Ride the celestial subway

Climb aboard the solar system's invisible network and you can travel anywhere for free, says **Ian Stewart**

WHAT is the most efficient route from the Earth to the moon or the planets? According to NASA engineers, the answer is simple. Travel the way Londoners do: go by tube.

The idea is not entirely original. Peter Hamilton's recent science-fiction novel *Pandora's Star* portrays a future in which people travel by train to planets encircling distant stars. True, the railway lines have to pass through a wormhole – a short cut through space-time – but once you can build wormholes to order, it's entirely logical to use trains. Much earlier, E. E. "Doc" Smith came up with the hyperspatial tube, used by malevolent aliens to invade human worlds from another dimension. And C. C. MacApp imagined a universe in which star systems were connected by a system of tubes, through which spaceships could travel faster than light.

Although we don't yet have wormholes, extra dimensions, or faster-than-light tunnels through space, mathematicians have discovered that our solar system does possess something remarkably similar to the wild inventions of these authors' imaginations: a network of tubes perfectly suited to space travel. The tubes can be seen only through mathematical eyes, because their walls are defined by the combined gravitational fields of all the bodies in the solar system, but they are real enough, for all that. If we could visualise the ever-changing fields that control how the planets, moons, asteroids and comets move, we would be able to see a network of tubes that swirl and twirl along with the planets as they perform their endless gravitational dance. NASA's engineers already refer to the network as the "Interplanetary Superhighway": science fiction wins again.

The existence of this interplanetary network would have surprised the pioneers of celestial mechanics. Yet, paradoxically, it was those pioneering efforts centuries ago that provided the first hint of the tubes' presence. Long ago, the planets were seen as the unruly members of the celestial club. The fixed stars appeared to be bolted to the heavenly sphere, spinning once every day about the poles. The planets, though, were wanderers – in Greek, planan means "to lead astray". Their place in the heavens, relative to the stars, was not fixed, and their motions were complex and difficult to describe. They seemed to move of their own volition, which is perhaps why they were identified with gods.

Johannes Kepler and Isaac Newton taught us that such appearances are deceptive: the planets are no more unruly than the stars. Planets revolve around the sun in tidy

▶

elliptical orbits, and their apparent wild gyrations are the result of a combination of their movements with those of the Earth as it follows a similarly elliptical path. The solar system came to be seen as a well-oiled piece of celestial clockwork, as if invisible gears and cogs were turning the great wheels of the planetary system. The devil was in the detail, of course, and the orbits were not precisely elliptical because each world affected the movement of the others. But it could all be summed up in Newton's law of gravity: every body in the universe attracts every other body with a force that is proportional to their masses and inversely proportional to the square of the distance between them.

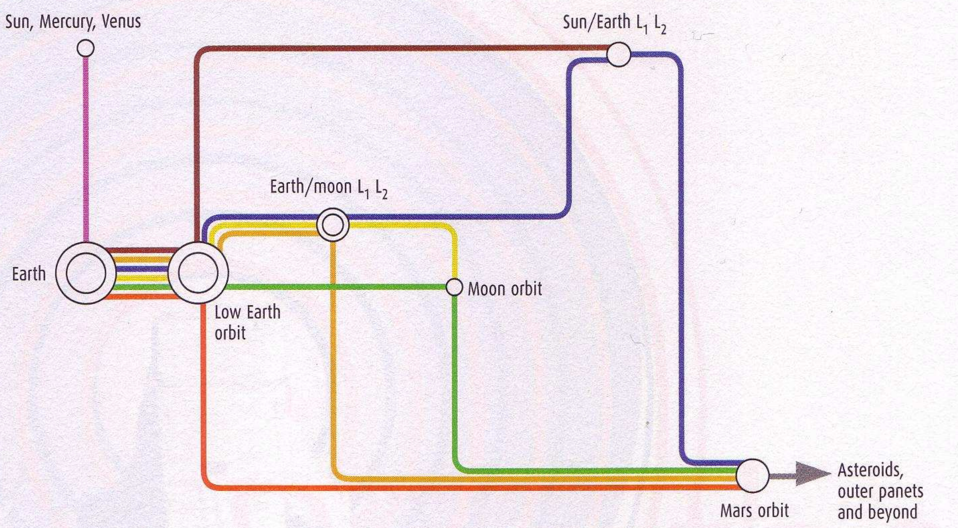
Celestial dance

Since the law of gravity is so simple, it was only natural to imagine that the movements of planets and moons must be simple too. The solar system's celestial dance was thought to be slow and stately, heavily constrained by natural law. While the end result might be complicated, it could never be surprising.

