Earth-Moon System

Earth at night

To see even the bright Moon properly you need clear skies and I can't resist taking the opportunity of beginning with NASA's spectacular Earth-at-night picture - or how the Earth would appear without cloud cover. It's a picture that is not only of astronomical interest, but one that says a lot about the world's demography and economy. This section of the course, taking two to three lectures, covers the Earth-Moon system.

Moon slide

There are many features of the Earth-Moon system that are relevant to the study of the Universe at large.

- It is held together by universal **gravitation**, whose basic law is simple but whose effects are not.
- The Moon has **craters**, like many other objects in our solar system and presumably throughout the Universe. How were they formed and what do they tell us?
- Measuring size and **distance** is a fundamental issue in astronomy. We have to start from homebase. The surer we are of distances in the solar system, the surer we are of measuring the much larger distances between stars and between galaxies. The Moon is the first permanent body beyond the Earth. The Earth-Moon system is the obvious first solar system distance to find.
- The Earth-Moon system provides the fascinating spectacle of both lunar and solar **eclipses**. These have influenced societies, ancient and modern, and provided valuable insights into the nature of the Sun in particular.
- There is a tendency to think of heavenly objects as points, because they are so far away. Of course heavenly bodies are all of **finite size** and with the Earth-Moon system you can see what a difference this makes.
- The Moon is the only other celestial body humanity has personally **visited**. It is a very different place from the Earth and certainly worthy of study.

The size of the Earth

Our international standard of length is the metre, a distance you can easily encompass between outstretched hands. In astronomy, a distance of 100 million metres is almost nothing. Even the Moon is further away than this. How can you even measure a distance that big? You certainly can't put 100 million metre sticks together end-to-end. The basis of measuring astronomical distances is to measure a large distance and then use that as the unit for measuring an even larger distance, and so on. One natural way of starting this chain is to measure the size of the Earth.

One of the stories in science that you should know about is how Eratosthenes (276-195 BC) measured the diameter of the Earth before 200 BC. He used a clever astronomical technique. He had heard that at noon on mid-summer's day the Sun shone down a well at Syene (now Aswan in S. Egypt). Eratosthenes believed that where he was in Alexandria was due North of Syene. He determined that the Sun was 7½º from the zenith in Alexandria at the same time as it shone down the well in Syene. He did this by measuring the length of the shadow of the great obelisk in Alexandria. He argued that Alexandria must therefore be 7½º due North from

Syene around the world and he knew the distance between the two cities was 5000 stadia or about 1000 km. (Some say he had this distance measured by commissioning a man with a camel to walk it). His value for the diameter was about 15,300 km, not too far wrong. The *next slide* shows the textbook figure.

The principle of the method is that if you know the latitude difference between 2 places and the perpendicular distance between the 2 lines of latitude, then you can find the Earth's radius.

K & K's picture

Eratosthenes' method wasn't particularly accurate because:

1) Syene isn't quite on the tropic of Cancer, so the Sun doesn't shine straight down a vertical well on mid-summer's day.
2) Alexandria isn't exactly due north of Syene, so the distance between these cities isn't the distance between latitude lines.
3) The distance was poorly known by modern standards.

Distance to the Moon

A useful way of measuring the distance to objects a long way away is to measure their **parallax** as viewed from two places a known distance apart. Parallax is the change in the angle of view as your observation position moves. For example, if I move 2 m to the right and my angle of view towards a person at the back of the lecture theatre changes by 10°, then I can calculate from the geometry of a triangle that the person is about 11 m away. No metre sticks are required to stretch over the 11 m. If the angle changed by only 5°, then person would be 23 m away. This geometry uses the relationship introduced in the very first lecture that a *small angle* is a measure of *width/distance*. In this case I know the *width* and the *angle* and can therefore deduce the third quantity, the *distance*. The change in angle of view is known as the **parallax**.

Now, the stars in the night sky have no parallax from anywhere on the Earth, at least none measurable by naked eye or simple instruments. I.e. there is no measurable change in the angle of view to any star.

The historic figures shown on the slide give a lunar distance that wasn't too far out. The average distance, surface to surface, from Earth to Moon is about 376,000 km.

