ALEXANDER VIKTORENKO COLLECTION

[WEIGHTLESSNESS SYNDROMES] Yawning as he is raised up after 16 days in bed to simulate weightlessness, a paid volunteer (left) feels faint, as many astronauts do on returning to Earth's gravity. The Harvard Medical School study seeks to learn why some space-conditioned bodies don't move enough blood to the brain to prevent fainting. Weightlessness can also complicate the simplest acts, such as donning trousers aboard Mir, the Russian space station (above).

Boarding a bus at the Gagarin Cosmonaut Training Center north of Moscow, 11 German tourists chat excitedly about their holiday—Russia's aerospace holiday, where you trade cash for thrills and spills. Three men report that tomorrow they will have a ride in the MiG-21 fighter ($4,000 apiece). A slender woman wearing thick glasses and a buzz cut reveals that she is going to do the centrifuge ($2,000), a whirling device that will subject her to perhaps 5 g's, or five times the force of gravity.

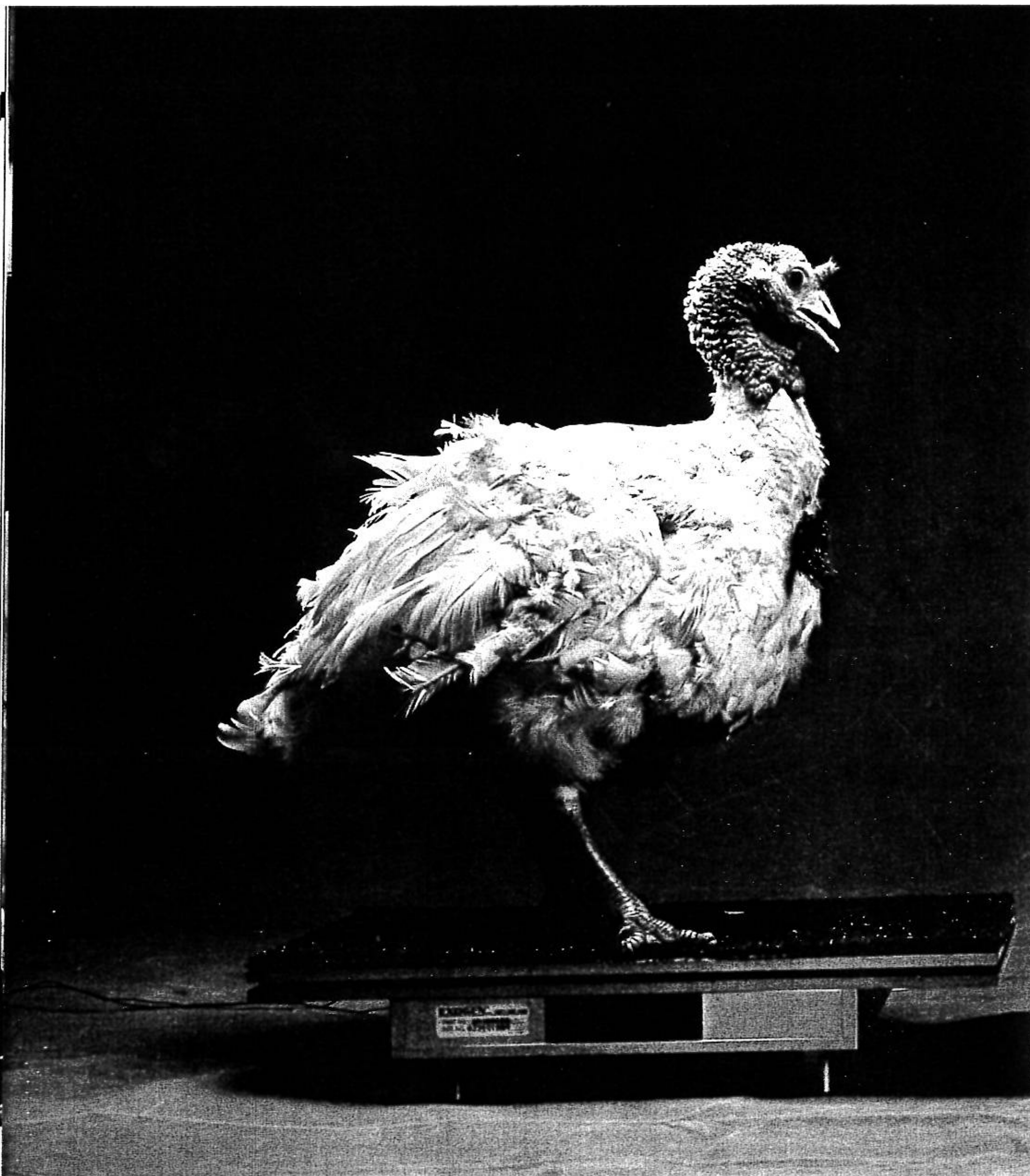
Right now they're all experiencing the 1 g common to Earthlings but are looking forward to a dose of zero gravity (for $1,500 a head) that produces weightlessness or, as the Germans call it, *Schwerelosigkeit.* At Chkalovsky Air Force Base they enter the huge cargo bay of a four-engine Ilyushin-76 MDK. The brilliantly white aircraft surges down the runway, engines screaming.

At altitude a steep 45-degree climb begins. Bright lights come on, and the pilot says, "Prepare for zero gravity," then lowers the nose of the airplane to produce about 30 seconds of weightlessness. Magically, we all rise like smoke and float and fly around. Just like that. People wriggling, eyes wide, mouths open, faces smiling, frowning. Bodies turning upside down—a stunning sight that my eyes record but that my brain seems unable to interpret. Maj. Boris V. Naidyonov of the Russian Air Force, my instructor, asks, "You OK?" He is concerned about nausea, and so am I. "I think so," I reply.