But that is just not true. Consider, for example, the unruly comet Oterma. A century ago, Oterma's orbit was well outside the orbit of Jupiter until, after a close encounter with that giant planet, its orbit shifted inside Jupiter's. After another close encounter, it switched back outside Jupiter. We can confidently predict that Oterma will continue to switch orbits in this way every few decades. If this all seems a far cry from Kepler's and Newton's tidy elliptical orbits, it is, and with good reason. The orbits predicted by Newtonian gravity are only elliptical when no other bodies exert a significant gravitational pull. In fact, the solar system is full of other bodies, and they can make a significant – and surprising – difference. Which is where those tubes come in.

INTERPLANETARY SUPERHIGHWAY

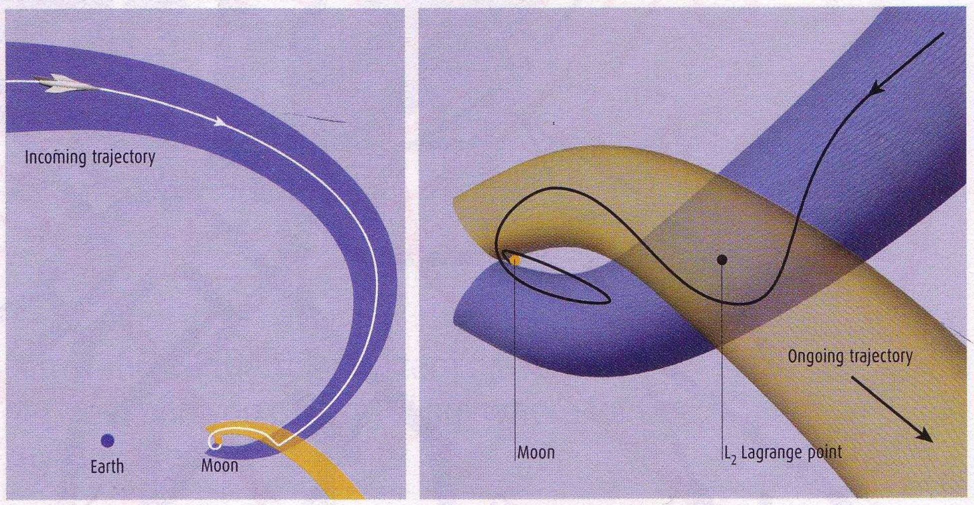
The gravitational fields of the planets and moons can pull spacecraft along "tubes" in space. NASA engineers have used this idea to chart an Interplanetary Superhighway that enables spacecraft to travel efficiently around the solar system



SOURCE: GARY L. MARTIN/NASA

PORTAL TO THE PLANETS

The chaotic dynamics where tubes intersect means that it only takes a small push to move spacecraft from one tube to another, as shown here at the Earth/moon "Lagrange point" L2