Careful observing of the angular size of the Moon or just taking a series of photographs at regular intervals shows that the Moon varies its distance. The change in distance is about ±20,000 km. This happens, of course, because the Moon is in an elliptical orbit around the Earth, just like the planets around the Sun. In fact the eccentricity of the Moon's orbit around the Earth is several times greater than the eccentricity of the Earth's orbit around the Sun.

It's hard to appreciate that in astronomical terms the Moon is very close to the Earth, about 30 Earth diameters away. Look at someone who is 30 times your own width away and they will be at 30 paces, well short of the centre line of a football pitch if you are the goalkeeper; not much further than your opponent if you are serving in a tennis match. Our nearest planet, Venus, is never closer than 100 times this distance away, 3 km on the same scale. Mars, the next target for a planetary manned landing, is never less than 5 km away on this scale. It's a sobering thought that we're not likely to have the technology to get a man or woman onto the Moon again for another decade or so, and that's just getting someone as far as the Moon. Exploring the solar system is not a trivial business.

Waxing and waning of the Moon

The Moon is lit by the Sun and viewed from the Earth.

Phases of the Moon: **new** (can't be seen) - **crescent - first quarter** (half lit) - **gibbous - full,** and back again though **gibbous – third quarter** and **crescent**. The animation shows the changing illumination of a lunar month. The Moon is a ball in space intercepting the blaze of light from the Sun. Half of the ball is always illuminated. Because we look side-on to this illumination, most of the time we see only a partly illuminated Moon disc.

Phases of the Moon

This slide shows the phases of the month over a lunar month. In 2006 'new Moon' occurred on the 1st of January and I've used this example on the slide to show the evolution of a lunar month. If you're lucky enough to get a run of clear nights in a row, look up at the Moon on successive days and you'll easily notice that you see more of it each day when it is growing towards full Moon, i.e. waxing. Our ancestors would have been very familiar with this. Of course the reverse happens with a waning Moon: we see less and less each day.

The Moon's phases are easily understood if you mentally clock how far the Moon is behind or ahead of the Sun passing the same direction you're looking in. For instance if the Moon is passing 6 hours after the Sun then it will be a first quarter Moon and lit from the right in the Northern hemisphere; 12 hours after the Sun and it will be a full Moon; 6 hours before the Sun and it will be a third quarter Moon, lit from the left.

Waxing Moon

One side of the Moon's shape is always a semicircle. The other is our perspective view of the line of longitude on the Moon that is at the edge of the Sun's illumination. This line is called the *terminator*.

I've used an Excel spreadsheet to calculate the typical position and shape of the terminator for all 14 days before and after full Moon. The results are plotted on this and the next slide. As the Moon is *waxing*, i.e. growing in appearance, the right-hand-edge of the Moon's disc is in permanent sunlight. The terminator moves across the Moon and its appearance from the Earth changes as shown. If you were to mark out on the Moon itself what is happening as the Moon waxes, you'd see that the terminator remains as a circular line wrapped around the Moon's globe, stretching more or less from lunar pole to pole. It moves slowly around the Moon as the Moon rotates in its orbit.

Waning Moon

When the Moon *wanes*, the left-hand side of the disc remains in permanent light and is always a semicircle. The illuminated right-hand side moves across, as shown.

In reality, the terminator isn't a smooth curve. When you look at the Moon through a low power telescope you see wonderful detail of the Moon's craters down the terminator. Just inside the geometric terminator the crater ridge walls glow brightly in the surrounding darkness. The larger ones reach up a few thousand metres into the sunlight. Just into the bright side of the terminator, the bowls of craters show black in surrounding light, because they lie in the shadow of lit crater walls.

There is another reason that the Moon doesn’t appear quite as in the simple picture shown on the slide. In reality, a crescent moon doesn’t appear to sweep out an arc of 180°, but sometimes much less: even less than 90° on occasions. The reason is to do with the difficulty that the eye has of seeing a very thin line of light that gets weaker and weaker towards the crescent point against the background illumination level. In brief, the fact that we don’t see 180° of crescent is due to a defect of our visual system, not any misunderstanding of how the Moon is illuminated.