During other zero-gravity periods, one of my companions ricochets off the ceiling. Another does weightless gymnastics. Naidyonov tosses me around the cargo bay like a javelin, twirls me like a baton. This is serious fun, as exhilarating as the airborne maneuvers I've taught as an aerobatics flight instructor.

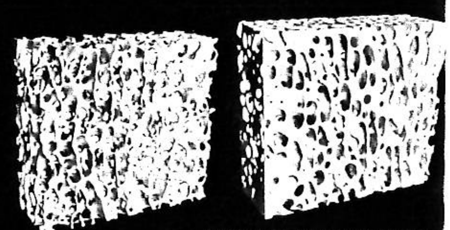
But the slender woman with the buzz cut and two others are silently vomiting into plastic bags. The remainder of the group, while not overtly sick, seem to have lost interest in Schwerelosigkeit.

They are experiencing the motion sickness that afflicts more than two-thirds of all astronauts

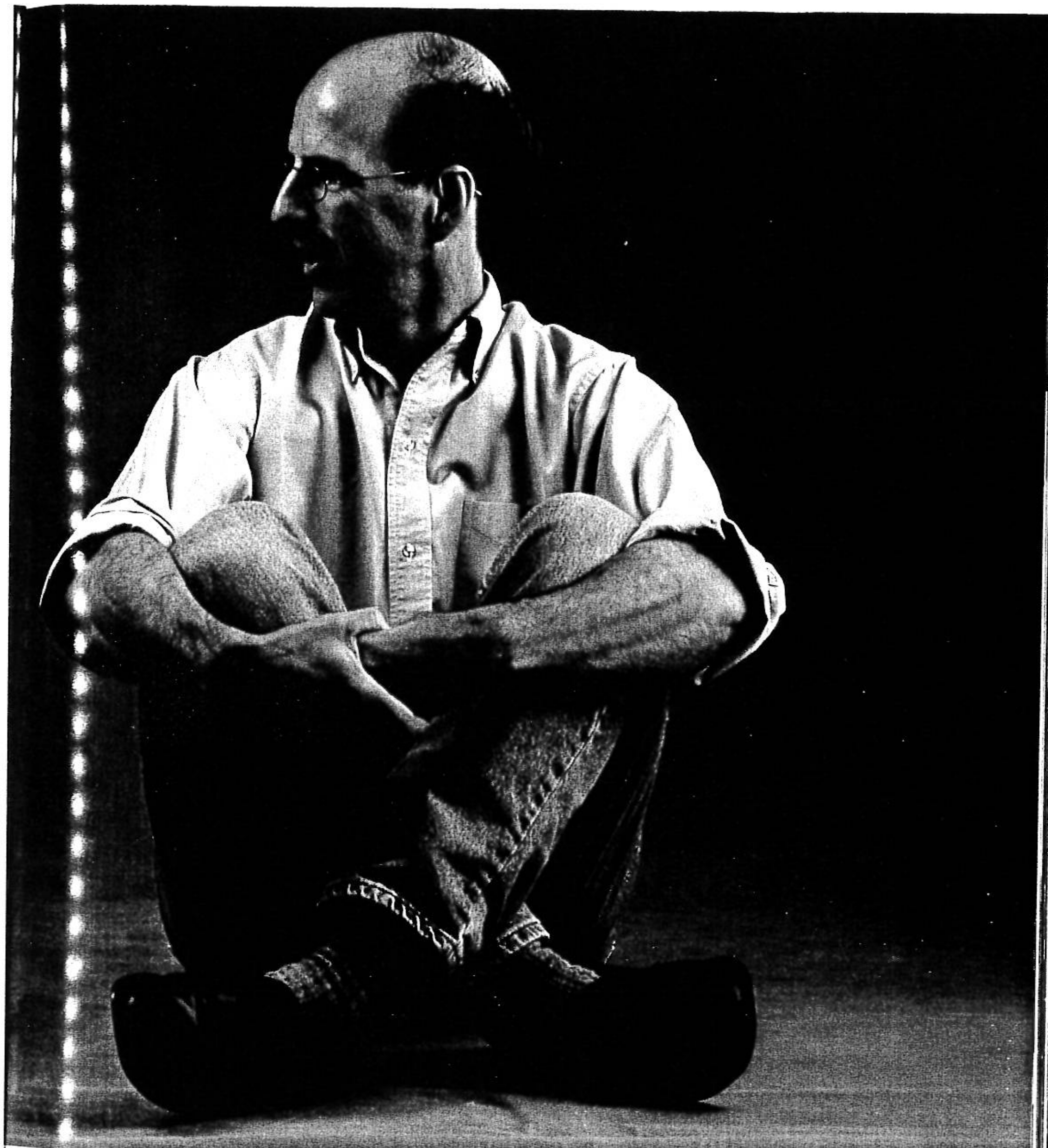


[A BETTER WISHBONE]

A turkey standing on a platform receives slight vibrations that stimulate muscle and bone interaction to promote bone growth. Clinton Rubin of SUNY at Stony Brook also experiments with larger subjects. After a year of daily 20-minute sessions on such a vibrating platform, a sheep showed the robust striations of increased density (far right). A sheep that had stayed in pasture showed normal bone (near right). Rubin's procedure may one day become part of an exercise program to preserve astronauts' bones, which typically decline in strength.



CLINTON RUBIN, SUNY AT STONY BROOK, AND RALPH MULLER, HARVARD MEDICAL SCHOOL



upon reaching orbit, even veteran test pilots who have never been airsick. Though everyone recovers after a few days in space, body systems continue to change.

Deprived of gravity information, a confused brain engenders visual illusions. Body fluids surge to chest and head. Neck veins bulge. Faces puff. The heart enlarges a bit, as do other organs. Sensing too much fluid, the body begins to excrete it, including calcium, electrolytes, and blood plasma. The production of red blood cells decreases, rendering astronauts slightly anemic. With the loss of fluid, legs shrink. Spinal discs expand, and so does the astronaut—a six-footer can soon measure six-foot-two and suffer a backache.

