Our neighbouring planets

Spacecraft have been dispatched to moons and other planets in the solar system for well over 40 years now. The cost to the participants in this venture, mainly NASA, ESA (the European Space agency) and the former Soviet Union, has been billions of pounds for each organisation. Has it all been worth it? Yes, without a shadow of doubt. The world has changed for the better because of the knowledge we've gained as a result of this effort. I remember as a young man buying a poster of the first picture of the world seen from seemingly distant space. The picture was taken by Bill Anders on the Apollo 8 mission that ran over Christmas 1968. It was the first mission in which mankind left low earth orbit for so-called deep space, sending astronauts around the Moon. Our small blue-white globe hanging in the darkness of surrounding space seemed an iconic image at the time. Some 50 years on, it still seems so. That picture shrank the world. Only 27 astronauts have ever left low Earth orbit and seen the Earth with their own eyes from far away. All were part of the Apollo space program that aimed and succeeded in landing a man on the Moon. No-one has left low Earth orbit since 1972. Spacecraft over the intervening decades have been dispatched to explore other worlds but arguably our perception of our own world has changed as much as our perception of other planets. And how that has changed, too. This chapter will outline some new knowledge we have of our three rocky neighbouring planets.

To design and build a spacecraft to explore another planet is a huge undertaking. It is an adventure occupying years and big teams. Typical costs are between $100 million and $500 million dollars per mission, more for the really big ones. At $50,000 per year per person, that money buys several thousand person-years of effort. Missions fail on the launch-pad, they fail a few km away from the launch-pad and sometimes they fail 100 million km away from Earth. Success isn't guaranteed and yet if it really is worth it, the risk has to be taken.

Planetary exploration is long-term science. You can't find out all that's worth knowing about a planet with a few probes, or even a few dozen probes. Nowadays each space mission has to sell itself as answering a 'big question' such as "Is there water on Mars?", "Has there been life on Mars?", "Has some of Venus' atmosphere been generated by microbial action", and so on. It's taken mankind centuries of serious inquisitive exploration to find out that the Earth has had a complex evolutionary history in its geology, in its biology, in its meteorology and in almost any aspect you care to name. Single space missions won't give satisfactory answers to any big questions – if they're successful they'll help illuminate part of a huge canvas of knowledge that's waiting to be explored. I'm proud to have been part of the generation that contributed the first 30 years of planetary spacecraft. My opening message of this section is that I hope succeeding generations, that's you, will keep supporting space exploration. There are still many questions, both big and small, that are worth answering. You'll be dead before *all* the answers come through, so pass the message on to the generations that follow you. Space exploration is worth it.

1 – 4 from the Sun

Mercury, Venus, Mars and the Earth are four astonishingly different planets. It makes you wonder at the diversity of the universe. Mercury and Venus have only been seen in any detail within the last half century. It is sometimes said that Copernicus lamented he had never seen Mercury, which is unlikely but he did obtain from others crucial measurements to support his book. He made observations with improvised instruments of the rest of the planets, but not Mercury. However, plenty of people share his success, or lack of it, with Mercury.

We'll move out from the Sun, coming to Mercury first. Mercury is a small planet; indeed it is smaller than our Moon. Mercury is only visible soon after the setting Sun, or not long before dawn. Mercury is hard to spot in the long twilight we get in this part of the world. In an earlier chapter we saw how the planet is never more than 28° from the Sun, along the ecliptic. It is usually much less. Official 'lighting up time' used to be an hour after sunset in this country, indicating the extent of twilight. In an hour the Earth rotates 15°, putting much of the space near the Sun below the horizon and the net result is that there aren't many days in the year when you can see Mercury clearly after dusk. Mercury has no moon.

Mercury's orbit was worked out long ago. In the heliocentric system, it is distinctly elliptical, with eccentricity 0.206 and average distance to the Sun of 0.387 AU. However, so little can be seen of the surface of Mercury from Earth because of the glare of the Sun that not even the period of Mercury's rotation about its own axis was correctly deduced from Earth observation. When the answer finally came, the result was bizarre. A Mercurian day is longer than a Mercurian year. I'll try to explain shortly. Our real feeling for Mercury comes from the Mariner 10 probe of 1974/75 that reached the planet, made several flybys, took photographs and many measurements. It was a technical tour-de-force. At the distance Mercury is from the Sun, the heat is so intense that around 10 KW per m^2 falls perpendicularly onto the sunny side of Mercury and spacecraft alike. That's serious heat.

Only one spacecraft since Mariner 10 has returned to Mercury, NASA's Messenger craft that left Earth in August 2004 and flew past the planet in January 2008 and twice since then. Messenger was finally put into a near polar orbit in March 2011. In flying to Mercury it is being pulled ever faster towards the Sun and hence stopping quickly is not a feasible option. 'Messenger' notionally stands for '**ME**rcury **S**urface, **S**pace **EN**vironment, **GE**ochemistry and **R**anging' but of course Mercury was the messenger of the Gods in ancient mythology. There's no need to remember the modern acronym! ESA's BepiColombo mission has finally launched in 2018 and is heading for arrival there in 2015.