The Moon looks different from day to day, because of the changing illumination over its surface, particularly at the terminator. Even the detail of its appearance doesn't repeat precisely from month to month because the synodic month is not a whole number of days. The Moon is indeed one of the best astronomical objects to look at with binoculars or a telescope.

Moon’s appearance – full Moon

The Moon can look quite big in the sky, especially when it is close to the horizon. As far as moons around planets in our solar system go, it is pretty big. It has a diameter of 3476 km. Its area is about the size of Africa.

The Moon is part of all our lives. I’ll spend some time in this chapter talking about when and where we see the Moon in the sky, what it looks like and why we sometimes see eclipses. You have to think about the relative positions of Sun, Moon and Earth, how these bodies move and how long they take to move. What’s going on isn’t straight forward and to get it you’ll need to think quite hard and try to visualise the changing positions of the bodies in space. I don’t guarantee everyone will get it in the lecture. You may need to draw your own diagrams to help you.

As I write this section of the notes I have just been looking at full moon through a pair of low-power binoculars (8×40s). It’s hard to imagine that what you are looking at is a 3-dimensional object, its centre bulging toward you by over 1700 km compared with the edges. As the Moon travels across the sky at night from where we are (Aberdeen) it seems to turn around its centre clockwise, so you can’t describe a particular feature as being at the top or the bottom, or wherever, and expect it always to be there. Of course it’s us on Earth who are doing most of the rotating. Where a feature is relative to the horizon on the disk you see depends on when in the night you look, or even when in the daytime because the Moon is quite bright enough to be seen in a blue sky and you can identify features with binoculars during the day too.

[The changing orientation of features on the Moon comes about because we measure orientation with respect to a plane containing the zenith and the direction of the Moon. As the Earth spins around, so the zenith spins around in space by an amount that depends on the zenith distance of our location from the pole. For Aberdeen, this is about 33°. The net result is that if we could see the Moon from Aberdeen over 24 hours it would appear to oscillate clockwise and anticlockwise over about 33°. Its apparent motion is even a bit more complicated since the Moon has some independent motion of its own about its own rotation axis that isn't perpendicular to its orbit. If you go to places much further south where the zenith distance is much larger, then the Moon appears to spin right round over 24 hours. It will stretch most peoples' 3D visualisation to make a mental picture of what's going on. Much better is to use some software where all the 3D geometry is correctly incorporated (such as the Stellarium software available on the class-room PCs and on the web) and follow the changing orientation of the Moon in time.]

At full moon the crater Tycho near the bottom edge in the evening shows bright, with bright conspicuous rays extending out from it all round. Tycho, like many of the larger craters, is approaching 100 km across, with crater walls some 5 km high, measured from the crater bottom. Looking through the binoculars you can just about imagine that it is the product of a big splat, but it helps to have seen much bigger images than the binoculars can show. The crater Aristarchus shines out bright in the dark Oceanus Procellarium, the largest dark area, towards 9 O'clock on the Moon's disk in the evening. The Sea of Tranquility (Mare Tranquilitatis), is conspicuous in the middle of a succession of dark patches, the site that will be forever famous as the location of mankind's first landing on the Moon ("*That's one small step for man, one giant leap for mankind*" as Neil Armstrong famously said when he stepped onto the surface). Many other features are visible with only modest binoculars such as the ones I had in my hands but you will need a good map of the Moon to identify them.

If you look at the Moon over a series of nights you'll find that what is conspicuous at full moon isn't so conspicuous at other phases, and vice versa. Different features stand out as the lighting changes. The Moon is an object to look at that will give you years of satisfaction.

The next 4 slides show an assortment of lunar features.

First slide of lunar features

- Top right shows a Mercator projection of the Moon's surface. Notice that the dark areas are only one side, the side facing the Earth.
- Left shows the Moon lit by reflected Earthlight, the Sun about to break at lunar dawn. Venus is visible at far right.
- Bottom right is the *Mare Imbrium,* one of the huge lava-flooded areas of the Moon.