In an astounding feat of adaptation, Earthlings are becoming spacelings, and though the process may sound terrible, astronauts adjust to it, come to enjoy it, and seem no worse for wear—at least for short missions such as space shuttle flights that last a week or two.

During longer flights, however, physiology enters an unknown realm. As director of

Russia's Institute for Biomedical Problems from 1968 to 1988, Oleg Gazenko watched cosmonauts return from long flights wobbly, pale, unable to stand without fainting, needing to be carried from the spacecraft. "We are creatures of the Earth," Gazenko told me. "These changes are the price for the ticket to space."

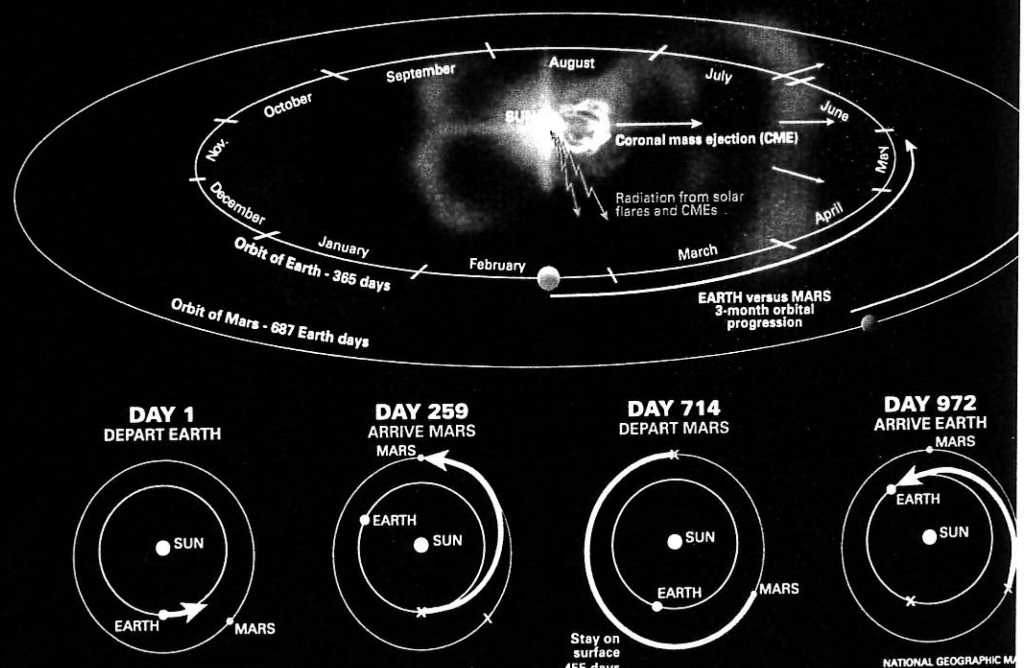
Americans returning from months-long flights on Mir, the Russian space station, also paid a price, suffering losses in weight, muscle mass, and bone density. NASA geared up to see how—even if—humans would survive the most demanding of space ventures, a mission to Mars, which could last as long as three years. Many biomedical problems could compromise a mission. During long-duration spaceflight the heart loses muscle mass, while the large weight-bearing muscles of the legs gradually atrophy, having little work to do in the absence of gravity. Density in such bones as the pelvis and legs relentlessly decreases—1 to 2 percent a month on average—about what a postmenopausal woman might lose in a year.

Waiting in ambush beyond the shield of Earth's atmosphere, solar and galactic radiation can pepper an astronaut's body like machine-gun fire. Radio communications to Earth and back from a Mars crew will take as long as 40 minutes, leaving astronauts pretty much on their own. Confined to a spacecraft roughly the size of two motel rooms, how will they get along with each other? And with themselves—what about loneliness, depression, and medical emergencies?

"If something bad happens to astronauts in low Earth orbit, we can bring them back to Earth quickly," says *(Continued on page 20)*

[THREE YEARS OUT AND BACK]

Traveling between Earth and Mars will require lots of fuel and good timing, if not new rockets, as some experts say. The most fuel-efficient trajectory with today's rockets occurs when Earth is at a six-o'clock position at launch (below) and Mars is at about four o'clock—a juxtaposition that occurs just once every 26 months. The first leg will take 259 days. Come what may on the surface, astronauts must wait on Mars for their launch toward home until Earth is in alignment. Total mission time: 972 days (bottom).



NATIONAL GEOGRAPHIC M

(Continued from page 12) Jeffrey Sutton, professor at the Harvard-MIT Division of Health Sciences and Technology. "That won't be possible when they're en route to Mars." Once launched on a trajectory to Mars, they're stuck on a round-trip journey that could take as long as three years.

Preoccupied with the demands of building the International Space Station, NASA has no Mars mission on the books. When I talked to NASA astronauts and scientists, though, I saw the gleam in their eyes. "I'd go to Mars in a minute," said astronaut Shannon Lucid, holder of the American record of 188 days in orbit.

These appetites were whetted last June when scientists reported indications of water, the broth of life, on Mars. But before a Mars mission can happen, experts agree, the physiology questions must be addressed. Gloomy premonitions are afoot: A sleep-deprived astronaut with weak muscles and bones and a weakened immune system takes a radiation hit en route. Upon landing he faints and breaks a leg, which renders him helpless and a distraction to his fellow astronauts. Stressed in their cramped quarters, the crew bicker among themselves and argue with mission control back on Earth. The mission is threatened.