Mercury

What have Mariner 10 and Messenger found? A planet that looks superficially like the Moon on the outside and the Earth inside; a planet with a huge iron core; a planet with a magnetic field; a planet that seems to have had a cooling history similar to the Moon. Mercury is an orbiting record of the genesis of the early solar system, as good as a written history, or even better in fact since no personal interpretation has been involved in writing it. Mercury was hammered in the bombardment of the early solar system, as was Earth and all the planets, but with negligible atmosphere, no plate tectonics and no water to change the surface, what we see is mainly what was there 3.5 billion years ago. Mercury's surface is as different from the Moon's as you'd expect from a planet with greater gravity and a slightly different cooling history. Its craters are shallower, ejecta streaks are shorter and it shows shrinkage features that arose as it shrivelled slightly with age.

Mercury close-up

In detail, craters can look quite different from those on the Moon, some having multiple rings of mountains. There are no big 'maria' as there are on the Moon but everywhere you see the effects of shrinkage of the surface in the form of scarps cutting across craters and lava flooding giving rise to plains much smaller than the lunar maria. Like the Moon, Mercury is covered with a fine dust that will preserve evidence of any landing for aeons, because, like the Moon, Mercury has a negligible atmosphere to effect erosion. No atmosphere is expected on Mercury because of its high temperature and comparatively small escape velocity for common gases. Some evidence of a very thin residue of hydrogen, helium, sodium, oxygen and argon has been found, with sodium the most prominent element. These constituents are almost certainly the result of solar wind trapped by the planet, with perhaps some material from the surface released by bombardment.

Very conspicuous in the photographs is one huge impact basin, the Caloris basin, about 1400 km across (on a planet only 4879 km diameter). This basin is thought to have beneath it the heavy remains of a huge impacting body, resulting in an off-centre distribution of matter beneath Mercury's surface. One consequence of this is that the Sun's gravitational force on Mercury is not only a pull but also a slight twist. Mercury's rotation period about its axis has been slowed down by this twist to a very low value (58.65 days, as can now be determined by radar from the Earth, see the Clea experiment referenced on the course web-page) and has been locked in to the orbital period around the Sun of 87.79 days. What is the connection? Three planetary rotation periods are exactly two orbital periods. This is illustrated by the animation in the textbook. Not only this but the Caloris basin is opposite the Sun or exactly facing away from the Sun at every perihelion. This inter-locking of orbital and axial rotational motions is called spin-orbit coupling and similar phenomena can be found in several parts of the solar system. The computer animation shows the effect.

One consequence of Mercury's dynamics is that if you were to watch the Sun from the surface of the planet there would be brief times when it appeared to go backward in the sky. If you remember the discussion of sidereal and solar days on Earth, you'll recognise that on Earth most of the movement of the Sun across the sky is caused by the rotation of the Earth about its axis and a little, backward, rotation of about 4 minutes per day is caused by the Earth's orbit around the Sun. The planet Mercury, in comparison, orbits the Sun about 4 times quicker than the Earth (once in ~88 days) and rotates so much slower that near the perihelion, where the planet's going fastest around the Sun, the retrograde motion of the Sun in the sky from the orbit is faster than the forward (prograde) motion due to the spin of the planet. You don't have to go far from the Earth to find that the universe looks very different.

What else do we know about Mercury? From the orbit taken by Mariner 10 around the planet, the planet's mass and hence density could be worked out. The answer came to 5430 kg m^{-3}, which is how we can deduce that there must be a large iron core (since this answer is twice the density of a typical rock but a good bit less dense than iron). Mercury's magnetic field is about 1% of the Earth's and the magnetosphere, defining the shape of the planet's magnetic field as it is distorted by the Sun's field, look's like the Earth's. Mercury's core is presumed solid, for the planet is too small to have retained primordial heat, and hence the magnetic field is likely to be frozen in to the iron core unlike the Earth's, which is generated by an active dynamo. Ganymede, Jupiter's largest moon, has also been found to have a frozen-in magnetic field.

Finally, could the rest of Mercury not photographed by Mariner 10 be significantly different in character? No. Since Mariner 10's journey, radar probing from the Earth confirmed that the rest of Mercury is similar in character to that already seen. More than 30 years after Mariner 10, Messenger on its flybys has taken pictures of the rest of Mercury. A wide-angle image taken in January 2008, which includes the whole Caloris basin, is shown on a lecture slide. By mid 2012 Messenger had completed 1000 orbits of Mercury and taken over 100,000 images covering a range of wavelengths and of course under a wide range of illumination conditions. To obtain the topography of the whole planet at high resolution requires many more pictures. Messenger is not only an orbital camera but includes X-ray and γ-ray spectrometers to determine the elemental composition of the surface rocks, a laser altimeter for accurate height measurements and other instruments to measure magnetic field effects. The Messenger mission was extended in the summer of 2012 but Mercury is no longer an unknown planet, though working out its evolutionary history will take many years.

