3 A BUS BETWEEN THE PLANETS

Gravity-assist trajectories between Earth and Mars would reduce the cost of shuttling human crews and their equipment, say James Oberg *and* Buzz Aldrin

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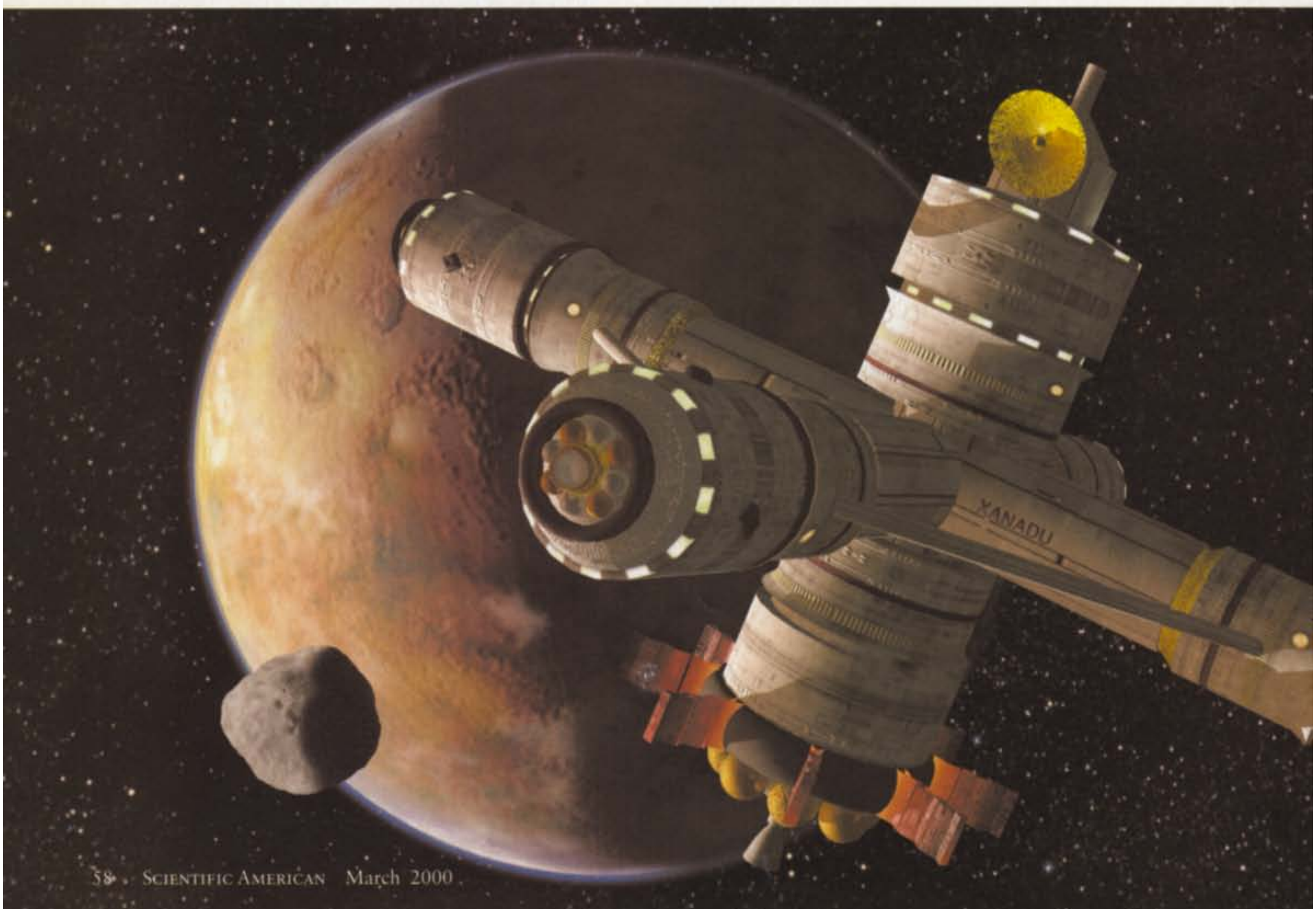
Chemical rockets have served humankind well in its first, tentative steps into space. Having ridden atop them to the moon and back, one of us (Aldrin) can vouch for the technology's merits. Nevertheless, for trips beyond our nearest neighbor in space, chemical rockets alone leave much to be desired.