A worst-case scenario, to be sure, but these things can happen in space, and some already have. At the Massachusetts Institute of Technology, astronaut David A. Wolf, who spent four and a half months on Mir, told aerospace students how weak he was on landing—"I had lost 40 percent of my muscle mass, 12 percent of my bone, and 23 pounds." Wolf's space-adapted balance system, dealing once again with gravity, gave him trouble turning corners and had him "running into doors," he related. "It took six months to feel strong again, a year to get the bone mass back, and two years to get the details of my life together."

The question of astronaut health is of grave concern to Daniel Goldin, NASA's administrator, who said, "We don't even know if a broken bone will heal in space." To get answers, in 1997 Goldin established the National Space Biomedical Research Institute (NSBRI), a consortium of experts from a dozen leading universities and research institutes. NSBRI will study biomedical problems and by 2010 will present NASA with a "go" or "no go" recommendation on a Mars mission.

I began my investigation with Sutton, leader of the NSBRI smart medical systems team, who has treated the head trauma, wounds, kidney stones, and heart rhythm irregularities that one could encounter on the way to Mars. Even the common headache could raise the angst level in attending flight surgeons, says Sutton, because a plethora of possible causes includes emotional stress or an imminent catastrophic bleed in the brain.

I asked Sutton how he would cope with the toxic exposure that took place on Mir in June 1997. Floating through the Russian space station one evening, commander Vasily Tsibliyev suddenly confronted a basketball-size blob of antifreeze leaked from cooling pipes.

"There was nothing Tsibliyev could do," writer Bryan Burrough relates in his book *Dragonfly*. "He hit the giant drop head-on. Its oily edges slathered his face and hair in a noxious embrace . . . he hung there . . . clawing at his face. 'Sasha! Please, the towel!'" he pleaded. Tsibliyev wiped off the mess. After several days of nausea he recovered and today prospers as head of cosmonaut training.

On the spacecraft Sutton envisions, Mars-bound in the year, say, 2018, there may lurk another glob of antifreeze or perhaps harmful bacteria or carbon monoxide. No problem. The deadly substances will be detected by smart sensors—microprocessors no bigger than a thumbnail—that roam autonomously through the spacecraft, communicating their finds to a computer that warns the crew.

To cope with infection, Sutton plans a factory to make drugs, even new ones, to cope with possible organisms on Mars. Miniaturized optical and ultrasound devices will image body and brain—perhaps pinpointing the cause of a headache—while a small x-ray machine keeps track of any bone loss. Smart sensors embedded in clothing will monitor an astronaut's vital functions. The crew will be able to craft body parts, Sutton says, precisely tooled to an astronaut's personal anatomy and genome stored in computer memory.

Excuse me, body parts?

Yes, says Sutton, researchers are building artificial liver, bone, and cartilage tissue right now. "Let's take two worst cases: An astronaut bangs into a piece of equipment and suffers a subdural hematoma, a blood clot on the brain,

[COMFORT]
A bit of home as well as nourishment, dwarf wheat on Mir draws a warm look from Shannon Lucid, who holds the U.S. record for endurance in space. A Mars-bound crew might grow lettuce, tomatoes, onions, wheat, and other food, while recycling air, water, and solid waste.

NASA

and also severs part of an ear. On Earth that's a helicopter flight to special treatment at a trauma center."

In sick bay on Sutton's spacecraft, an astronaut not necessarily a doctor will wield the optical imaging system to locate the clot with a laser, then dissipate it with a tightly focused beam. To deal with the ear, he consults a three dimensional computer model of the injured person's body. The computer teaches him how to build a polymer model of the ear, then to grow new cartilage containing the astronaut's DNA. The computer guides him in seating the new ear part. "You just align part A with part B," says Sutton. "Then an ultrasound pulse heats and seals the wound."

The same ultrasound could be used to treat a ruptured artery. "You locate the bleeding by ultrasound," says Sutton, "then focus the same sound waves to heat the beam and cauterize the bleeding. That's completely noninvasive vascular surgery."

While Sutton prepares for the future, the question of bone loss pervades the present. It became an issue when two Skylab astronauts returned to Earth after long flights in the early 1970s, both with a bone deficit in their heels of 7 percent. Scientists suspect that the process begins with the atrophy of large weight-bearing muscles. The weakened muscles exert less torsion and compression on bones, which initiates a little understood process that drastically reduces bone renewal.

The obvious countermeasure seems to be exercise to keep the muscles fit, a course that has been pursued for many years. At the Institute for Biomedical Problems in Moscow, Inessa Kozlovskaya, a physiologist who has worked with cosmonauts for 25 years, details an exercise regimen developed in the early 1970s: a four-day cycle of bungee stretching and sessions on bicycles and treadmills.

The message according to Kozlovskaya is clear: Do the exercises, and you will be all right. Don't, and we will carry you off the spacecraft. "But it is up to them," she says. "I'm not a policeman." She tells me of Yuri V. Romanenko, a conscientious exerciser who landed after 329 days aboard Mir. Later nagged by reporters, he performed a one-arm handstand.

Kozlovskaya gave high marks to astronaut Shannon Lucid. "Shannon was not athletic, and she was not a young lady"—Lucid was 53 at the time. "I'm sure the exercise was torture for her, but she persisted. When everybody was going to lunch, Shannon was on the treadmill. In flight she was excellent in everything and was in good shape when she landed."

The undisputed star of the Russian program is Valery Polyakov, assistant director of the institute. When presented with a November 1996 issue of NATIONAL GEOGRAPHIC featuring pictures of Earth taken from space, Polyakov called out locations without bothering to look at captions. And no wonder. He's been in space longer than anyone, logging more than 14 months on Mir in 1994-95 and 8 months on an earlier flight.

Polyakov told me he spent two hours in intensive exercise every day, sweating a liter and a half. "My goal was to demonstrate the ability to work on Mars and come back in good health," he said, adding that he walked from the spacecraft under his own power.