We think of Mercury as being so close to the Sun that it must be almost as hot as hell. However, recent speculation is that there are craters near the poles that may never see sunlight at their bottom and perhaps the temperature there remains less than -100°C all the time, cold enough to preserve some frozen water. Water means life support; water and sunlight can be made to generate rocket fuel so perhaps Mercury isn't quite as inaccessible to exploration as it looks in the Mariner 10 and Messenger photographs.

Venus – our neighbour

I've used the phrase 'hot as hell' to describe Mercury. In fact the equatorial surface temperature reaches in excess of 450°C, enough to turn any pizza to charcoal. Venus is almost twice as far from the Sun, receives only a quarter of the radiation per square metre and is surely a much better bet for future habitation? Not a bit of it. Venus has a surface temperature just as hot as Mercury, if not a little warmer. More charcoal pizzas. It's so hot on Venus that lead piping would melt into liquid pools, if there were any lead piping. Don't solder any electronics you send to Venus. Why is it so hot? That's another story, and a very important one I'm coming to shortly.

The 15th century Dutch artist Hieronymus Bosch was famous for depicting visions of heaven and hell. Perhaps he alone would not have been surprised that a place really exits in the solar system where it is hotter than an oven, the atmosphere is suffocating, corrosive, filled with sulphurous dust and so dense that every cubic metre has a mass of about 100 kg, the whole scene is bathed in an overcast orange glow and lightning bolts zap the landscape at all times. Such a place exits and it is the surface of Venus.

Venus is another evening and pre-dawn 'star' (to use the vernacular expression) but more visible than Mercury. Of course it's a planet and not a star. Venus is the Earth's nearest neighbour, 95% of the size of the Earth, 82% of the Earth's mass (and therefore less dense on average). Venus, like Mercury, has no Moon, although that hasn't stopped a few astronomers in the past reporting they have seen one. At its best, Venus is brighter than the brightest star by some way. The brightness of Venus depends on how far it is from Earth and on how much of its illuminated disk we can see.

Through the telescope Venus appears as a brilliant white object with changeable blemishes. Eventually the correct conclusion was drawn by astronomers that the planet is totally enveloped in cloud. Venus being nearer the Sun than the Earth might be expected to be hotter than the Earth but we know from our own experience that cloudy days are generally cooler than bright sunny days. It was not unreasonable for astronomers in the past to speculate that temperatures on Venus mightn't be much different from those on Earth. Surely, they thought, with its permanent cloud Venus is likely to be a watery world of fog and mist where dry land is probably rarer than on Earth. Perhaps the seas contain plants and fish of a kind; the land Venusian grass, bushes and trees, with lakes surrounded by waving rushes? Even at the start of the space-age, in mid 20th century, many people would have agreed that this was a likely scenario. How completely, utterly and totally wrong they were, but it took space-probes sent to Venus to reveal what the planet is really like.

What we see when we look at Venus is certainly its permanent, 100% cloud cover. Beneath that cloud is a very inhospitable world. It is a world that has almost stopped rotating. Indeed it rotates backwards compared with most objects in the solar system, taking 243 of our days to spin once. The Sun rises in the West and sets in the East. So the retrograde motion of the Sun in the sky due to the orbital motion of Venus (whose year is 225 Earth days long) is compounded with the retrograde motion of its spin to produce a Venusian day 117 Earth days long, or almost 4 of our months. Weird! This wasn't discovered until radar signals were bounced off the surface. The cloud layer on Venus is so thick that you'd never see the naked Sun sinking towards the horizon even if you had the patience to wait for it.

The clouds race around the planet at high speed and that's all we see through an Earth-based telescope or even through a camera on an orbiter. Better than bouncing radar signals off the Venusian surface from Earth is to send a spacecraft to orbit the planet and using radar imaging technology obtain a map of the land through the dense clouds. This was first done by Pioneer Venus 1 in 1978 and later by the hugely successful Magellan space probe that mapped 98% of Venus's surface between 1990 and 1994 at a resolution of less than 100 m. I'll show some of these radar pictures.

Our neighbour's property

The only probes to land on Venus and transmit back data have been some of the Russian Venera series. At the start of their programme of exploration of Venus I the 1960s the Russians shared the belief everyone had that Venus was not that much different from the Earth. Their early probes all fell silent in the Venusian cloud: toasted, crushed or etched by acid, who knows. But the Russians learnt what Venus was really like and the slide shows the famous March 1982 Venera 13 picture of rocks on Venus's surface, with sharp edges, bathed in the orange light that filters down through the dense clouds. This colour has been applied to the Magellan radar pictures to give them the appearance of real visual pictures.