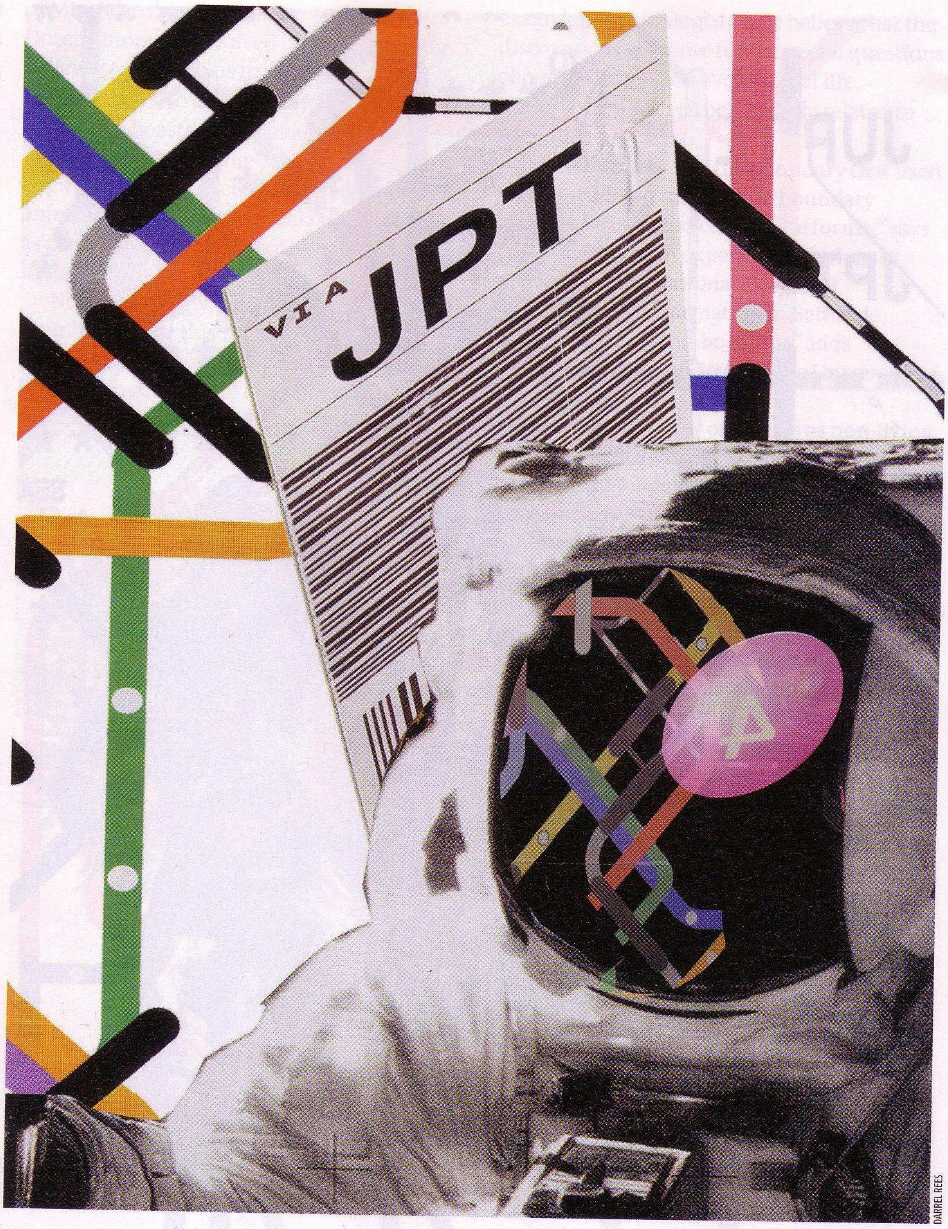
The tubes are a feature of "gravitational topography". The solar system is like an alpine landscape – but with the gravitational fields of the sun, planets and their moons providing the mountains and hills. A gravitational contour map of the solar system has similar features to a terrestrial contour map. There are closely packed rings where the gravitational field strength peaks near the sun, say, and there are flat contourless "valley floors" where the gravitational fields of two neighbouring bodies cancel out. And just as Victorian railway engineers realised they could run trains most easily along the contours of a landscape, mathematicians have realised that a spacecraft will run most efficiently along the gravitational contours of space.

"The solar system is like an alpine landscape, but with the gravitational fields providing the mountains and hills"

There is a complication, however. The trajectory of a spacecraft is influenced by its own speed as well as the local gravitational fields. In the late 1960s, Richard McGehee of the University of Minnesota and the late Charles Conley pointed out that each contour's path is effectively surrounded by a nested set of tubes, one inside the other. Each tube corresponds to a particular choice of speed: the further away it is from the optimal speed for following a particular path, the wider the tube becomes. A spacecraft can travel along one of these tubes, following a gravitational contour at a certain speed, without expending fuel. When it needs to change course, it can do so by applying a little power boost in the right direction to move onto another contour.

Better still, there is an even more efficient way to change course: use the Interplanetary

"Mathematicians have realised that a spacecraft will run most efficiently along the gravitational contours of space"



DARREL REES

Superhighway's natural interchanges. The calculations that disclosed the existence of these interchanges were completed more than 200 years ago by Joseph-Louis Lagrange. They revealed that in a system consisting of just two bodies – the Earth and the moon, say – there are five places where the gravitational fields of the two bodies cancel out exactly (in the frame of reference rotating with the two bodies). Three are in line with both Earth and moon: L1 lies between them, L2 is on the far side of the moon, and L3 is on the far side of the Earth. There are also the two "Trojan points" L4 and L5, in the same orbit as the moon but 60 degrees ahead of it or behind it. As the moon orbits the Earth, the Lagrange points orbit it too. Other pairs of bodies also have Lagrange points – Earth/sun, Jupiter/sun, Titan/Saturn, and so on. At some of the Lagrange points there also exist "halo orbits" in which a body can stably loop about the Lagrange point.