Though Americans are impressed with the benefits of the Russian program, they bring up the nagging question of bone loss. "No one has returned from long-duration flight without bone loss," says Adrian D. LeBlanc, a professor at Baylor College of Medicine. LeBlanc explains that on Earth our bones are constantly renewed: Old bone is absorbed, new bone is formed. In space there is almost no renewal. "It's like a million Pac-Men chomping away," he said. "People have lost as much as 20 percent bone density in the hip."

How long does it take to replace the lost bone mass? The process varies widely among individuals. Two of the American Mir astronauts who were in space longer than four months still have bone deficits more than two years after their return. The other five astronauts recovered their bone within six months to three years.

Scientists believe that bone loss during long spaceflights would level off after a while, pointing to paraplegics whose bone loss stops at around 40 percent, but this is unknown.

Researchers must find a way to stop bone loss before a Mars mission, says Jay R. Shapiro, a professor of endocrinology at the Uniformed Services University in Bethesda, Maryland, who is head of the NSBRI bone-loss team. "You better have 100 percent of your bone and muscle when you land on Mars," he says. "If you can't protect yourself on the way up, the risk of fracture is a very big deal."

One idea envisions giving astronauts drugs used on Earth to prevent osteoporosis. Another is an artificial gravity device that would provide doses of gravity to counteract the effects of weightlessness.

One day at the Man Vehicle Laboratory at MIT, I viewed a contender, a bedlike contraption that rotates at 23 rpm to produce 1 g on the occupant's feet. A researcher invited me

[GO DIRECTLY TO JAIL] Or something very like it passes the time for sets of identical twins (above) confined to bed for 30 days in artificial-gravity exercise tests at the University of California at San Diego. Bart Bradley gets a workout on a treadmill housed in a pressure chamber (left). In space this equipment would mimic gravity by raising blood pressure in his lower body. Research seeks to determine if Bart maintains his physical fitness compared with his reclining twin, Bret, whose workout amounts to a yawn.

to take a ride, which, he promised, would be "provocative."

"Turn your head 90 degrees to the right," he suggested. Though I have experienced the gyrations of air-combat maneuvering in such fighters as the F-15, I was stunned by a sudden, dizzying visual illusion—a pull-up followed by a roll to the right.

"Now turn your head to the left," I was told. An immediate and violent pitch down was accompanied by a roll to the left. Provocative, indeed, and to many people sick-making. Tests conducted after my visit showed that the illusions decrease with time, and the short-radius centrifuge remains a candidate to give astronauts a gravity fix, says Laurence R. Young, principal investigator and NSBRI director.

Earthlings who enjoy the sun's benign warmth may find its radiation tantrums difficult to believe. Coronal mass ejections fling billions of tons of electrically charged gas into space, relegating Earth's volcanic outbursts to mere hiccups. Colliding with Earth's magnetic field in March 1989, one such pulse shorted out a power grid in Quebec—like a power surge from a lightning strike—leaving six million Canadians murmuring in the dark. Solar flares explode on the sun's surface with the force of a hundred million Hiroshima bombs, launching protons toward any spacecraft in the neighborhood.

Nevertheless, NASA officials are confident that accurate monitoring will warn astronauts of such events, sending the crew scurrying into the space equivalent of a storm cellar, where polyethylene shielding will absorb the radiation.

A second kind of radiation, cosmic rays from the Milky Way or other galaxies, is a more serious threat—possessing too much energy, too much speed for shielding to be effective. Heavy ions such as iron forged in supernovae can travel up to a fantastic 185,000 miles a second, nearly the speed of light. "There's no way you can avoid them," says Francis Cucinotta, manager of space-radiation health research at NASA's Johnson Space Center. "They pass through tissue, walloping cells and leaving them unstable, mutated, or dead. Understanding their biological effects is a priority."

In one experiment researchers beamed

Seat-of-the-pants flying is replaced by a buzz on the torso. Lighted here in red, vibrators keyed to the position instruments tell the inventor, U.S. Navy Capt. Angus Rupert, that he's inverted. The vest could help astronauts orient during extravehicular activity.

nonlethal doses of heavy iron particles into the brains of rats. A significant reduction in the release of the brain chemical dopamine resulted—a factor in motor ability, cognition, and memory, all of which were impaired in the rats. Remarkably, when fed a diet that included blueberry extract rich in antioxidants, the rats seemed to improve.

Other researchers have found that tamoxifen, an anticancer drug effective in humans, reduces the number of tumors in rats irradiated with the same heavy iron particles.

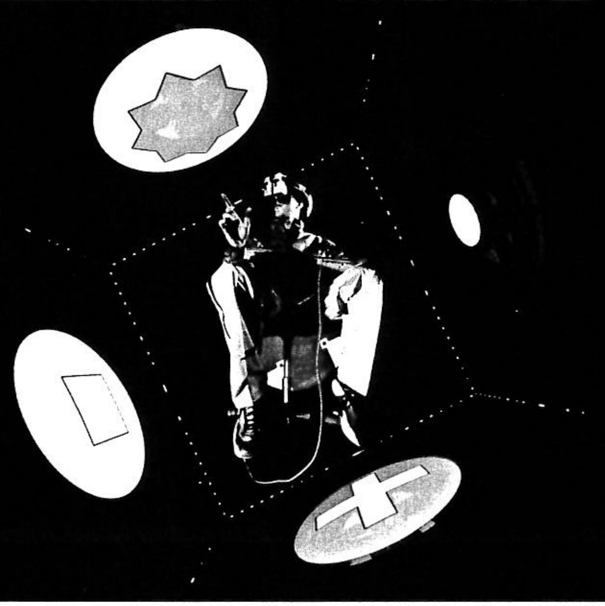
Another major concern is the psychological health of astronauts, despite their right-stuff exploits cooly performed in the face of danger and stress. Michael Collins cruises the dark side of the moon in 1969 out of radio contact with Earth—a situation that would set my hairs on end—and reports "almost exultation." After an explosion aboard moon-bound Apollo 13 in 1970, commander James Lovell, Jr., calmly tells Houston that there is a "problem" and proceeds, with his crew and help from Earth, to patch things up and return safely. My favorite: astronauts who nap on the launch pad while waiting for the rocket to fire.

