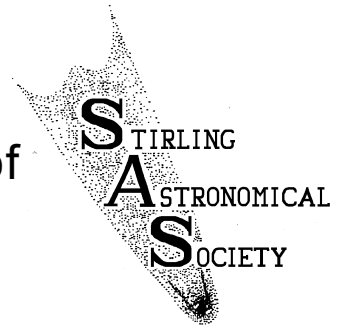


Newsletter of



Vol. 18 No. 2 April 2003

MAINTENANCE ON VOYAGER FROM SEVEN BILLION MILES AWAY

In the last issue of *Mercury* Bert Mackenzie commented on the durability of the Voyager spacecrafts. The Voyager Interstellar Mission was launched back in 1977 and now, 26 years later, it is still going strong. Voyager 1 and Voyager 2 completed their tour of outer planets in 1989 and are now heading towards the heliopause or boundary zone where the Solar System and the Sun's influence give way to interstellar space. Both spacecraft have adequate power and communications capability to explore that frontier for about another twenty years, if the onboard systems continue to operate satisfactorily.

Astronauts are able to make regular visits to the Hubble Space Telescope, nearby in orbit around the Earth, to service it and make replacements of instruments and other items as necessary. But of course this is impossible for the Voyager spacecraft now *7 billion* miles away, where communications signals take nearly twelve hours to travel each way between Earth and the spacecraft, making reaction times excruciatingly slow. How then, is it done?

As any external replacement of components is not possible, the original designers of the Voyagers built in duplicate backup systems for key components in anticipation of possible failures due to their wearing out or other unforeseen causes. Having brand new unused backup systems available is one thing, but switching them on, testing them and bringing them smoothly on-line in place of malfunctioning existing systems from such an enormous distance away, is a completely novel challenge. It also doesn't help that the Voyager team at the control centre back on Earth has been reduced from its level of more than 300 people in the 1980s to just fourteen at the present time. And it has to be remembered that the spacecrafts' onboard computers use technologies of 25 years ago - now obsolete and considered to be very primitive.

Voyager 1's attitude control system started to show signs of a problem two years ago and it became steadily less reliable. Diagnostic interrogation from the control centre (taking nearly 12 hours each way!) indicated the source of the problem to be an electronic component which accepts analogue signals from position-sensing devices and converts them into digital form for input into the onboard computer. The component had a backup but, due to the original design, switching to the component's backup also meant activating the backups for both the Sun sensor and star tracker as well. These provide the reference points for the spacecraft's orientation in space. This whole backup system had last been tested more than 20 years ago when Voyager 1 was approaching the Sun in 1980. If it didn't work correctly this time, changing over to it could confuse the onboard computer about the spacecraft's orientation. This would be disastrous as it would result in incorrect pointing of the communication antenna and so to complete and permanent loss of communication between Voyager 1 and the control centre on Earth.

The change-over to the backup system had to be planned very carefully, taking every precaution

that could be taken. The key precaution was to program a temporary change-over so the backup system could be tested, but with automatic reversion to the original system as quickly as possible, in case the backup didn't work properly. Potential problem areas were identified in advance, and provision was made to correct them if necessary before the final permanent change-over, nine days after the temporary one. These precautions paid off, as during the temporary change-over the system made an unexpected lock-on to the Sun. This was able to be avoided during the final change-over by instructing the spacecraft to keep itself steady using its gyroscopes during this critical period.

The change-over was completed in April 2002 and Voyager 1 continues to operate satisfactorily with its newly commissioned system. The old system, which still works although it is not so reliable, is available as a backup for the future. The success of this carefully planned and executed change-over bodes well for the continued success of the whole Voyager Mission, with its now proven ability to change-over to other backup systems on both Voyager 1 and Voyager 2, should the need arise.

Derek Allen

GOOD BYE, PIONEER 10

While the Voyager missions continue successfully on their way, NASA's longest and most enduring space mission, Pioneer 10, has finally passed into oblivion, at least as far as we on Earth are concerned. 7.6 billion miles from Earth, it is heading towards the red dwarf Aldebaran in the constellation Taurus. Pioneer 10 was launched 31 years ago, in 1972, and famously carries a gold plaque depicting humankind, for the benefit of any extra-terrestrials it may encounter.

After launch, Pioneer 10 passed the Moon in eleven hours and crossed the orbit of Mars twelve weeks later. It went through the asteroid belt and then accelerated in a sling shot past Jupiter in December 1973, reaching 82,000 mph. Ten years later, in 1983, it passed the orbit of Pluto and became the first spacecraft to break free from the Solar System.