Magellan spacecraft

What has radar told us about the Venusian topography? Venus is a planet of clouds and rocks. There are no birds, no trees, no grass, no seas; almost certainly no life as we know it. Igneous rocks, rocks, more rocks and sand. 90% is rolling plain, probably covered with sulphurous dust and perhaps even condensed metallic deposits, it's that hot. There are a few thousand craters of more than a km across, often with floors flooded with lava. The highland regions covering about 10% are volcanic in origin with Maat Mons, the tallest, about the height of Everest (8 km). There is no sign that there is any active volcanism on Venus and no sign of tectonic plate movement such as we have on Earth building mountain ranges. The last time Venus' landscape was re-formed seems to have been about 500 million years ago, when planet-wide volcanism created the Venus we now see. Venus has a heavy metal core, like Earth, but no magnetic field, tending to confirm that the inside of the planet is solid. The slides show some radar-imaged topography of Venus.

Science fact is almost stranger than science fiction in giving us a sister planet that is such an inhospitable place – a crushing atmosphere of gas poisonous to humans, clouds of sulphuric acid droplets, a surface as dry as dust with temperatures that would incinerate most man-made objects. Even the starship 'Enterprise' would never land on Venus. Should we just abandon the planet?

Venus' hellish atmosphere

There's one very good reason for studying Venus very carefully, and that's the composition and behaviour of its atmosphere. It contains 96% CO_2, 3.5% N_2 and, as I've said before, clouds of H_2SO_4 and a little water, with no gaps to see through. No-one messes with sulphuric acid [*Little Willie's dead and gone/ His face will see no more,/ For what he thought was H_2O/ Was H_2SO_4*].

The pressure at the surface is 90 bar, compared with about 1 bar on the Earth's surface, and the surface temperature some 460°C. The high winds in the upper atmosphere move the clouds around the planet at speeds of up to 350 km hr^{-1}. An orangey-yellow light filters down to the surface, coloured by sulphur dust. How did the atmosphere get this way? If this is 'in the family', could something the same happen to the Earth if we mismanage what we've got? That's a frightening thought. So how did Venus get this way?

The overheated greenhouse

Venus's trouble stems from the huge CO_2 content of the atmosphere. On Earth we used to have more CO_2 but three things have happened to our CO_2. Biological growth has broken the CO_2 down into C and O_2. That's where our atmospheric oxygen comes from, 21% of the air we brreathe. Secondly, biological growth has locked away a lot of CO_2 in limestone rocks. So much so, it is said, that if the CO_2 in all the limestones in the world were released into the atmosphere, there would be as much CO_2 here as on Venus. Thirdly, the huge oceans that cover two-thirds of the Earth have dissolved in them about 50 times more CO_2 than we have left in the atmosphere. As a result the Earth has a bit less than 0.04% of CO_2 in the atmosphere, and the surface pressure of our atmosphere is 1 bar. Venus has 96% CO_2 and the surface pressure is 90 bar. What's special about CO_2? It's the gas in fizzy lemonade, in fire extinguishers and in the news whenever global warming is mentioned. CO_2 is an excellent 'greenhouse gas'.

The greenhouse effect

Those taking the meteorology course will know how a greenhouse gas works. Very briefly, it absorbs a significant amount of the IR radiated by the surface of the planet that would have gone out into space and re-radiates some of the energy back to the planet's surface. It therefore prevents incoming energy escaping as fast as it would do if the CO_2 were absent. The planet therefore heats up. On the Earth this greenhouse effect brought on by a combination of the influence of water vapour, CO_2 and other gases raises the average temperature of the Earth by some 30°C from sub-zero to a habitable 15°C. Venus is closer to the Sun and receives almost twice as much solar radiation as the Earth. Without any greenhouse effect the surface of Venus would have an average temperature close to that of a warm day beside the Mediterranean. Sounds promising. Well it would do if there were few clouds in the sky and an atmosphere of moderate thickness. Given the cloud cover it has, if Venus had no greenhouse effect it would actually be too cold for life because the clouds reflect away more than twice the fraction of the sunlight than Earth's clouds do. However, Venus's does have a greenhouse effect. Its atmosphere acts like a blanket around the planet, and one that can't be thrown off when it gets too warm. Not any old blanket but a super heavyweight, one-off, top-of-the-range, no-one makes 'em any thicker in the solar system version. The Sun beats down; 72% is reflected back into space by the high, white clouds but enough energy gets through to keep the surface beneath Venus's thick blanket at over 400°C. The planet is roasted, unfit for humans, or even bugs. If you want a planet-sized sterilisation chamber, there's one next door to the Earth. No charge by the owners for its use.