But there's a new stressor on a three-year Mars mission—people, other members of the crew. "The problem is," says Mir astronaut Andrew Thomas, "they're always the same people."

To observe how the same people get along

[WHICH WAY IS UP?]

A virtual room seen through a headset at MIT challenges a real person's sense of location. Symbols serve as orienting cues as the person moves. Researchers hope to adapt the technique to help astronauts maneuver in large spacecraft. Operating in complex passageways and modules without gravity cues, they share a predicament—which way to go?



CARY WOLINSKY WITH COMPUTER ENHANCEMENT BY BRIAN STRAUSS, NGS STAFF (RIGHT)

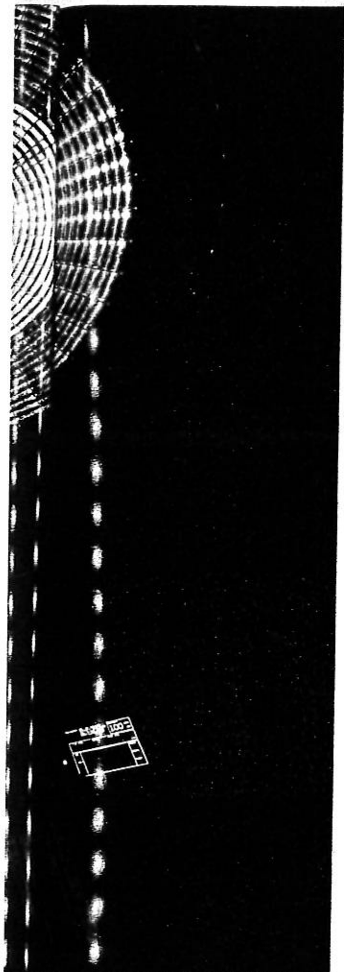
over time, the Russians have confined volunteers for as long as eight months, with mixed results. "All hell can break loose in there," says an observer. Last year during one such confinement two Russians brawled on New Year's Eve, a Canadian woman claimed she was forcibly kissed by one of the Russians, and a Japanese volunteer asked to leave the experiment because of the commotion.

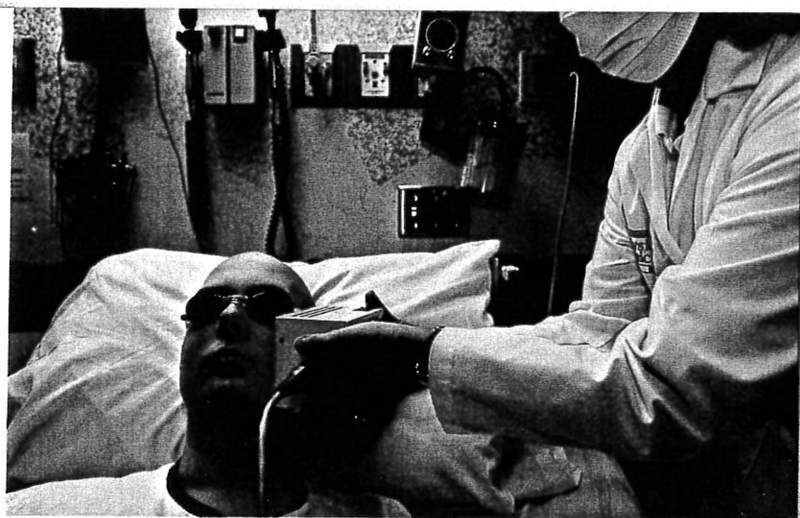
NASA found that the stresses of isolation and confinement can be brought on rapidly, simply by giving people few tasks. Astronaut Thomas described how six astronauts were confined in a 12-foot-square room for a week. "If you give them little to do, stress can be achieved in a couple of days," says Thomas. "Some astronauts treat this as a piece of cake, but it can be extremely difficult." The goal is for astronauts to manage themselves, to pull together, to structure time so that everyone meets his personal needs. "The response has been very positive," says Thomas.

NASA had already learned that too much supervision can be a problem as well. Every day on a Skylab mission that ended in 1974, mission control sent the three astronauts a six-foot-long sheet of instructions. "Our system was designed to squeeze every minute out of an astronaut's day," said the lead flight director. The ground even began scheduling experiments during the crew's mealtimes.

Finally, the astronauts rebelled. In a stinging rebuke to the ground, commander Gerald P. Carr announced that the crew was on strike. They were going to relax and do as they pleased. They were going to look out the window, take pictures they wanted to take. Stunned controllers got the message and finally concluded that astronaut time off was "mandatory" and "inviolate."

Cultural differences pose significant challenges for a Mars crew that will likely be





[LIGHT THAT HEALS] Weakened by chemotherapy in his fight against Hodgkin's disease, Eric Tydd (above) gets a 91-second dose of near-infrared light from light-emitting diodes (LEDs) at the children's hospital in Milwaukee, Wisconsin. The light penetrates tissue to energize cells and prevent the growth of chemo-induced mouth sores that keep patients from eating. Waving the magic LEDs (left), neurologist Harry T. Whelan has successfully treated wounds, third-degree burns, and brain cancer on Earth and thinks the same can be done in space.

multinational. Aboard Mir, astronaut David Wolf had problems with the two Russian cosmonauts. "Where Americans say 'please,' Russians tend to bark orders," he said. "So you feel like you're being yelled at. At mealtimes, they go after the best food. I felt like they were stealing the best food. After a while I asked, 'Why are you doing this?'

"They were surprised. They told me, 'David, you need to jump in. We wondered why you weren't jumping in.' So I started to jump in, and everything was fine." Wolf concluded: "When you understand these cultural differences, they don't make any difference anymore. But they do make a difference until you understand them."