The Pioneer 10 mission was originally designed to last only 21 months, but its plutonium power source has just kept going and going, and Pioneer 10 has continued to keep in touch with Earth, with its signals gradually getting weaker all the time. In the Millennium year 2000 its faint signal was detected at a received power of only a third of a *billion trillionth* of a watt. Its last signal was detected on 22 January this year. In February, NASA tried to contact it again but there was no response - Pioneer 10 was at last completely out of range and gone forever. It was indeed a pioneering forerunner of the Voyager missions.

Derek Allen

LONGEST TOTAL SOLAR ECLIPSE

A total eclipse of the Sun occurs when the Moon passes directly between the Earth and the Sun, covering the Sun's disk completely. By a fluke of nature, the apparent sizes of the Sun and Moon in our sky are almost the same, although both vary a little because the distances between the Earth and the Sun, and the Earth and the Moon, are not constant. This variation affects the duration of a total eclipse. In theory, the longest time totality can last during a total solar eclipse is 7 minutes 31 seconds. In practice, no eclipse this long has been recorded. The longest of recent times was the eclipse of 20 June, 1955. Seen from the Philippine Islands, its totality lasted 7 minutes and 8 seconds. The longest eclipse so far predicted for the future is due on 5 July 2168, when totality will last 7 minutes 28 seconds.

DHA

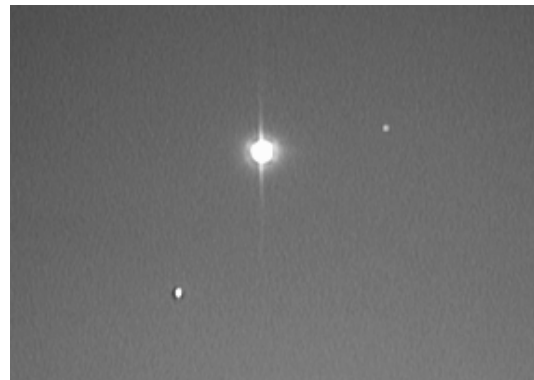
EXAMPLES OF VIDEO ASTRONOMY

A previous article (*Mercury* Vol 17 No 3 p3) described the use of a camcorder, and the digital processing of images obtained, in astronomical photography. Here are some results of this technique taken and processed by Douglas Cooper and Chris Davis.

The Ikeya Jhang Comet



The Orion Nebula



The Triad of Mars, Venus and a Star

ORBITAL DYNAMICS

Quantum physics does not have the monopoly on weirdness; good old Newtonian orbital dynamics is full of surprises. Imagine you are piloting a Shuttle (they will fly again eventually) and you are in orbit around the Earth a couple of kilometres behind the International Space Station. You need to catch up and dock, so you fire the rear manoeuvring thrusters to nudge forward. Result of trying to accelerate forwards: the Shuttle moves further away from the Earth and slows down, falling still further back from the ISS!

Next, a piece of space junk looms into view ahead; to avoid collision the retrorockets are fired. Result of trying to put on the brakes: the Shuttle loses height and shoots forward under the junk and the ISS. You see it pass over the top of the Shuttle cabin and get left behind!

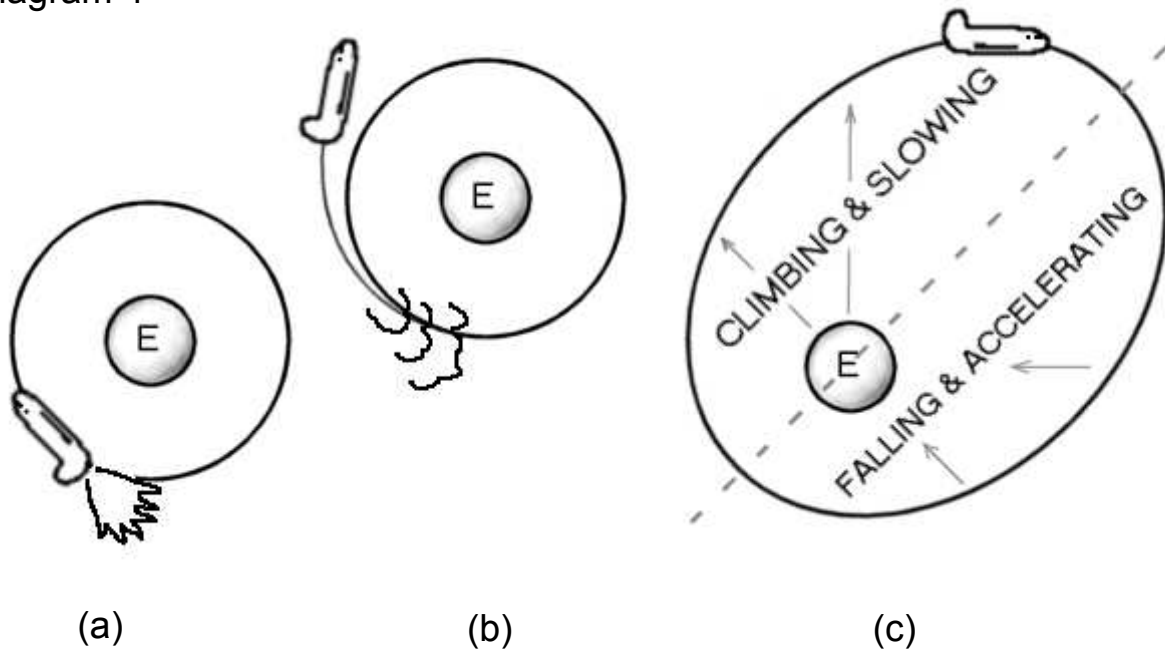
As amateur astronomers, we are better placed than most to understand what is going on here - we already know something about planetary orbits. We know the planets closest to the Sun are moving much more quickly than those further out. The Sun's gravity is trying to pull the planets in, while their speed is trying to throw them out. The nearer a planet is to the Sun, the stronger the gravitational pull and the more speed the planet needs to balance the pull.