The big question is: "How much CO_2 do you actually need to roast a planet?" We are well known to be increasing the CO_2 content of the Earth's atmosphere. Is our understanding of the meteorological influence of CO_2 good enough to predict with certainty what will happen? (The answer, by the way, is 'quite well but not with certainty'). Is our understanding of how an atmosphere creates climate good enough to model the climate of Venus, whose atmosphere and conditions are so different from the Earth's? Meteorologists have taken a close interest in the climates of other planets, and any moons with an atmosphere, to extend their understanding of the very complex interactions between the factors causing weather and the actual weather itself. Venus is certainly a very different place from Earth but the laws of atmospheric physics are obeyed there just as well as on Earth and if we think we understand these laws, then climatologists should be able to model the climate of Venus. They are trying. You'll have to do your own investigating if you want to find out how far they've got with Venus. [See our web-page side panel piece '*New light on global warming*' for the reason why the Earth will not follow Venus' example in the foreseeable future].

Mars from Earth

Mars got to its closest distance from Earth for more than 60,000 years in 2003. Yet the words of the song "*we're goin' to collide with Mars*" didn't come true. The distance was still over 55 million km. The closest distance between Mars and Earth occurs when Mars is 'in opposition', which means it's in the opposite direction to the Sun. When this happens Mars is seen due south at around midnight. The closest encounter happens when opposition coincides with the Earth being furthest from the Sun and Mars being closest. It's nothing but a geometrical co-incidence and has no portent on human life. What we see is just that Mars appears bigger in the sky, so get out your binoculars when this happens. In fact the changing size and brightness of Mars with its changing distance from Earth ranging from about 55 million kilometres to over 300 million kilometres is strong evidence for the Copernican model of the solar system. In the old Earth-centred system, the distance of Mars from Earth didn't vary nearly as much.

Mars' orbit *has had* an influence on society. You'll remember that it was the orbit of Mars that led Kepler to the realisation that planetary orbits are elliptical. The idea of elliptical orbits made people realise that many traditional ideas were based on repeated dogma and not on evidence. Mars' orbit is the most eccentric of all those Kepler knew about (he didn't know much about the even more eccentric Mercury), having almost 6 times the eccentricity of the Earth's orbit.

Mars is a small planet, approximately half the diameter and therefore a quarter of the surface area of the Earth and an eighth the volume. The surface area of Mars is similar to the land of Earth (a lot of whose surface is sea). The small size of Mars means that if you were standing on the surface the horizon would appear more curved than the Earth's horizon and noticeably nearer. A smaller planet is also likely to have less gravity and, indeed, Mars' gravity is only

38% of the Earth's. If you stood on Mars, you'd only weigh as much as you did when you were about 10 years old.

Mars has polar ice-caps visible through amateur telescopes, ice-caps that shrink in the summer of the appropriate hemisphere. The changing area of the ice-caps is due mainly to CO_2 ice that freezes from the atmosphere in winter and sublimes in summer. The permanent parts of the ice-caps are mostly water-ice, some 2 km thick, comparable to our Greenland and Antarctic ice sheets. The planet has summers and winters much like Earth, because its rotation axis is tilted at almost the same angle (25.2°) as the Earth's. Because the Martian year is almost twice our year, the seasons are each about twice the length of our seasons. The Martian day (24.6 hrs) is also very close to the Earth's day - the similarity of these figures is a rather spooky co-incidence. Over much of Mars it's very cold, average temperatures being less than -40º C, but near the equator daytime temperatures can become more comfortable. If ever a planet said to mankind 'come here, I've maybe got something for you', then Mars is it. Since space probes became possible, Man has gone there vicariously and looked, again and again.

Mars from Space

First were the *Mariner* fly-pasts in the late 1960s, followed by an orbiter in 1971. These were followed by the two *Viking* landers of 1976, to look for evidence of life on Mars. They found none. You may know the well-known phrase that 'absence of evidence is not the same as evidence of absence', so the search is not dead. The famous *Pathfinder* mission of 1997 introduced robotic exploration to the public at large, securing hours of prime-time news coverage for weeks on end. The more recent *Mars Reconnaissance Orbiter* programme and the *Mars Odyssey* mission are still returning data after years of operation. The web sites for the *Mars Exploration Rover* missions that landed in 2004 have returned thousands of fascinating pictures from two regions of the planet over the past few years. In addition the European Space Agency's (ESA) *Mars Express* has returned spectacular full-colour high-resolution topographic pictures and all the missions return much more data than simply images. Now the *Mars Science Laboratory* (aka the *Curiosity* rover) is moving across Gale Crater with a complex program of exploration set to last for several years if all goes well.