Even Mars, the next logical destination in space, would be a stretch for chemical rockets. To deliver a human crew to the planet would require so much fuel that essentially all scenarios for such a voyage involve producing, on the planet's surface, large amounts of fuel for the return trip. That requirement adds another element of risk and complexity to the proposed mission. Much more powerful plasma rockets, on the other hand, are still probably a decade away from use on a human-piloted spacecraft.

We think there is a middle ground: using chemical rockets and augmenting their modest propulsive power by taking creative advantage of gravity-assist maneuvers. In these excursions, mission planners send a spacecraft hurtling so close to a celestial body, typically a planet, that the body's gravitational field changes the spacecraft's velocity. The scheme is commonly used to boost the speed of a probe headed toward the solar system's outer planets, which would otherwise be all but unreachable. Mission controllers began using gravity assists in the 1970s on such missions as Mariner 10 to Mercury, which got an



assist from the Venusian gravitational field; Pioneer 11 to Saturn, which flew by Jupiter; and Voyager 1, catapulted by Jupiter's prodigious gravitational field and now hurtling through interstellar space at 62,000 kilometers per hour. Even though there are no sizable celestial bodies between Earth and Mars, a mission between the two planets can still be executed so as to benefit significantly from their gravity.

Boing!

A gravity-assist maneuver can be likened to a rubber ball bouncing off a wall. In this analogy, the spacecraft is like the rubber ball, and the planet is like the wall. As the ball bounces off the wall, the bounce-off velocity will be higher or lower if the wall is moving toward or away from the ball as they meet. The mathematical relation is described by a fundamental principle of Newtonian physics: conservation of momentum. The change in the ball's momentum is balanced by an inverse change in the wall's momentum.

In a gravity assist, the spacecraft "collides" elastically with the planet's gravitational field. If the planet is moving into the arc of the spacecraft's trajectory as the craft flies by the planet, the "rebound" speed of the vehicle will be higher than its approach speed. As with the ball bouncing off the wall, momentum is conserved: the planet's momentum changes as much as the spacecraft's. Because of the immense difference in their masses, though, the planet's velocity change is not significant.

The more massive the planet, the more sharply it can alter the spacecraft's trajectory. Jupiter, the most massive planet in the solar system by far, can effect a change as great as 160 degrees in a vehicle's direction relative to the planet. Not only can mission controllers change the spacecraft's speed and direction within the orbital plane, they can also put the craft in a new orbital plane quite different from that of the planet's orbit around the sun.

How can gravity assist help transport people to Mars? The answer is that it would be used to make critical adjustments to the trajectories of "cycler" spacecraft. These would use the gravity of Earth and Mars as the primary shaper of their trajectories as they cruised back and forth repeatedly, like buses on a scheduled route, shuttling crews and supplies between the two planets. Typically the cycler would not have to be decelerated into orbit around Mars, and it would never have to blast off the planet's surface for the return to Earth. The basic concept goes back more than three decades but continues to produce novel mission strategies, ones that we believe merit more attention than they generally receive in discussions of human missions to Mars.

The gravity-assist cycler approach is attractive because it would minimize the need for propulsive maneuvers. Because of the massive life-support equipment that would be required to sustain humans on an interplanetary voyage, huge quantities of rocket fuel would be required for each such maneuver [see "How to Go to Mars," on page 44].