However, just as a stone thrown up into the air gains more potential energy the higher it gets off the ground, planets have more potential energy the higher they are off the surface of the Sun, i.e.

the further out they orbit in space. Be under no illusion; if any planet lost all its orbital velocity it would drop like a stone into the Sun. The further out the planet originally was, the harder it would hit the Sun, having converted all its potential energy into kinetic energy and a furious speed.

Fortunately this does not happen to planets around the Sun, but the principle is the same for any object orbiting any large mass, in our case the Shuttle orbiting the Earth. Therefore when our Shuttle fired its retrorockets to avoid debris, it cancelled out some of its orbital velocity and started to fall towards the Earth, gaining speed on the way as potential energy was converted to kinetic energy. That is why it was able to overtake the ISS "on the inside".

Diagram 1



When an object is in a stable circular orbit, speed and height remain constant and there is no conversion between potential and kinetic energy. Upset this balance by firing rocket motors and things will start to happen (Diagram 1a). If the Shuttle's kinetic energy is increased by briefly firing its rear motors, as when trying to catch up the ISS in the example, then the excess of kinetic energy starts to convert to potential energy, that is the Shuttle starts to gain height. Another way of looking at it is to say that the motors tried to eject the Shuttle off at a tangent from its circular orbit, so the curved path is no longer curved enough to fit around the Earth's sphere and the Shuttle ends up further away from Earth i.e. it gains height (diagram 1b).

The motor impulse given to the Shuttle is similar to the throwing impulse given to a lofted stone. The Shuttle will initially climb to a maximum height then fall back again. But in falling back it regains the excess speed and kinetic energy imparted by the rocket impulse, and consequently starts to climb again. As there is no air friction, this height oscillation is perpetual and gives the Shuttle an elliptical orbit round the Earth (diagram 1c).

What NASA does when it wants to launch a satellite into high orbit, is to first send it up into low orbit with the Shuttle. Then they fire the satellite's own rocket motors so it goes into an elliptical orbit, leaving the heavy Shuttle behind (1st burn, diagram 2).

This is called a "transfer orbit" because it is profiled to take the satellite between the Shuttle's

