. Congress directed NASA to build a new heavy-lift rocket, the Space Launch System (SLS). As announced this past September, NASA plans to develop this vehicle in steps starting at roughly half the capacity of the Apollo Saturn V and working up to just beyond the full launch capability of that rocket. The first SLS launcher, plus the *Orion* capsule now in the works, could carry astronauts on three-week excursions to lunar orbit and the Lagrangian points but can take astronauts no farther without the development of a new system.

Fortunately, journeys to deep space do not need to wait for the SLS to be completed. Preparations could begin now with the development of the life-support and electric propulsion systems that will be needed for trips beyond the moon. By making these systems an early priority, even while the new rockets are still under development, NASA would be better able to refine details of the SLS design to make it better suited to deep-space missions. These components could even be designed to fit on commercial or international launchers and then assembled in orbit, just as the ISS and the *Mir* space station were. The use of existing rockets would generate momentum toward deep-space exploration. With the flexibility from a portfolio of options, NASA could fit more exploration into its increasingly limited budget.

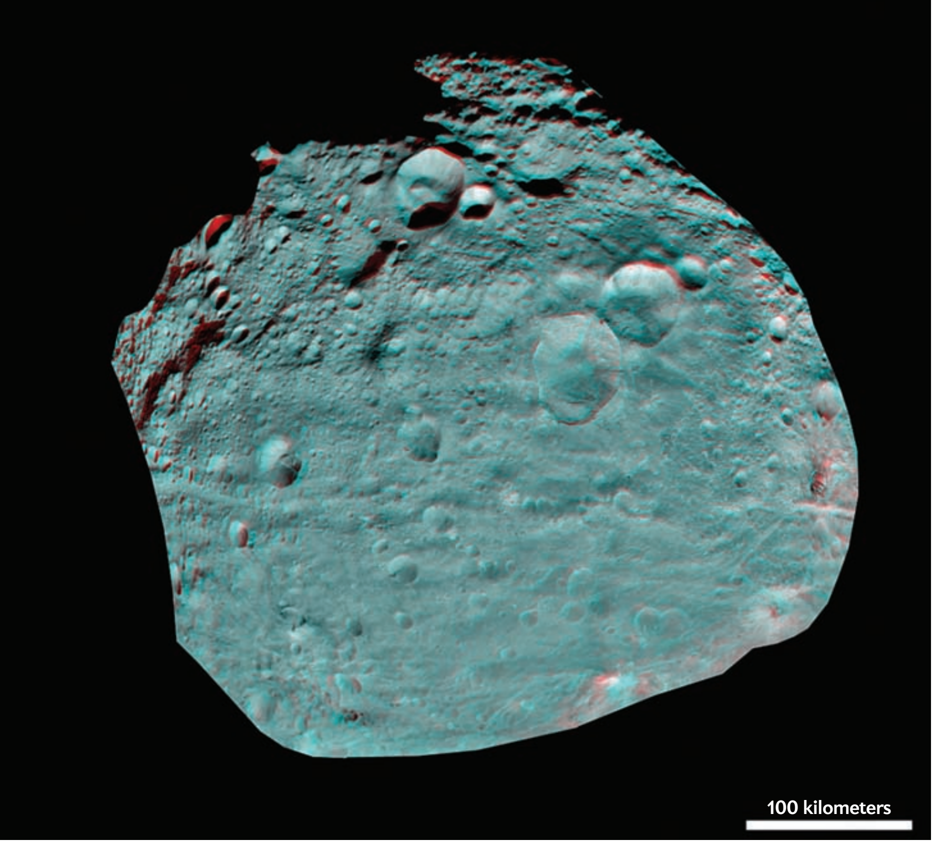
MISSION: 2008 EV5

In our plan, NASA's renaissance begins by constructing the means for people to travel between the planets—the deep-space vehicle. A solar-powered ion drive provides the oomph, and a new transit habitat provides a safe haven away from home. The most basic deep-space vehicle would consist of two modules that could both be lofted into low Earth orbit with a single launch of the smallest of NASA's new SLS rockets. Alternatively, three commercially available rockets could do the trick, two for the vehicle components and one with supplies for the trip.