I particularly like the image on the slide that shows the Mars polar lander *Phoenix* hanging from its parachute as it descended through the Martian atmosphere in May 2008 to its resting place just above Mars' arctic circle. Even on a full-screen enlargement, the descending craft is just a few white pixels but an improved full-resolution image of the parachute and lander is shown in the inset. The *Mars Reconnaissance Orbiter's* High Resolution Imaging Science Experiment (HiRISE) camera acquired the images. Although it appears that *Phoenix* is descending into the 10 km diameter crater in the background, it is actually about 20 km in front of the crater. Here in one image is planetary exploration in full swing – one probe landing imaged by another probe orbiting. In August 2012, the *Mars Reconnaissance Orbiter* also imaged NASA's *Curiosity* rover landing in Gale Crater near Mt Sharp. At the time of updating these notes, *Curiosity* has had a successful start to its mission. If all goes well it should return a huge amount of information about Mars and its evolution. It also has a suite of instruments to detect signs of microbial life should any be available for detection.

What kind of place have all these missions found?

Mars is a dry and dusty planet, showing plenty of signs of past water and, the evidence is now clear, of water still trapped frozen beneath the surface. Mars has some very large, apparently completely dead volcanoes – indeed *Olympus Mons* at 25 km high is the largest in the solar system. The interior of Mars is hot so it is possible that another era of volcanic activity could erupt in the future but like Venus, Mars has no tectonic, mountain building and continent drifting, activity. Mars is indeed the red planet, red with iron oxide rust in its surface rocks, a dust that is whipped up sometimes by planet wide storms sufficiently vigorous to obscure the planet's surface to the cameras of our circling spacecraft.

The multi-coloured image on the slide is a false colour contour image showing terrain height across the whole planet. Huge areas are very low, like past ocean floors, and there is a raised continental area – we would call it that on Earth – on which sit massive shield volcanoes.

Atmosphere of Mars

Yes, Mars has an atmosphere but don't take off your helmet when you step out of your lander. Mars atmosphere is only about 1/200th of the pressure of the Earth's atmosphere. This is about the pressure on Earth at a height of some 100,000 feet, or over 30,000 m. Worse, the atmosphere is 96% CO_2, which means that in absolute terms there is much more CO_2 in the Martian atmosphere than there is on Earth. Fine for fizzy drinks and fire extinguishers but no good for animals like us to breathe. (Fires are pretty unlikely of course, because the atmosphere contains very little oxygen and there is no naturally flammable material on Mars). Also on the unhelpful side, night-time temperatures plummet to -140°C and there is no ozone layer to protect us from harmful UV. One of the consequences of this is that any water molecule that is released from the surface, drifts to the upper atmosphere where it is eventually decomposed into H_2 and O. The H_2 escapes, because Mars is a planet too small to hold on to gaseous hydrogen, and hence the water is lost forever. There are clouds in the Martian atmosphere, but they are mainly, but not exclusively, clouds of solid CO_2, or dry ice as we know it better. The odds seem to be stacking against mankind moving permanently to Mars in the near future.

To come back to the issue of atmospheric pressure being about 0.5% of the Earth's, this doesn't mean that the mass of atmosphere above you on Mars is only 0.5% of what it is on Earth. In fact it's more, nearer 1.5% when you put in more accurate figures. The basic reason is that atmospheric pressure is essentially the weight of air above you and gravity on Mars is a lot less on Mars than on Earth. Hence there needs to be more air (mainly CO_2 in Mars' case) above you in Mars to create a given pressure. The atmosphere is quite sufficient to slow descending satellites by 'aerobraking' and for parachutes to slow landers to a safe speed as they plummet towards the surface. I was wondering about the feasibility of ballooning in other places in the solar system and did some 'back-of-the-envelope' sums for Mars, Venus and Titan using basic physics. You can see the results in the note I've linked to on the blue panel of our astronomy web page, called "Planetary ballooning". The figure I've used for surface atmospheric pressure on Mars is 8 mbar, which is a representative average between the higher pressures in the lowest chasms and the much lower pressure on the Tharsis Plateau and the volcanic heights.

Moons of Mars

Mars has two tiny moons, Phobos and Deimos named after the dogs that used to accompany Mars. They look like captured asteroids, in shape and colour, yet the question of where they come from is far from settled. Capturing without collision requires 3 bodies to be interacting in almost the same place and at the same time and since this is so unlikely nowadays, the conclusion is that if the moons were captured then this took place early on in the history of the solar system. However, the moons are close to being in equatorial orbit around Mars, just where you would expect to find a body that had been ejected from Mars. Since our Moon is now reckoned to have come from the Earth, are the chances that Mars' moons came from Mars not greater than the chances that they have been captured from a distant asteroid field?