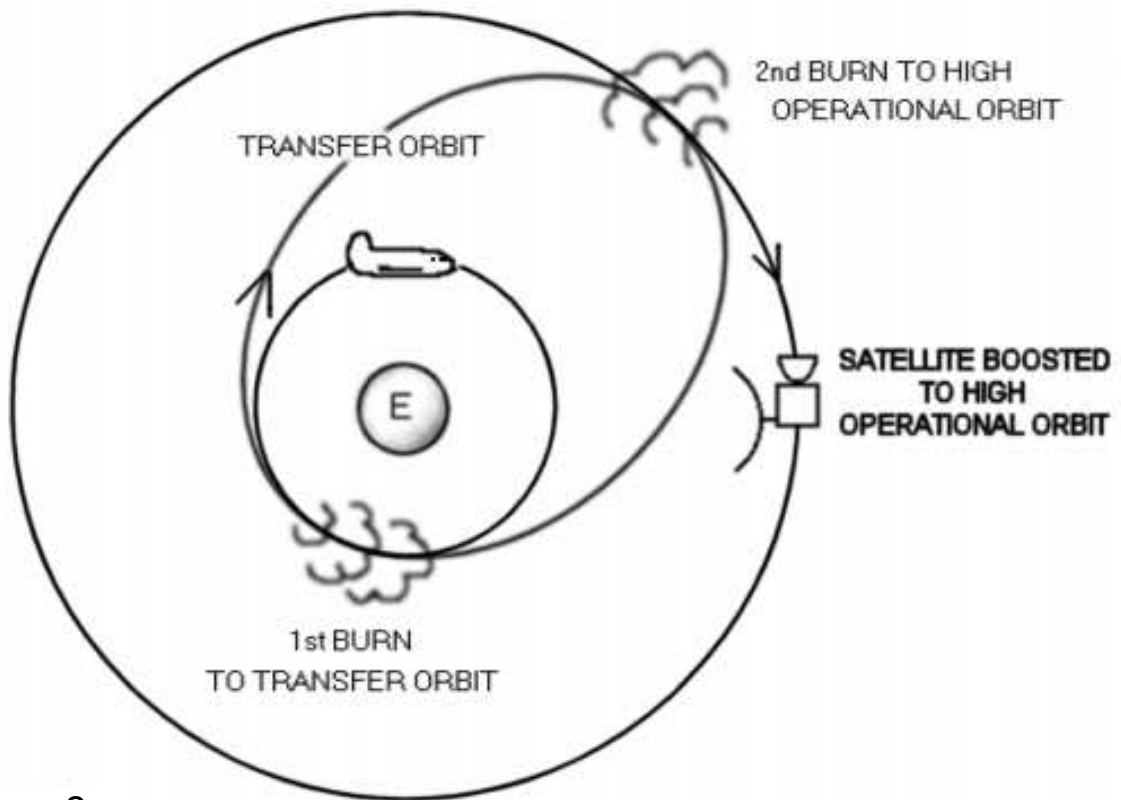


Diagram 2

relatively low altitude and the satellite's target high altitude on each elliptical journey around the Earth. The transfer orbit can be checked and adjusted if necessary before the next major rocket burn. Then, when the satellite reaches its required operational height at the maximum reach of the transfer orbit ellipse, the motors are fired again to give the satellite enough speed to maintain that height without falling back (2nd burn, diagram 2). This injects the satellite into its final stable circular operational orbit, and demonstrates how the science of orbital dynamics is used to position the World's communication satellites.

Chris Davis

THE NIGHT SKY : April, May, June 2003

SUN	April				May				June	
	13		27		11		25		8	22
(approx) Rises			06.16		05.42		05.11		04.46	04.31
(approx) Sets	20.16		20.45		21.13		21.38		21.56	22.04
MOON	April					May				
Phase	NM	FQ	FM	LQ	NM	FQ	FM	LQ	NM	
Date	1	9	16	23	1	9	16	23	31	
Rises	07.00	09.36	19.47	03.56	05.34	11.05	22.07	02.02	04.23	
Sets	19.12	03.39	06.11	10.25	20.44	03.27	04.56	12.15	22.20	

		June		
Phase	FQ	FM	LQ	NM
Date	7	14	21	29
Rises	11.43	22.34	01.30	03.25
Sets	02.05	03.46	12.34	22.19

PLANETS

Magnitude

MERCURY	<i>April</i>	Evening low W sky at end of twilight for first three weeks	-1.2 to +1.0
	<i>May</i>	Unsuitable for observation, but a transit across the Sun on 7th	
	<i>June</i>	Unsuitable for observation	
VENUS	<i>April</i>	Extremely low ESE horizon for short time before dawn	-3.9
	<i>May</i>	During month becomes unavailable for observation as too low in sky	
	<i>June</i>	Unavailable for observation	
MARS	<i>April</i>	Poorly placed morning object moving east from Sagittarius into Capricornus	+0.3
	<i>May</i>	Poorly placed morning object in Capricornus, low SE sky	0.00 to -0.7
	<i>June</i>	Low SE sky from midnight, Capricornus into Aquarius	-0.7 to +1.4
JUPITER	<i>April</i>	Bright evening object W sky until after midnight, in Cancer	-2.0
	<i>May</i>	Bright evening object W sky until midnight, in Cancer	-2.0
	<i>June</i>	Bright evening W sky, in Cancer. Lost to view before midnight	-1.8
SATURN	<i>April</i>	Evening object W sky in Taurus, with rings almost wide open	+0.1
	<i>May</i>	Evening object for first fortnight only, low W sky	+0.1
	<i>June</i>	Unavailable for observation	