Second slide of lunar features

- *Hipparchus* is an ancient crater ~100 km across. The crater walls show points of light lit within the geometrical terminator region and the crater creates dark areas in the light region. The crater walls rise ~1200 m but the level of the outside line is comparable to the tops of the crater. Notice that the crater walls are themselves heavily cratered. Notice the partly lava-flooded ghost crater in the floor.
- *Cleomedes,* a circular crater foreshortened by perspective, is another large crater that shows well the broken light around the terminator.
- *Alphonsus* is a typical large crater ~100 km across with a central mountain. I'll say more about the reason for this later.
- *Hygnius Rille* is an example of a typical linear feature found on the Moon. These may be old lava tubes or cracks in the surface. They are a few km across.

- *Copernicus* is a most conspicuous, large 'young' crater, dated at 810 million years old. Notice the terraced walls, rising to ~3200 m, the internal mountains and the lack of craters breaking down the walls.

Third slide of lunar features

- *Tycho* is the most conspicuous crater on the Moon because of its size and hugely extending radiant white rays that are particularly visible when the Sun shines straight down. *Tycho* is 'very young', ~109 million years old, and occurs in an upland area otherwise sparsely populated with large craters.
- *Sinus Iridium* shows how the lava flooding of the adjacent Mare has broken down and covered half of a large crater wall.

More Lunar features

The rays emanating from some craters are best seen when the Sun shines more nearly straight down than at a sloping angle. The picture two slides back of *Copernicus* didn't show the rays. This picture from the Digital Lunar Orbiter Photographic Atlas of the Moon shows the rays clearly. The rays are the tracks of ejected material, shot out many hundreds of km in the case of *Copernicus*. The rays are peppered with small craters. The crater *Kepler* one third the size of *Copernicus* shows similar rays but on a smaller scale.

The crater *Plato*, just North of the *Mare Imbrium*, is a fine example of a crater formed early on in the Moon's history that has been flooded with lava. Maybe Galileo wasn't so far wrong in calling the dark areas *Mare*, or seas. When they were formed they were seas of lava, not water, and being liquid when they formed they are pretty flat, except where disrupted by later cratering.

The illustrations of the past few slides show lunar features in close-up. Let's return to the Moon seen as a feature of the night sky seen by the naked eye.

Far side of the Moon

NASA's Lunar Reconnaissance Orbiter has used laser ranging from orbit to make the most detailed topographic map of the Moon, reporting results in late 2010. The orbiter can measure heights to within about 1 metre. It has taken several billion point measurements that also determine the local slope of the land, implying a coverage of the lunar surface about every 30 m. In spite of the comparatively small size of the Moon (less than 2000 km in radius) the tallest peaks exceed Everest in height, measured from the average level of the Moon. The deepest craters are almost as deep as the Earth's deepest ocean trenches. The slide is from an image that shows the far side of the Moon in unprecedented detail.

Moon keeps the same face to the Earth

The Moon almost keeps a constant face to the Earth. It rotates with sidereal period of 27.322 days.

The animation shows how rotation of the Moon about its axis is needed to keep the same face of the Moon towards the Earth. This is called *spin-orbit coupling*. It is thought to have happened a long time ago in the evolution of the Earth-Moon system.

Notice that if you are standing on the Moon looking up at the Earth, then you'll see the Earth hanging in the sky. The Earth, though, will go through phases from full Earth to night-time Earth. The accompanying is a picture taken by the Clementine mission.

Lunar librations

It's a slight complication that the Moon's rotation axis is inclined at about 6° to its orbital plane. This causes a small apparent wobble of the face, known as a *libration*.

Moon's synodic period

The *synodic period* is the time between successive new moons, namely the Moon having the same longitude as the Sun. It's also the time between successive full moons. The synodic period is 29.53 days (to 2 decimal places). It is different from the sidereal period of 27.3 days because Earth-Sun line has moved round in space due to rotation of Earth around Sun in the same direction as the rotation of Moon. Another 2+ days is caused by the rotation of the Earth during a complete rotation of the Moon. See the slide.