Recent measurements by the Mars Express team of the mass and volume of Phobos suggest that it has substantial cavities in it, occupying from 15% to 45% of the volume, depending on what the moon is made of. One might expect this if it had been assembled from rocky debris blasted into orbit by an impact of Mars. Enter a planned Russian soil-sampling probe, launched in 2011, called 'Phobos-grunt' in Russian (Phobos-ground), that was to land on Phobos and sample the ground. Unfortunately the mission failed to leave low-Earth orbit. In spite of this particular set-back, Phobos, the nearer to Mars of the two moons, will be a significant exploration target in the next decade, possibly even becoming a site for manned landings in future decades well before Mars itself is attempted. The gravity on Phobos is less than 1/1000th that on Earth, making Phobos easy to get back from; the escape velocity of 11 m s^{-1} is big enough to hold you down when you jump up from the surface; at about 6000 km from Mars' surface the views of central Mars will be stunning and the lack of atmosphere scarcely any less troubling than the lack of atmosphere on Mars. Indeed Phobos will have scooped up ejected Mars rocks over billions of years. Exploring it may be as useful as raking though a Hoover bag to sample what the carpets in a house contain. Watch the science news for the next episode of the Phobos story.

Mars topography

Readers of Arthur C. Clarke will be intrigued to learn that Phobos really does seem to have a monolith on its surface. Of course it's most likely Martian debris hovered up, but……… . Mars itself has a wide and varied topography, from the fantastical to the mundane, the beautiful to the evocation of the rubble and residue of a long deserted quarry. There's no hiding it beneath clouds and haze, at least for most of the time. As a result of past and present interest, there are an enormous number of pictures of Mars on the web. Indeed, the surface if Mars is much better known than most of the Earth's sea floor. In close-up Mars turns out not to be the god of war but the nearest the planets can offer to a red-headed beauty. The slides show a few of the diverse features, including the huge Vallis Marineris canyon complex (named after the *Mariner* missions) as photographed in high resolution and full colour by ESA's *Mars Express* orbiter. Many features show the evidence of water erosion and others show the evidence of wind erosion. A very few examples are illustrated on the slides.

Mars images

We can't go there just yet but we do know what it would be like to stand on Mars. See the accompanying 3D pictures taken by the Pathfinder mission of 1997 and the Mars Exploration Rovers of 2004. You need cyan and red anaglyph glasses (issued in the class) to re-create the 3D experience. The first slide, not in 3D, shows the *Pathfinder* rover on its landing pad. The next slides show the landscape looking around from this landing site. Not a lichen nor a blade of grass is in sight. Not a drop of rain has fallen on the plain for millions of years. No birds fly overhead, no insects buzz around your helmet; indeed the absence of an atmosphere as we know it would surely make the surface of Mars deathly quiet. Our technology being what it is at the moment, the landers have been targeted at some of the safest places to land, not the most dramatic places such as the Vallis Marineris. In many ways the landscape itself doesn't look that alien. As one of the mission scientists running the Pathfinder programme said, the scene "*looks like Arizona without the cactus*". Maybe. But if you dig in the Arizona desert you'll find life. No-one has found any signs of life on Mars yet.

Pathfinder wasn't about finding life. One of its aims was to measure in detail the reflectance spectra of the rocks, essentially identifying different kinds by their colour. The rocks are evidence of planetary history past. If the area contained a variety of rocks, which it was found to do, the only conclusion is that the rocks had been brought to the same place by geological process, such as water transport, that have since stopped. Also following are a few 3D pictures from the rovers called *Spirit*, that landed in Gusev Crater, a huge crater region, and *Opportunity* that fell into a tiny crater in the extensive Meridian Plane region (Meridiani Planum), well around on the other side of Mars. These rovers have found detailed geological evidence for the existence of past surface water on Mars.

Mars Odyssey, launched in 2001 and still returning results over a decade later, is continuing its look at rock types, though on a much wider scale, from orbit. It is also trying to assess whether the radiation hazard is acceptable for future manned missions.

Exploration of Mars has concentrated on 3 aspects. First, mapping and photographing all the visible features; secondly looking at the composition of the surface; thirdly looking for evidence of water on Mars. Liquid water, the argument goes, means life is likely to have evolved. Clearly Mars hasn't got liquid water on its surface. Looking for evidence of past water has been the motivation behind the two Mars Rover missions *Spirit* and *Opportunity*. 'Follow the water' has been the theme. Apart from topographical features left by past water, there are three good ways to look for close-up evidence of past water. 1) Look for salts left behind from salty water that evaporated. 2) Look for rocks that show evidence of being originally laid down wet. 3) Look for signs of volcanic explosions where water contacted hot, molten rock. All three kinds of evidence have been found, sometimes all together at the same spot. Water is the key to eventual human habitation of Mars. One of NASA's main drives, and ESA's, has been to follow the trail of evidence for water on Mars. There is now plenty of evidence that surface water has existed and further evidence that there is still lots of trapped water in the form of ice beneath the surface. The *Curiosity* rover trundled over rounded shingle not long after setting off. There's absolutely no doubt that surface water used to exist on Mars. In fact an early geological period of Mars around 4 billion years ago has been called the Noachian, reflecting the fact that surface water was likely to be abundant at that time, (along with substantial early solar system bombardment).