CONSTELLATIONS (near meridian at 22.00)

1st April Cepheus (below pole), Ursa Major, Leo Minor, Leo, Hydra

1st May Cassiopeia and Cepheus (below pole), Ursa Major, Canes Venatici, Leo Minor, Leo, Hydra

1st June Cassiopeia (below pole), Ursa Minor, Ursa Major, Bootes, Coma Berenices, Virgo

METEORS

Possible show of Lyrids 22 April

TOTAL LUNAR ECLIPSE

16 May in SW sky, about 05.00 BST

ANNULAR SOLAR ECLIPSE

31 May at sunrise in NE, visible N and W of Inverness

TWILIGHT

Astronomical twilight lasts all night around the summer solstice

Compiled by Hamish MacPhee

TERRESTRIAL TELESCOPES, GREAT AND SMALL

The light gathering power of optical telescopes has increased enormously since Hans Lippershey, a spectacle maker from Leiden, in 1608 used a converging lens to collect light from an object, and a magnifying lens of short focal length to inspect the image. It is an interesting exercise to set out the chronological development of larger and larger telescopes from 1600 to the present day.

Lippershey's type of telescope was developed by Galileo, who used a convex lens as an objective in a refracting telescope, in conjunction with a concave lens as an eyepiece to give an upright image. The Great Equatorial Refractor at the original Greenwich Observatory had a 28 inch diameter objective lens with a focal length of 28 feet. But the largest refractor ever built is the one with a 40 inch diameter objective at Yerkes Observatory near Chicago. The objectives of most refractors are achromatic doublets or triplets of long focal length, designed to minimise chromatic and spherical aberration. The first achromatic lens was invented by C M Hall in 1733 and was first used by Dolland in 1758.

The idea of a reflecting telescope, in which a primary mirror would replace the objective lens of a refractor as the light gathering system, was first mooted by James Gregory in 1663. He proposed building a reflector with a paraboloidal primary mirror having a central hole, and a secondary ellipsoidal mirror. This design was never achieved by Gregory, and the first reflector was actually constructed by Newton and demonstrated to the Royal Society in 1671. The primary mirror was paraboloidal in shape. A flat secondary mirror was placed at 45° to the optical axis and this formed an image just outside the main tube, in front of a magnifying lens. Although Gregory himself was unsuccessful in making a practical reflector to his own design, it is recorded by R W Wood that the firm of James Short of Edinburgh was making telescopes to the Gregorian design in 1732.

A 60 inch reflector was installed at the Mount Wilson Observatory near Pasadena, at an altitude of 5,700 feet. This was superseded by a 100 inch diameter primary mirror with a focal length of 43 feet in 1917, financed by J D Hooker. An even larger reflector with a 200 inch diameter primary mirror was built at the Mount Palomar Observatory in California in 1948. Named the Hale telescope, it is owned and used by CalTech. Other instruments at Palomar are 48 inch and 18 inch Schmidt cameras and a 60 inch reflector, the joint property of CalTech and the Carnegie Institute.

The early reflectors all used speculum metal mirrors. This is an alloy of tin and copper which takes a high polish, does not tarnish, and has a reasonably small temperature coefficient of expansion. This has been superseded by silvered or aluminised Pyrex glass, which has a very low coefficient of expansion.

Although it only has a 140 inch primary mirror, it is worth mentioning the Canada-France-Hawaii telescope at the Mauna Kea Observatory in Hawaii. Commissioned in 1979, it is a major facility for French and Canadian astronomers. After the 200 inch Hale telescope, the next step upwards was the astonishing 400 inch diameter Keck telescope. The Keck was built in 1992 and is also located at the Mauna Kea Observatory. Further instruments are planned. The Keck has a Richey-Chretien optical design in which both the primary and secondary mirrors are hyperbolic in shape. This gives a wide field of view, free from coma. The more common parabolic mirrors are free from spherical aberration only. A detailed account of the Keck telescope has already appeared in *Mercury* Vol 10 No 2, p1-2, and this should be consulted by interested readers.

Harry Stout

ROBOTS IN SPACE

The conventional space robot in science fiction has a humanoid appearance, with arms and legs. In many situations though, limbs or external manipulators are not needed and can actually be a disadvantage. For jobs such as monitoring air quality in a space station, or inspecting the corners of some structures, a sphere is the best shape because it is easier to move around using gas thrusters. Also, if it collides with anything, it can just bounce off.