Castles in the Firmament

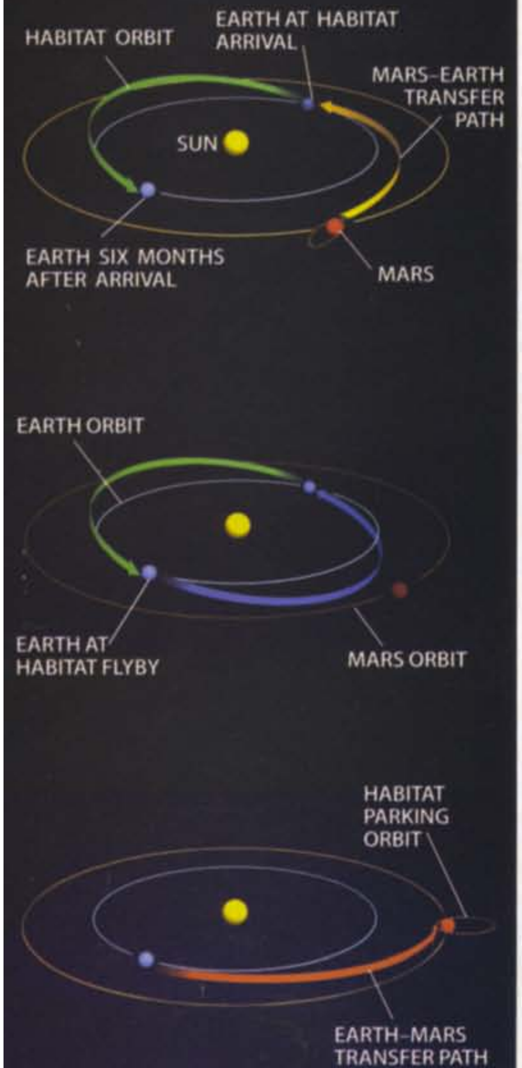
The cycler concept goes back to the early 1980s. Alan L. Friedlander and John C. Niehoff, both then with Science Applications International, described a system in which several long-lived space habitats (which they called castles) would be placed in solar orbits that would periodically approach Earth and Mars. Human crews would occupy these castles during the interplanetary cruise, which would last two or more years. Then, during the encounters with Mars or Earth, the travelers would make use of more spartan vehicles ("taxis") to go back and forth between a castle and a planet. The castles would be resupplied using propulsion technologies, such as ion drive, that are highly efficient but too slow for human passengers. The trip on board the taxi between a castle and a planet would take about a week or less.

As originally conceived, the castles would orbit the sun in such a way that they would encounter Earth about once every five years and Mars every 3.75 years. In a second proposal the habitats would encounter Earth every three years and Mars every 7.5 years. Neither of these orbits would have been significantly modified by the planetary encounters. Thus, gravity assist was not a factor in these early concepts.

In 1985 Aldrin proposed a cycling habitat orbit that would make crucial use of gravity assist during each Earth flyby. These castles would also circle the sun, but the strategy would speed up the interplanetary transit time by exploiting orbits whose farthest point from the star (or aphelion) would be well beyond Mars. A major advantage of this scheme is that the habitats would encounter each planet every 2.7 years, and the planet-to-planet transit time would be as little as six months. A drawback would be that periodic propulsion maneuvers would be needed to keep the cycling habitat in this advantageous orbit. Because these maneuvers would not be time-critical, however, they could be performed by high-efficiency, low-thrust propulsion systems.

Moreover, one of the most critical maneuvers would be accomplished largely by gravity assist. The interval separating encounters between the habitat and Mars would not be an exact, whole-number multiple of a Martian year. So the planet would be in a different place, relative to the solar system, each time the habitat was about to make its approach. For this reason, the orbit of the habitat would have to be adjusted each time so that it would encounter the planet. In technical terms, mission controllers would have to rotate the habitat orbit's line of apsides (the line from its perihelion—closest point to the sun—to its aphelion) enough so that the trajec-

CASTLE IN ORBIT around Mars might feature four docking ports, at the ends of the crossed arms, to receive robotic resupply vehicles and planetbound "taxis." Food and supplies would be stored in the arms, one of which might have an artificially lit greenhouse. In the central shaft the living quarters would include a heavily shielded solar-flare storm shelter. If it were nuclear-powered, the craft would also have radiators to dissipate engine heat (*bottom*).



CYCLING TRAJECTORY would carry the habitat from Mars to Earth (*yellow, top*). Then, orbiting the sun, the craft would periodically reencounter Earth (*green* and *blue, top* and *middle*), where it would use Earth's gravity to tweak its trajectory. After returning to Mars, it would settle into an elongated "parking" orbit (*bottom*).

SLIM FILMS

tory would coincide with the position of Mars at the next planned encounter. Aldrin's insight was that this shift could be accomplished mainly by gravity assist as the habitat swung by Earth.