The next question to be settled is whether Mars had a long wet period, perhaps exceeding a billion years, in which life could have evolved significantly, or did it just have some moderately short wet phases of perhaps a few million years each, triggered by extensive volcanic activity, in an otherwise cold and dry history. The average temperature on Mars is sub-zero now, even with the Sun hotter than it was in the early solar system. Maybe Mars has always been very cold and pretty dry. We are hoping the *Curiosity* rover will provide much more evidence from which the evolutionary history of Mars can be re-constructed.

In future, the motivation for missions will shift to assessing the habitability of Mars. This topic is already on the agenda, with measurements of UV and radiation levels on Mars. It will progressively rise up the priority list. The problem that will be hardest of all to crack will not be protecting people from radiation bursts while they live on Mars but protecting people during the many-month journey from Earth to Mars, and back. In fact that problem alone could delay by years, if not decades, our present aspirations to get to Mars.

Life on Mars

One only has to look at the surface of Mars to realise it has no life of the kind we are used to seeing around us. The reasons are pretty obvious: there is no surface liquid water, there is negligible oxygen in the atmosphere, UV radiation levels are high, as is ionising radiation from the Sun and comic rays. Temperatures are typically Antarctic or lower. It's a multiple whammy. In spite of all this there is lots of carbon around in the form of atmospheric carbon dioxide and iron and sulphur minerals can be found everywhere on the planet. These ingredients have allowed anoxic microbial life to take hold in otherwise biologically hostile environments on Earth. The likelihood gets stronger by the year that Mars did have some form of life in times past. It's well established that the early vestiges of life on Earth were present 3.5 billion years ago. In that era, Mars also had liquid water, an atmosphere and land of volcanic rocks similar to Earth's. It would not be surprising if life had started there too. Maybe Mars could even now harbour some lifeforms well below the ground, but the chance of there being little green men is very small indeed. Could the Martian meteorite ALH84001 really show a fossil Martian bacterium? The case is not proven, but not disproved either. In the last year or two the balance of opinion has swung back in favour of an organic origin of the feature in the rock.

It's worth re-emphasising the point that today's presumption by astronomers and the public at large that the solar system beyond the Earth is lifeless unless proven otherwise is quite different from public expectations before probes were sent to other planets. An example of past perceptions can be seen reflected in science fiction stories concocted in the first half of the 20th century. To be good stories they had to have some degree of plausibility associated with them within the general understanding of the times. Mars could be seen to be desert-like through the telescope but deserts support cacti, insects, scorpions and other specialised plants and animals, so why not Mars? Indeed, might Martian versions not be better adapted to desert conditions than our own desert life, for there is more desert on Mars? Venus being permanently covered in cloud was seen as likely to be a wet and marshy place, stocked with its own version of aquatic and pond life. Our neighbouring planets were seen to be like countries too far off to have been visited, but no-one assumes that unexplored countries are totally barren. Such ideas had been floating around since it was realised that the planets were real bodies orbiting the Sun with us. Respected science fiction writers such as Ray Bradbury wrote stories about Mars and Venus as if they were alternative film-sets with most of the attributes of Earth. The 'space age' blew such ideas out of the water, to use the well-worn idiom. It happened in the 1970s and 80s, thanks to space probes. Mars and Venus are our neighbouring planets but they are now known to be so different from the Earth that most past assumptions have been revealed as the baseless fantasies they were. 4 billion years or so ago, though, the three planets may have been much more similar. How Venus, Earth and Mars evolved so differently is a story that will take many decades and many probes to unravel.

Whether Mars had life in the past is fascinating but in the long run it's an academic argument. What seems to me the next best thing to certain is that Mars will have life in the next few thousand years, if not even in the next few centuries. You are likely to see a Mars manned mission within your lifetimes. Even I may see one. Making Mars habitable for people is theoretically possible. It will happen. As was one once said, 'there has never been a flower on Mars', but someday there will be. My own view is that it's probably just as well we can't colonise Mars at the moment since the society we would set up would likely just reflect today's on Earth: sectarian, nationalistic, opinionated, disputatious, prone to fighting, greedy, unequal… . Yes, I know we have our good points but it would be better to leave many of today's attitudes behind when we colonise a new planet and I doubt if mankind is yet ready to do that. Fortunately, a colony on Mars in the 21st century is unlikely, for reasons I've discussed in a separate piece referenced in the web-page blue panel. Maybe in a century or two.

JSR