NASA is currently developing two limbless robots, one for use outside its space station, and one for use inside. Both are intended to take over duties which are dangerous or time-consuming for a human crew to perform. For example, the exterior skin of a space station is bound to be punctured every so often by micrometeorites. The resulting holes may be too small to see, but they will nevertheless allow air inside to gradually escape. It is much easier to find such leaks from the outside rather than from the inside, and so astronauts frequently have to go outside the space station checking for leaks. This is not very practical to do, considering the inherent difficulties of any extra-vehicular activity, and could be much more easily performed by suitable robots.

A prototype external robot, an "autonomous extra-vehicular robotic camera", was produced by NASA and has been tested on a space shuttle flight under astronaut control. Now under further development, it is a well-padded, free-flying sphere weighing about 16 kg, the size of a basketball, fitted with TV cameras and sensors. It has six degrees of freedom of movement, i.e. it can move in the three spacial dimensions (up and down, sideways, and back and front), and it can also rotate about each of these three axes. It moves with the aid of small cold gas thrusters which squirt compressed gas to produce appropriate reaction forces. The latest version is endowed with more decision-making ability and is also due for shuttle testing, before being given true autonomy. It is hoped that robots based on this design will be able to continually monitor and inspect the space station from the outside.

For inside the space station, a robotic "personal satellite assistant" (PSA) is being developed. The prototype is also spherical, but is smaller than the external robot. The eventual purpose is for it to assist astronauts by taking care of many more trivial or routine tasks which astronauts have to carry out regularly. PSAs will have several functions. One is environmental monitoring by patrolling living areas checking for levels of oxygen, carbon dioxide and humidity, and monitoring temperature and pressure. Under the weightless conditions in the space station, convection currents do not occur to mix air in different areas, and so local potentially dangerous pockets can occur.

PSAs will also be equipped with a microphone, loudspeaker, camera and display screen for communications. They will be able to connect astronauts to one another throughout the space station for voice and video communication, and also with ground stations for video conferencing. This will also enable ground personnel to manoeuvre PSAs to specific locations instead of the astronauts having to do this. Another planned function of PSAs is to be a helpful database to provide astronauts with a stream of information, such as tasks to be done, tracking of inventory (e.g. where tools have been left), and the current status of any experiments in progress. A PSA could also provide detailed instructions to an astronaut carrying out a difficult task to make sure he/she does not miss anything or make a mistake.

Each astronaut will have their own PSA of a different colour for identification - and no doubt they will have their pet names, to come when they are called!

Derek Allen

ARE THERE CONDITIONS TO SUPPORT LIFE ON EUROPA?

In 1999 NASA's Galileo probe, in orbit around Jupiter, imaged 10% of the surface of Jupiter's moon Europa at high resolution. The subsequent analysis of this data has increased optimism in some quarters for eventually finding life on Europa. Europa has a water ice crust of considerable thickness. If the crust is so thick that nothing penetrates it, the only possibility for life would be for organisms deep down using chemical energy from hydrothermal vents, as occurs in some places at the bottom of oceans on Earth. Hydrothermal vents on Europa could result from heat generated by tidal effects from nearby Jupiter.

However the Galileo findings indicate that the ice crust may be less than 10 km thick and liable to cracking. Half of the 10% of the surface analysed consists of long straight ridges and fault lines in the ice, as if cracks had appeared and frozen over again. The rest consists of blocks of ice randomly frozen in place as if they had drifted around in water, before the surrounding ice froze. There are also signs of tectonic ice plates moving apart and converging, as happens to continental plates here on Earth. A conclusion from this is that cracks in the ice and upwelling melted regions on it have repeatedly exposed the ocean below to the surface. Calculations suggest that regular tides would push warmer water from below up into and through cracks and prevent them freezing over again for long periods - even thousands of years. As Europa rotates relative to Jupiter, tidal stresses in the crust would slowly change so that old cracks would eventually freeze over and new ones be formed elsewhere.

How could this affect the prospects for life on Europa? With relatively stable conditions in the water in and around a crack, organisms could live there near the surface, getting access to sunlight for photosynthesis and also to organic material from impacting comets. Some could anchor themselves to the ice at the side of a crack near the surface, while others could float up and down in a crack with the tidal current. When a crack eventually freezes over again organisms would either have to hibernate in the ice until the crack re-opened, or they would have to be able to migrate down into the water far below and find another crack to go up.

A conflicting view is that the images seen by Galileo are caused by flows of warmer ice like those found in glaciers here on Earth, and not by cracks. The only way to resolve this is to take a closer look at Europa. The US Congress has recently funded \$40 million towards a mission to Europa, so we may not have to wait too long for this to happen.

Derek Allen

Stirling Astronomical Society

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EDITORIAL

Our thanks to all contributors. Everyone please think about items or articles for the next issue.