Running downhill

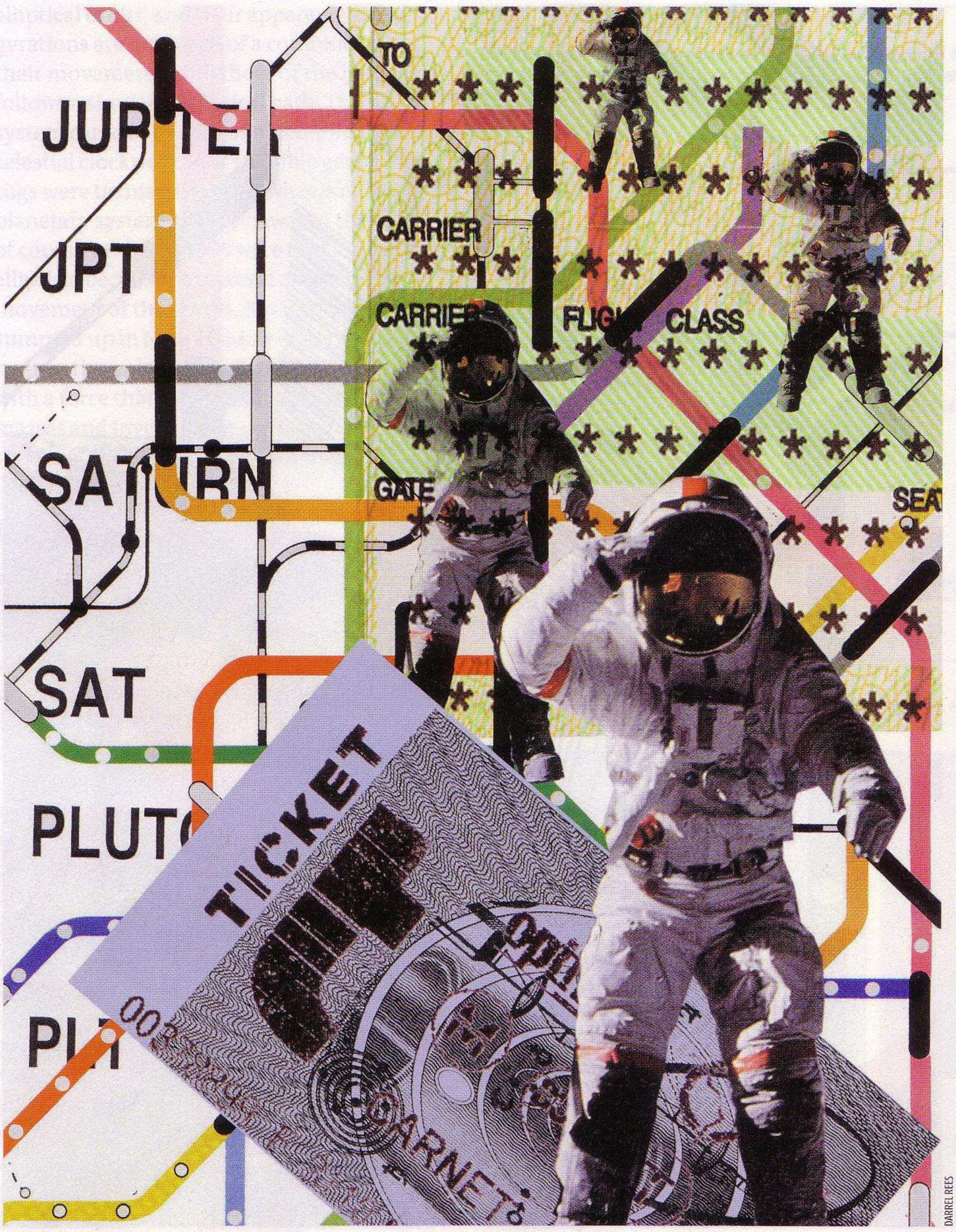
Now imagine the gravity landscape surrounding a spacecraft sitting at the Earth/moon L1 point. If the craft is given a small push, it will start to run "downhill", following a tube that leads into an orbit around either Earth or the moon. The good news for space engineers is that these tubes trace out the most energetically efficient path from Earth to the moon. To make the journey, you would first give a little kick to move out of Earth orbit into the tube that runs to L1. Once there, you can nudge your spacecraft into the tube from L1 to the moon and let gravity do the rest.