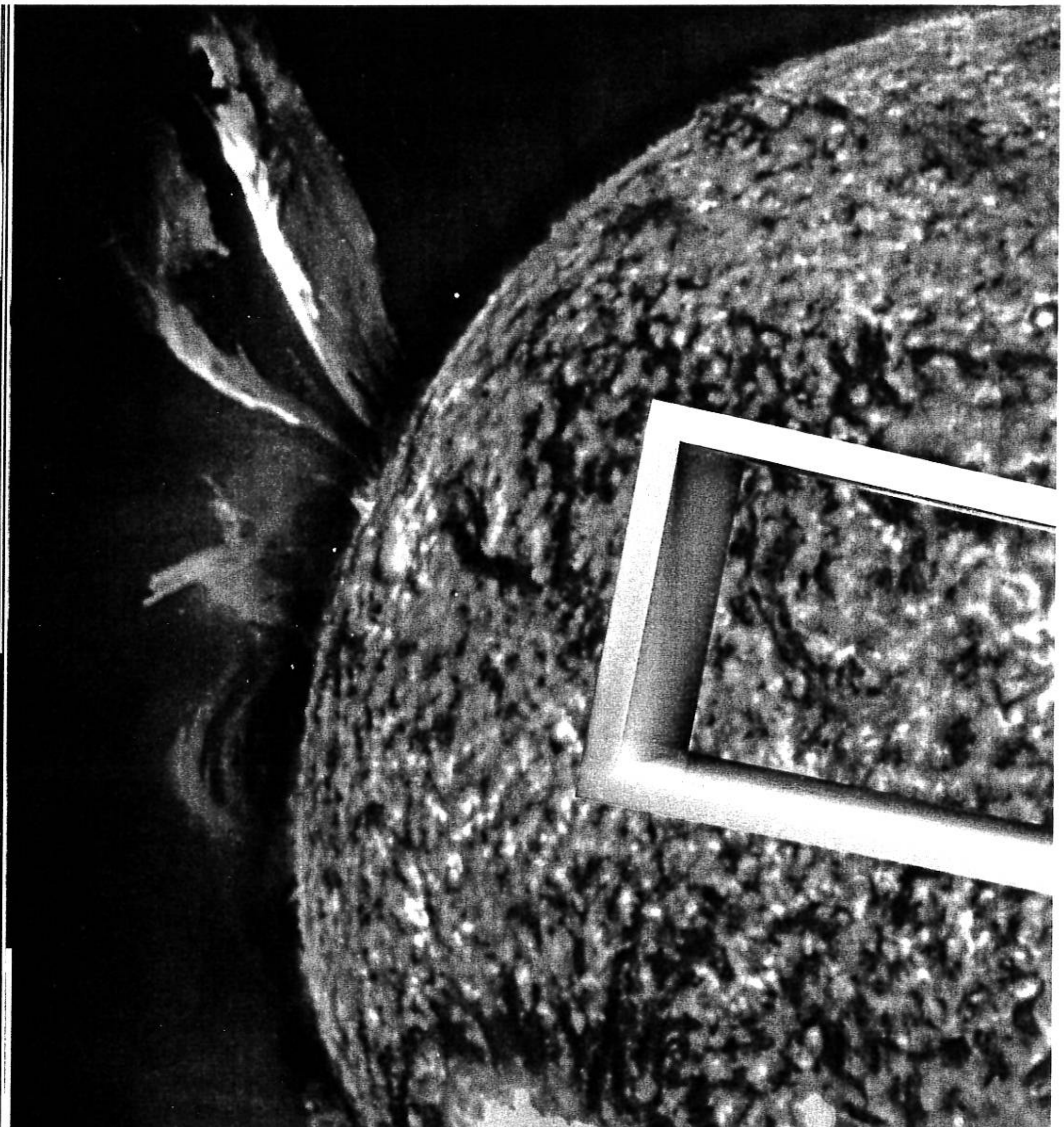
Christopher F. Flynn, a NASA psychiatrist and flight surgeon, worries about the mental health of astronauts, including depression. "Even in healthy people the risk of depression remains high through the fifth decade of life," he says. "How can we tell whether an astronaut is depressed or suffering from isolation? At the moment, I'm stumped."

So is everyone else. David Dinges, head of the NSBRI neurobehavioral team and a psychologist at the University of Pennsylvania, searches for a quantitative means of recognizing stress, mood, and perhaps depression: "We can't rely on anecdote, what people are saying on the way to Mars. We need a measure of behavior."

Dinges and Dimitris Metaxas, a professor of computer science at the university, aim to build a computer program that can recognize emotional states. Already Metaxas has shown that a computer can recognize sign language. "The task ahead," says Dinges, "is to train the computer to recognize facial expressions associated with human emotion, the slanted eyebrows of sadness, the wide eyes of surprise." The computer's imaging system records information in tiny pixels, which enables it to determine subtle changes in expression.

How might astronauts react to such monitoring? "I think we'd have trouble trusting it," Andrew Thomas said. "And I think many of us would consider such a computer invasive."

Dinges counters: "Clearly astronauts have a right to privacy. At the same time the public is paying to learn how we're going to get humans into space safely. We need to balance these two



things." Don't expect this issue to go away any time soon.