Please send your contribution to (or first discuss it with) one of the Editors :

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Copy can be in clear handwriting, typescript, e-mail, or on floppy disk, preferably in rich text (.rtf) format, in that ascending order of preference for editing. Contributions should usually be not more than about 750 words in length, or 1000 at the most. Please have material ready by the end of May for the next issue of *Mercury* due out the beginning of July 2003.

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WHAT IS TITAN LIKE?

NASA's Cassini mission to Saturn is carrying the European Space Agency's Huygens probe to study Saturn's giant moon Titan. The probe is due to arrive at Titan in January 2005. What will it find? Titan is larger than the planet Mercury and is the only moon in the whole Solar System with an obvious atmosphere. Its atmosphere is half as thick again as the Earth's and is very opaque. It blocks our view of the actual surface, which is thought to be made of water ice. The atmosphere itself contains mainly nitrogen, hydrogen and methane and may be similar to the atmosphere of the Earth in the early stages of its existence. Thus a study of Titan and its atmosphere could help us to understand more about the history of our own Earth.

From a study of the information which is at present available about Titan, predictions have been made about what Huygens will find. Titan is nine and a half times further away from the Sun than we are, so the winds in its atmosphere are expected to be much less, since atmospheric disturbances such as wind are driven by solar energy. Therefore, it is predicted, wind erosion should be very much less on Titan compared with the Earth, and the surface of Titan is expected to be still covered with largely uneroded craters from impacting bodies. Meteorites and small asteroids should disintegrate and burn up because of the thickness of Titan's atmosphere. Only larger bodies would therefore impact to form craters and so craters on Titan should be at least ten kilometres across, it is calculated. Some of them may contain liquid hydrocarbon lakes, condensed out of the atmosphere.

A layer of liquid water mixed with ammonia may lie below the surface water ice crust. Convection currents from deep within Titan, caused by tidal heating effects from the proximity of Saturn, could create "titanquakes" in the surface ice layer and even form ice mountains, but these tectonic forces would be much weaker than comparable forces on Earth. However, as erosion is so much less, these mountains should grow faster. On the other hand, the crust of ice would be too weak to support large ice mountains, so mountain peaks may be numerous, but not very high.

In another two years, when the Huygens probe arrives to study Titan at first hand, these predictions may be found to be true, but undoubtedly there will be surprises as well, if previous space missions are anything to go by.

Derek Allen

STIRLING ASTRONOMICAL SOCIETY MEETINGS, 2003

11 April	Lecture	(Speaker and title to be confirmed)
25 April	Members' evening	
9 May	Lecture Dr Ross McLure	(Title to be confirmed)
30 May	Last members' evening	

All lectures are on the second Friday of the month at The Smith, Dumbarton Road, Stirling, from 7.30 to 9.30 pm.

All members' evenings are on the last Friday of the month at the Mayfield Centre, St. Ninians, Stirling, from 7.30 to 9.30 pm.

HMacP

THE SPEED OF GRAVITY - SO EINSTEIN IS RIGHT AFTER ALL !

The precise nature of gravity has exercised astronomers and physicists for a long time. Among other things, at what speed does its effect propagate? Is the effect of gravity instantaneous or does it propagate at a finite speed, and is this the same as the speed of light, which according to relativity is the limiting maximum speed possible for anything? To take a hypothetical situation, what would happen to the Earth if the Sun suddenly disappeared? If the effect of the Sun's gravity propagates with the speed of light, Earth would remain in its orbit for another 8.3 minutes - the time it takes light, and thus gravity, to reach Earth from the Sun - and then, without the effect of the Sun's gravity, Earth would fly off into space in a straight line. If the effect of gravity is instantaneous, however, this would happen immediately, 8.3 minutes before we actually saw the Sun disappear.

When Isaac Newton discovered gravity he believed that its influence is instantaneous. In his day, the speed of light and its universal significance were of course not yet known. Einstein assumed that gravity travels with the speed of light and this is a necessary assumption in his general theory of relativity. While many other aspects of general relativity have been thoroughly tested and confirmed over the years, it has not been possible to check the assumption that gravity propagates at the speed of light. Although there has been indirect evidence that it is correct, there has been no way to try to verify it directly until recently. It has been one of the fundamental constants in physics that has never been measured.

The speed of gravity has become an important issue in recent years as it is important in investigations into the ultimate nature of the Universe. In some cosmological theories, space has more than the familiar three dimensions - up to ten or eleven - and gravity can take a short cut through these undetected "rolled up" higher dimensions, and so appear to us to travel much faster than the speed of light, or even be instantaneous.