The maiden voyage is, ironically, its most boring. For two years the ship, without crew, is remotely piloted to follow a slow spiral from low Earth orbit through the Van Allen radiation belts and up to a high Earth orbit—a trip that goes easy on propellant but is too long and radioactive for astronauts. Once the spaceship is poised on the outer edge of Earth's gravity well, just one push away from interplanetary space, it can undertake lunar flybys and other maneuvers to reshape the orbit for efficient departure. The astronauts then fly up from the ground on a conventional chemical booster.

For a test flight, astronauts steer the vehicle into an orbit that almost always remains above the south pole of the moon. From there they could control a fleet of robotic explorers and investigate the composition of ancient ice deposits in the forever-dark craters of the Aitken basin. Such a mission puts long-duration exploration through its paces with the safety of Earth just a few days away. After the crew returns to Earth, the deep-space vehicle remains in high Earth orbit, awaiting refueling and refurbishment for its first asteroid mission.

We have investigated a wide range of such missions. Some would take astronauts to small objects (less than 100 meters across) just beyond the moon and back to Earth in under six months. Others would venture to large objects (bigger than a kilometer) almost out to Mars and back in two years. Focusing only on an easier mission could stunt exploration by setting a dead end for technological capability. Conversely, striving for a harder mission could perpetually delay any meaningful exploration by setting targets too far out of reach. Our design baseline falls between these two extremes. It is a one-year round-trip that launches in 2024, with 30 days spent exploring asteroid 2008 EV5. This object, about 400 meters across, appears to be a type of asteroid of great interest to many planetary scientists—a type C carbonaceous asteroid, a possible relic from the formation of the solar system and perhaps representative of the original source of Earth's organic material.



Asteroid Vesta is currently being orbited by NASA's Dawn robotic spacecraft. The mission is remarkable for using hyperefficient ion engines, as human interplanetary missions someday could. (You can use red-blue glasses to view this image in 3-D.)

COURTESY OF NASA/JPL-CALTECH/UCLA/MPS/DLR/IDA

The most efficient way to get there is to use Earth's gravity for an old trick known as the Oberth effect. It is the reverse of the orbit-insertion maneuvers that robotic space probes routinely undertake. To prepare for it, mission controllers outfit the deep-space vehicle with a high-thrust chemical rocket stage, carried up from Earth by an electrically propelled resupply tug. After the stage is attached and the crew is onboard, the deep-space vehicle free-falls from the vicinity of the moon down to just above Earth's atmosphere to build up tremendous speed. Then, at just the right moment, the high-thrust stage fires, and the vehicle frees itself from Earth's grasp in a matter of minutes. This maneuver works best at the moment when the vehicle is traveling at top speed near Earth because the amount of energy the ship gains is proportional to how fast it is already traveling. The Oberth effect is an exception to the rule that ion drives are more efficient than chemical rockets; you need a lot of thrust, quickly, to take full advantage of the gravitational kick start from Earth, and only high-thrust rockets can provide it. Together the ion-propelled spiral and chemical-powered Oberth effect cut the amount of fuel it takes to escape Earth's gravity by 40 percent compared with an all-chemical system.

Once the astronauts escape Earth, the Hall effect thrusters turn on and steadily push the vehicle toward its destination. Because ion drive provides continuous thrust, it lends itself to flexibility. Mission planners can develop a robust set of abort trajectories should a malfunction occur at any point in the mission. (The Japanese robotic asteroid mission Hayabusa was able to recover from several mishaps because of its ion drive.) If technical or budgetary problems prevent us from getting the deep-space vehicle ready in time to reach the asteroid 2008 EV5, we can choose another target. Likewise, if we encounter technical difficulties, we will improvise. For instance, if high-performance propellants are too hard to store in deep space, we can switch to lower-performing propellants and revise the mission accordingly. Nothing in the mission is locked in.

THE PLUSES OF PODS

IN OUR PLAN, the astronauts have a month at the asteroid for exploration. Rather than donning space suits, they can take a lesson from deep-sea submersibles and use exploration pods. Space suits are basically big balloons, and an astronaut constantly fights air pressure for every little movement, making space walks hard work and limiting what can be accomplished. A pod with robotic manipulator arms not only alleviates this problem but also provides room to eat and rest. In a pod, an astronaut could zip around for several days at a time. NASA is already developing a Space Exploration Vehicle (SEV) that can be used as a pod at asteroids, and the same design could later be adapted for a surface rover for the moon and Mars.