The beauty of all this is that the tubes slinking their way through the solar system can be interconnected. Oterma's orbit, for instance, follows two tubes that meet near Jupiter. One tube lies inside Jupiter's orbit, the other outside. Where they meet, the comet can switch tubes – or not, depending on rather subtle effects of Jovian and solar gravity. Once inside a tube, Oterma is stuck there until the tube returns it to the junction; Oterma has no propulsion so it can't choose its trajectory, and will always remain near Jupiter.

Spacecraft, however, can do almost what they like – and Jupiter is not the only junction. The way to plan an efficient mission profile, then, is to work out which tubes are relevant to your choice of destination. You then route your spacecraft along the tube to a Lagrange point, and when it gets there you give it a quick burst on the motors to redirect it to the next Lagrange point on the route…and so it goes on.

It gets better. The dynamics of a spacecraft near L1, for example, are chaotic, so you can achieve large changes to the trajectory ▶

"Once at the intersection you can nudge your spacecraft into the tube to the moon and let gravity do the rest"



DARREL REES

"Dellnitz has uncovered evidence of a remarkable system of tubes connecting Jupiter to each of the inner planets"

through very small changes of position or speed. By exploiting chaos, spacecraft can be redirected to other destinations – again, in a very fuel-efficient, though possibly slow, manner. This trick was used in the mid-1980s to redirect the almost dead International Cometary Explorer to rendezvous with comet Giacobini-Zinner. It was used again for the Genesis mission, launched in 2001, whose prime purpose was to bring back samples of the solar wind.

Though calculating and exploiting the topography of the energy landscape requires some clever mathematics, today's computers have made it almost routine. In 2000 the tube technique was used by Wang Sang Koon, Jerrold Marsden and Shane Ross of the California Institute of Technology, and Martin Lo of NASA's Jet Propulsion Laboratory in Pasadena, to find a "Petit Grand Tour" of the moons of Jupiter, ending with a capture orbit round Europa. The path requires a gravitational boost near Ganymede followed by a tube trip to Europa. A more complex route, requiring even less energy, includes Callisto as well. And last year, Michael Dellnitz, Marcus Post and Bianca Thiere of the University of Paderborn in Germany, with Oliver Junge of Technical University of Munich, used tubes to plan an energy-efficient mission from the Earth to Venus. The main tube here links the sun/Earth L1 point to the sun/Venus L2 point. Its low-thrust engines would require only one-third of the fuel used by the European Space Agency's Venus Express mission; the price paid is a lengthening of the journey time from 150 days to about 650 days. Future interplanetary missions for which fuel rather than time is of the essence will no doubt make routine use of tubes, and plans for such missions are already being drawn up.

These plans may soon have to be radically revised, however. Unpublished work by Dellnitz has uncovered evidence of a remarkable natural system of tubes connecting Jupiter to each of the inner planets. The planets appear to have positioned themselves at the receiving end of the tubes emanating from Jupiter, where those tubes are calculated using only the gravitational fields of the sun and Jupiter. It is as if the gravitational fields of the sun/Jupiter system determine the main features of the landscape, and the planets have somehow situated themselves in locations that lie at the far ends of these tubes. Together, Jupiter and the sun seem to have orchestrated the locations of all the other planets.

It is not clear what has brought this about. One possibility is that during the formation of the solar system, Jupiter reached a large size early on, and dust was transported around the solar system along the tubes to accumulate at certain spots. To put it another way, it may be that in the landscape set up by Jupiter and the sun there are preferred locations where the other planets are more likely to form.

Whether or not this happened, the implications for the Interplanetary Superhighway of this remarkable structure are clear. Jupiter, long known to be the dominant planet of the solar system, has a new role: the fifth planet from the sun is the solar system's very own Grand Central Station. ●

Ian Stewart is professor of mathematics at the University of Warwick, UK