One way to measure the speed of gravity would be through the detection of gravitational waves, which are ripples in space-time which propagate out from accelerating masses. No-one has yet managed to detect these, although attempts are being made [See for example previous issues of *Mercury*: Vol 15 No 1 Jan 2000, Vol 17 No 1 Jan 2002, Vol 17 No 2 Apr 2002].

Then, with recent advances in radio telescope interferometry, radio astronomer Ed Fomalont and theoretical physicist Sergei Kopeikin realised in the 1990s that it might be possible to take advantage of a relatively rare astronomical configuration to actually try to measure the speed of gravity experimentally. Kopeikin had developed the equations of general relativity to show that the gravitational field of a moving body could be expressed in terms of its mass, velocity and the speed of gravity. If the gravitational field of Jupiter, for example, could be measured sufficiently accurately while also knowing Jupiter's precise mass and velocity (which is not a problem), then it should be possible to work out the speed of gravity from this information.

Ever since Einstein, it has been known that a strong gravitational field deflects the path of light from a star, or radio waves from a quasar, making the source appear to be in a slightly different position from what it really is. Fomalont and Kopeikin's idea was to measure Jupiter's gravitational field and its velocity by the amount it deflects radio waves from a quasar. Quasars (short for 'quasi-stellar radio source') are very distant objects, billions of light-years away, which are sources of highly energetic electromagnetic radiation, including radio and light waves. They are not fully understood, but are generally thought to be galaxies with massive black holes at their centres.

What was to be measured was how soon the gravitational, space-curving effect propagated by

Jupiter is "felt" by the space around it through which the radio waves from the quasar pass, as Jupiter moves around the Sun. If the speed of gravity is infinite the quasar image should trace a perfect circle as Jupiter passes almost in front of it; if the speed is finite, the trace should be an ellipse, the shape of which depends on the speed of gravity. A suitable alignment between Jupiter and a quasar only occurs once every decade or so and Fomalont and Kopeikin had to wait until 8 September last year for Jupiter to align within seven arc minutes of a suitable quasar, bright in the radio spectrum and designated J0842. They calculated that if the speed of gravity equals that of light, the minuscule ellipsoidal deflection of the quasar to be measured would be equivalent to one-billionth of the visual diameter of the full Moon as seen from Earth, or to accurately measuring the size of a coin on the Moon's surface from here. The reference frame for the measurements would be by comparing the quasar's position with the positions of other quasars in the sky whose radio waves would be completely unaffected by Jupiter.

So how could these measurements be made to the degree of accuracy required? Radio telescope technology has only recently advanced to the point where this has become feasible. Using radio interferometry, the data from eleven different radio telescopes could be treated as if it were from a single giant radio telescope 6000 miles across, to improve resolution and eliminate interference. The resulting precision in measurement turned out to be a hundred times better than that which is achieved optically by the Hubble Space Telescope.

The event was simultaneously observed in September 2002 by a team using a network of radio telescopes consisting of the ten 25 metre instruments of the Very Long Baseline Array in the USA (including Hawaii), and the Max Planck Institute's 100-metre radio telescope in Effelsberg, Germany. Observations were carried out for five days at all eleven telescopes, giving a total of 55 "telescope-days" of observations. A number of problems were encountered, including bad weather and short power glitches on eight of these 55 telescope-days. As with light from stars, atmospheric turbulence affects radio waves so that the quasar source "twinkles". This happens much more slowly than light twinkling, on a time scale of minutes, and moves the apparent position of the quasar by an amount which is typically ten times more than the effect of Jupiter attempting to be measured. Consequently, 12% of the data obtained had to be discarded as unreliable.

On 7 January this year Fomalont and Kopeikin announced at a meeting of the American Astronomical Society their conclusion, that the speed of gravity is equal to the speed of light to within a 20% margin of error. If the weather had been perfect throughout the observations, the extra data would have enabled the speed of gravity to be measured to within a 10% margin of error. Their view is that this result is sufficient to state with reasonable confidence that the speed of gravity is actually the same as the speed of light, and that it represents confirmation of this important and necessary assumption in Einstein's theory of general relativity.

This result has come as a relief to many astronomers, as a different result would have been at variance with general relativity and been very difficult to explain. But it may also have implications for theories of cosmology. There has, however, been some criticism of the interpretation put on the result, and its validity. While acknowledging that the experiment has been a great achievement, some are not convinced that the claim to have measured the speed of gravity is correct - there may be some other explanation of what was measured. No doubt the debate will continue until the experiment can be repeated, but it will be ten years before Jupiter and a suitable quasar are in the right configuration again to have another go.

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