Because of its elongated orbit, the habitat would encounter Earth and, especially, Mars at relatively high velocities. Those high speeds would be problematic if it were the massive habitat that would have to be slowed down for reentry. But it would never need to slow down, because passengers would use the taxis to go to and from the planets.

Those advantages notwithstanding, it is difficult to compare the costs of the cycler strategy with those of more traditional approaches to Mars exploration. Clearly, a great deal of infrastructure would have to be built and orbited to carry out the cycler mission. Once up and orbiting, however, that infrastructure could be used to send dozens, if not hundreds, of people to Mars. Calculating how many passengers would be necessary to break even, though, is extremely difficult because of uncertainties about how many habitats would be required, how much it would cost to build, launch, supply and maintain them, and how much it would cost to carry out missions with one-shot rockets.

Improved Cyclers

Aldrin has continued refining his ideas about cycling habitats and Mars exploration. In his latest conception the habitats would follow trajectories that would encounter the planets at lower velocities, allowing more time and flexibility for trips between the habitat and the planets. Instead of a simple, alternating Earth-Mars-Earth-Mars encounter sequence, this latest scheme would exploit creative celestial mechanics to add "dwell time" at both Mars and Earth.

In this plan the single Earth swingby would become a multiple Mars-Earth-Earth-Earth-Earth-Mars sequence of encounters [*see illustration at left*]. During the Earth portion of the trajectory, the habitat would remain in an Earth-like orbit around the sun, but every six months it would fly by Earth, using the planet's gravitational field to help adjust the orbit for the next encounter. Also, the Mars swingby would have a hesitation period during which the habitat would be waiting for Earth to come into position for the return leg. The trajectory repeats itself once every 52 months, during which time Earth and Mars come into conjunction with each other twice (two synodic periods).

To accomplish the biannual Earth flyby maneuvers, controllers would use Earth's gravity to shift the spacecraft's orbital plane around the sun into one inclined more than 10 degrees to that of Earth's but with the same orbital period as Earth (one year). This cycler strategy uses three such back-to-back maneuvers (or one six-month encounter followed by or preceded by a 12-month reencounter), followed by a gravity assist onto the Mars-bound leg. NASA now plans to use the Earth-Earth six-month reencounter trajectory for the Mars Sample Return mission scheduled for 2005 and for the CONTOUR Discovery science mission.

At Mars, introducing a dwell time presents many challenges. The planet's mass cannot induce even a 10-degree bend in a spacecraft's trajectory under approach velocities typical of cycling orbits. So it is likely that controllers would have to use a Martian gravity assist, plus perhaps a small propulsive maneuver, to turn the spacecraft toward the inner solar system. The vehicle would then encounter Venus and exploit that planet's Earth-like gravity to aim itself back for another Mars encounter.

Dennis V. Byrnes of the Jet Propulsion Laboratory in Pasadena, Calif., recently analyzed similar trajectory options. Byrnes, who is deputy manager of the Navigation and Mission Design Section at JPL, verified the feasibility of a cycling system based on three habitats following a trajectory that covered three synodic periods (about 78 months) with five Earth flybys, each a year apart, between Mars encounters. Such a system would offer an opportunity to travel from Earth to Mars, or vice versa, every 26 months.

Analyses such as Byrnes's underscore the fact that space scientists have just scratched the surface in their studies of the suitability of cycling in human interplanetary travel. As they continue refining their ideas through a series of successively better mission designs, these specialists are making it more likely that humankind will someday rely on this remarkably flexible and robust concept to reach the Red Planet—not once, but over and over again. SA

JAMES OBERG *and* BUZZ ALDRIN *have been collaborating on orbital strategies for Mars exploration since they met at the first "Case for Mars" conference in Boulder, Colo., in 1981. Oberg, an aerospace writer and consultant, was an engineer at the NASA Johnson Space Center in Houston from 1975 to 1997. Aldrin, who was the second man to walk on the moon, retired from NASA's astronaut corps in 1970 to return to the U.S. Air Force, where he commanded the test-pilot school at Edwards Air Force Base. He is now an aerospace consultant based in Laguna Beach, Calif.*