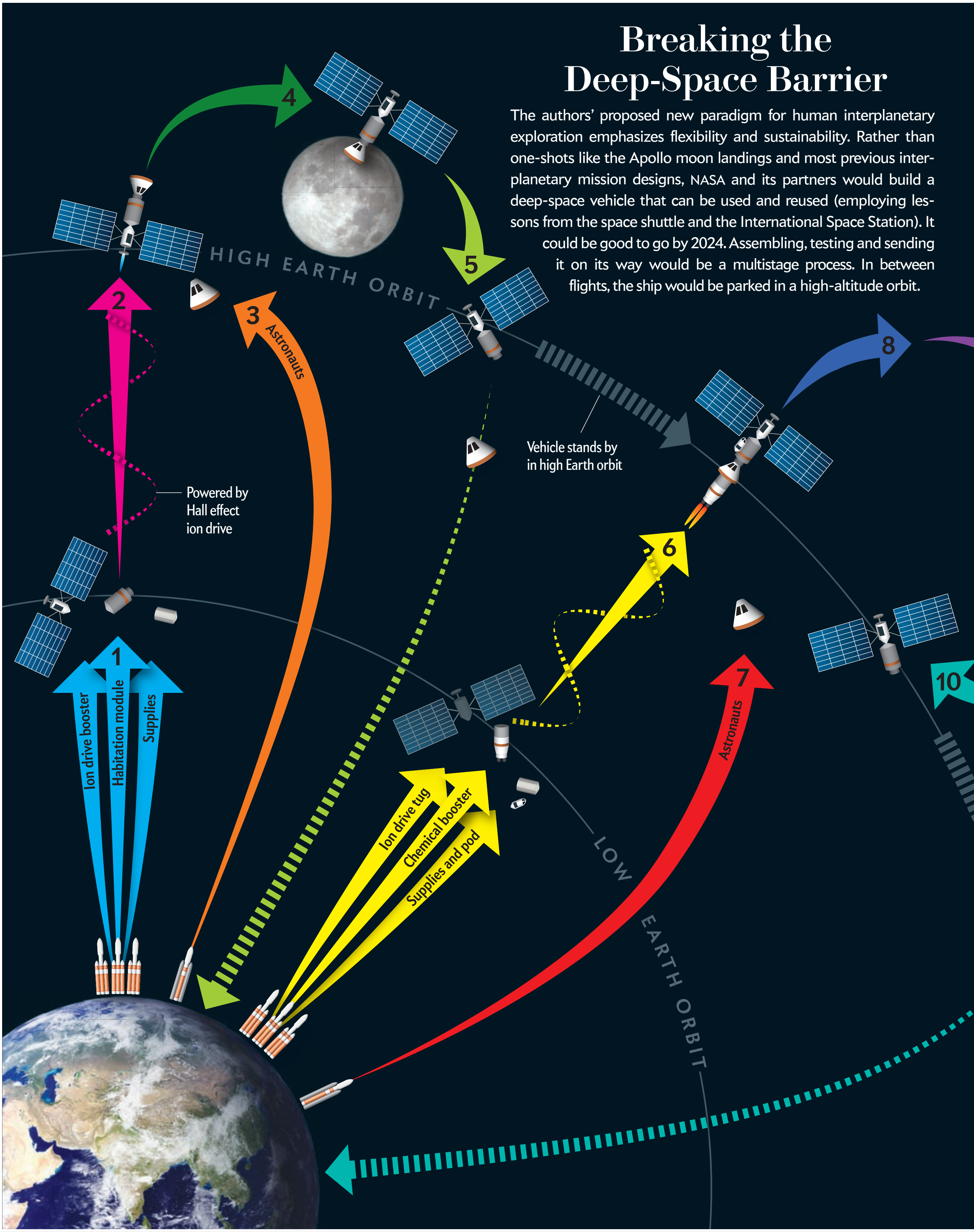
The astronauts conduct a full survey, looking for unusual mineral outcrops and other promising places to dig for samples that might date to the earliest days of the solar system. NASA will want to send a crew that is half Indiana Jones and half Mr. Scott: astronauts with both the scientific background needed to spot precious samples hidden in the dust and the engineering background needed to fix any problems along the way.