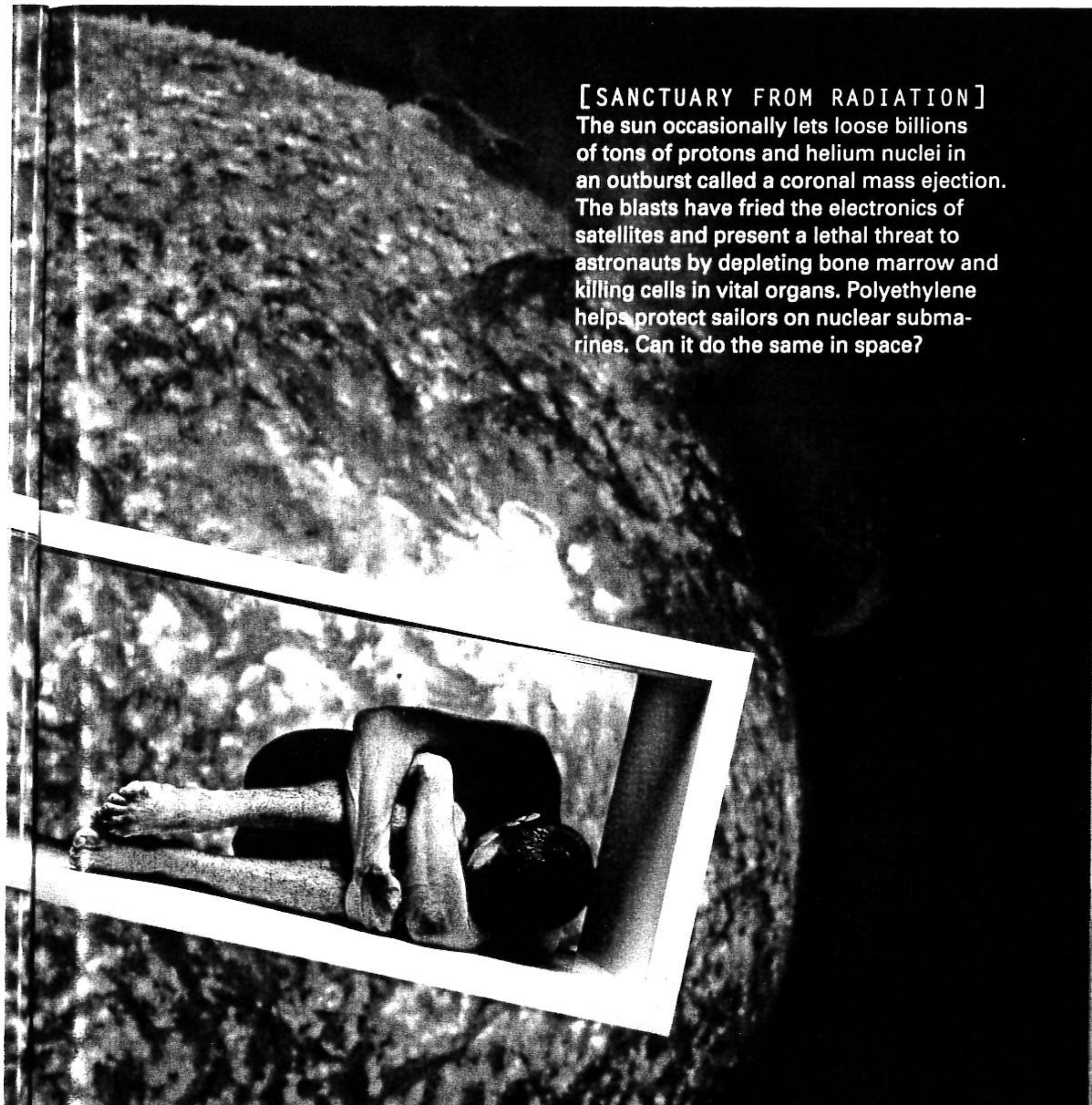
Will NSBRI meet Daniel Goldin's 2010 deadline for a decision on Mars? "Yes, we will, perhaps even before. We're very confident," says Laurence Young, the director of NSBRI. Young, who was a backup payload specialist on a 1993 shuttle mission, looks fit enough to fly tomorrow.

Meanwhile, some of NSBRI's research may bear fruit on Earth. The institute has made one discovery that promises to save many people at risk of sudden cardiac death, usually brought on by a heart-rhythm disturbance called ventricular fibrillation. This kills 225,000 people in the U.S. each year.

Richard Cohen, a cardiologist at MIT and head of the NSBRI cardiovascular team, explained that zero gravity may—emphasizing "may"—incite this condition in astronauts. So the team invented a noninvasive diagnostic device that measures extremely tiny changes in heart rhythm on the order of a millionth of a volt.

The team found that the device can be used as part of a standard stress test to identify patients at risk. Then pacemaker-like devices can be implanted to regulate the rhythm anomalies. "This technology has the potential to save hundreds of thousands

PHOTO COMPOSITE: SOLAR PROMINENCES, NASA; CARY WOLINSKY



[SANCTUARY FROM RADIATION]
The sun occasionally lets loose billions of tons of protons and helium nuclei in an outburst called a coronal mass ejection. The blasts have fried the electronics of satellites and present a lethal threat to astronauts by depleting bone marrow and killing cells in vital organs. Polyethylene helps protect sailors on nuclear submarines. Can it do the same in space?

of lives," says Cohen. "NASA can be proud."

Such discoveries are no accident, says Michael E. DeBakey, a board member of NSBRI and a cardiovascular surgeon who has saved many hearts himself. After returning from Russia—a nine-hour time change—DeBakey, 91, worked all day at Baylor. At 6:15 p.m. the corridors were deserted when he sat down with me, attired in a blue surgeon's smock.

The key word is research, DeBakey said. "When I was a medical student, and a patient came to the hospital with a heart attack, things were mostly up to God. Today there's a better than 95 percent chance to survive. Now that all comes from research.

"The unfortunate thing is that there are people, even some scientists, who look at the money that goes to NASA and say, you know, we could use that money to support our work. That's very shortsighted. The more research that's done in any area of science, the better off everyone is going to be. The more that's done in physics, the better off I am in cardiology. There's no better investment for a society than research." □

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Do humans belong in space or should society place its resources elsewhere? Join our forum at nationalgeographic.com/ngm/0101.