When the month is up, the ion drive nudges the deep-space vehicle away from the asteroid and onto a six-month trajectory back home. A few days before reaching Earth, the crew climbs into a capsule, separates from the main ship and sets course to splash down. The empty deep-space vehicle remains on an orbit around the sun. It performs a flyby of Earth and continues thrusting with the ion drive to lower its energy with respect to the Earth-moon system, so that when it comes back to Earth a year later, it can use a lunar flyby to reenter high Earth orbit and await its next mission. Its ion drive and habitat module could be reused multiple times.

After several yearlong asteroid missions, incremental improvements to life-support systems and radiation shielding will pave the way to Mars. The first Mars mission might not actually touch down on the planet. Instead it will likely explore its two moons, Phobos and Deimos [see "To Mars by Way of Its Moons," by S. Fred Singer; SCIENTIFIC AMERICAN, March 2000]. Such an expedition is essentially an asteroid mission stretched out to a two-and-a-half-year round-trip. At first glance, it might seem silly to go all the way to Mars and not land on it, but landing would enormously complicate the mission. Missions to the Martian moons allow astronauts to become adept at traveling through interplanetary space before attempting the challenge

Breaking the Deep-Space Barrier

The authors' proposed new paradigm for human interplanetary exploration emphasizes flexibility and sustainability. Rather than one-shots like the Apollo moon landings and most previous interplanetary mission designs, NASA and its partners would build a deep-space vehicle that can be used and reused (employing lessons from the space shuttle and the International Space Station). It could be good to go by 2024. Assembling, testing and sending it on its way would be a multistage process. In between flights, the ship would be parked in a high-altitude orbit.



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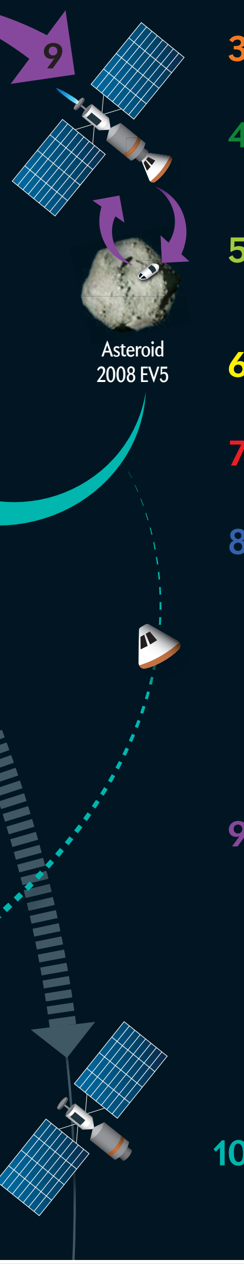
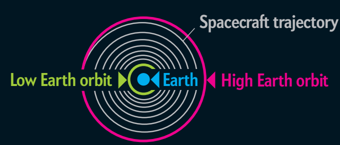


1 Two modules—the solar-powered ion drive and the transit habitat—are launched separately into low Earth orbit onboard existing government or commercial rockets, such as the Delta IV Heavy. Ground controllers remotely assemble them into a kind of mini space station. A third launch lays in supplies for the journey ahead.

2 Ion drive is too weak to break out of Earth orbit in one shot but slowly pushes the ship outward like a car switchbacking up a mountain. To avoid the radiation and boredom of the two-year trip, the astronauts do not need to be onboard yet.



3 Once the ship has reached an extremely high altitude orbit, with almost enough energy to escape Earth's gravity, the astronauts fly up on a small, fast rocket.

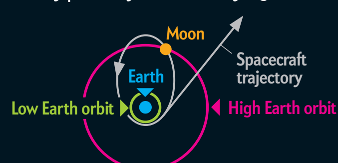
4 To put the ship through its paces, the astronauts steer it into a lunar orbit. Though mainly an engineering test flight, this voyage would also let the astronauts do some useful science, such as remote-controlling a fleet of rovers.

5 After a test flight of, say, six months, astronauts steer the deep-space vehicle back into a high Earth orbit, then continue back to Earth and splash down in an *Apollo*-style capsule.

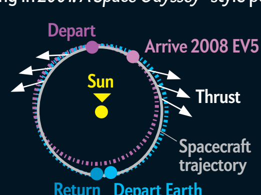
6 To prepare for breaking out of Earth orbit, ground controllers send up fresh supplies and a small chemical rocket booster using an ion-propelled interorbital tug.

7 Once the stage is attached to the deep-space vehicle, another crew of astronauts flies up on a conventional rocket, as before.

8 The deep-space vehicle moves into a highly elliptical orbit and, at the moment it is closest to Earth, fires the booster—thereby reversing the orbit-insertion maneuver routinely used by planetary orbiters. Away it goes.



9 Ion drive takes over and slowly pushes the ship toward its first target, perhaps asteroid 2008 EV5. The outbound trip takes six months. The crew spends a month exploring in *2001: A Space Odyssey*–style pods.



10 The ship turns on its ion drive and heads home. Six months later the crew splashes down in the capsule it used to fly up. The ship is remote-piloted back to high Earth orbit using gravity-assist maneuvers.

NASA (Earth and moon)

of touching down on Mars, traveling around and lifting off again.

Engineers have already come up with various tactics to maximize the flexibility and minimize the cost of a Mars surface mission. The most compelling begin by preplacing habitats and exploration systems on the surface so that the astronauts have a base ready for them when they arrive. This equipment can go by slow (ion) boat. Once there it will produce propellant on Mars itself, either by distilling carbon dioxide from the atmosphere and mixing it with hydrogen brought from Earth to generate methane and oxygen or by electrolyzing water from the permafrost to make liquid hydrogen and oxygen. By sending an empty return rocket that can be fueled in situ, mission planners reduce the launch mass from Earth dramatically [see "The Mars Direct Plan," by Robert Zubrin; Scientific American, March 2000].

The relative motion of Earth and Mars gives the astronauts about one and a half (Earth) years on the surface before the planets come back into alignment, so they will have plenty of time to reconnoiter. At the end of their stay, they board a launch vehicle filled with locally manufactured fuel, blast off to Mars orbit, rendezvous with a deep-space vehicle derived from the asteroid campaign and return to Earth. The vehicle could even be placed on a cycler trajectory that shuttles back and forth between Earth and Mars, using gravity slingshots to provide all the propulsion for free [see "A Bus between the Planets," by James Oberg and Buzz Aldrin; Scientific American, March 2000].

Even with the advance placement of matériel, a Mars lander and return rocket are extremely heavy and will need the largest planned SLS launcher to send them on their way. But the first deep-space missions can be built from smaller parts that are launched on the first SLS or even on existing rockets. The gradualist approach we recommend will maximize the resilience of the program and let NASA concentrate on solving the truly hard problems, such as radiation shielding.

NASA now has the best opportunity in a generation to refocus itself on new types of space vehicles that reach into interplanetary space. The greatest barriers to space exploration are not technical but a matter of figuring out how to do more with less. If NASA plans an incremental sequence of technology development and missions of steadily increasing ambition, human spaceflight can break free of low Earth orbit for the first time in 40 years and enter its most exciting era ever. With flexible planning, NASA can forge a path to wander among the wandering stars. SA

MORE TO EXPLORE

Plymouth Rock: An Early Human Mission to Near Earth Asteroids Using Orion Spacecraft. J. Hopkins et al. Presented at the AIAA Space 2010 Conference & Exposition, August 30–September 2, 2010. http://tinyurl.com/PlymouthRockNEO

Target NEO: Open Global Community NEO Workshop Report. Report of a workshop held at George Washington University, February 22, 2011. Edited by Brent W. Barbee. July 28, 2011. www.targetneo.org

Near-Earth Asteroids Accessible to Human Exploration with High-Power Electric Propulsion. Damon Landau and Nathan Strange. Presented at the AAS/AIAA Astrodynamics Specialist Conference, Girdwood, Alaska, July 21–August 4, 2011. http://tinyurl.com/ElectricPath

300-kW Solar Electric Propulsion System Configuration for Human Exploration of Near-Earth Asteroids. J. R. Brophy et al. Presented at the 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, San Diego, July 31–August 3, 2011. http://tinyurl.com/300kWSEP

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