Everyone knows that the synodic month doesn't fit in exactly to the solar year. This means that full moon, for example, occurs on different days in successive years. In fact it is about 11 days different in the same month on successive years. However, around 430 BC the Greek astronomer Meton re-discovered that 19 solar years was a close fit to a whole number of synodic months, namely 235 months. Try it on your calculator. 235 synodic months, or lunations as astronomers tend to call them, is now known as the Metonic cycle. After 19 years, the same days of the year have the same phases of the Moon (give or take a day due to the presence of leap years).

The lunar month determines some important religious dates. In Christianity, Easter Sunday is the first Sunday after the first full Moon after the equinox. From this you can easily deduce that Easter is more likely to be in April than March. It's also not hard to deduce that Easter can never be in March in two successive years. The Islamic calendar is a lunar calendar of 12 months. The most holy month is the 9th month, Ramadan, during which Muslims fast between sunrise and sunset. Since 12 lunar months are about 11 days short of a year, then Ramadan moves slowly through the calendar over the years.

The Moon's orbit

The orbit of the Moon controls where in the sky, and when, the Moon is seen. It also controls eclipses. However, the orbit of the Earth's only natural satellite isn't as simple as you might expect. The Moon certainly doesn't go round and round the Earth in circles.

If the Moon's orbit were in the same plane as the Earth's orbit, then the Moon would follow the track of the Sun in the sky over a year, but do so in about 4 weeks. It almost does. We'll come to the complications shortly. The Moon goes around its orbit about once every ~28 days (actually 27.3 days, as we've seen). This means that it moves through the stars from West to East by about 13° per day. It's for this reason that the Moon is seen in the same azimuth direction typically 50 minutes later each day.

Where is the Moon in the sky?

Ask the 'man in the street' and he may well say something like 'it's just there'. After some thought, he may add 'some of the time'. What should the Aberdeen University graduate say?

Let me begin again with a digression. You know how the Sun changes its position in the sky over the four seasons. In the summer it rises from around NE in the small hours of the morning, travels high in the sky at mid-day and sets near the NW in our latitude. In winter it rises near the SE, is low at mid-day and sets about SW. The complete seasonal cycle takes close on 365 days.

The Moon goes through a similar set of changes in only about 28 days, the time it takes to go around its orbit once. Every night the Moon not only rises about 50 minutes later, but does so from a different point on the horizon and follows a different track across the sky. I've used another Excel spreadsheet to calculate the altitude and azimuth changes of the Moon each day over half the lunar month, as seen in our latitude when the Moon is close to the ecliptic. The result is on the slide. The tracks could equally well be for the Sun over a period of 6 months instead of the Moon for a fortnight. One complication you can now appreciate is that as the line of nodes slides around the Moon's orbit, the inclination of the orbit to the equator changes by ±5.15°. When the inclination of the orbit to the celestial equator is at a maximum, the Moon gets even higher in the sky at its maximum and sets even further North than NW. 2 weeks later, it is even lower in the sky than shown on the slide.

Which track on the slide is full moon and which is new moon? That changes throughout the year. I'll show what's happening by taking the example of full moon. Remember that full moon occurs when the Moon is opposite the Sun in the sky, with the Earth more or less in between. In summer, the Sun's declination is greatest and it rises highest in the sky. At full moon the Moon's declination must therefore be least and the summer full moon is the lowest of all full moons, following the bottom track. At midwinter, the opposite happens. The Sun's track across the sky is lowest and the winter full moon rises to its glorious highest. If you've followed this argument you should be able to deduce that around the autumnal equinox, both Sun and full moon have near zero declination. When the Sun sets due West at around 6 pm GMT (which is 7 pm BST), the full Moon rises due East, following the same track in the sky as the Sun. The Moon therefore extends the day for farmers gathering their crops, which is part of the phenomenon of the *harvest moon*. No prayers are necessary, it's all provided by nature. Now you know how.

Comparison of Orbits of the Sun and the Moon

Before discussing the details of the Moon's orbit, first a quick recap on the Sun's orbit in the sky (which is, of course, due to the Earth's orbit around the Sun). The Sun goes around the ecliptic once per year. The summer occurs when the Sun has its highest declination, of 23.5°; the winter here occurs when it has its lowest of -23.5°. The nodes occur at vernal and autumnal equinox and are denoted by the old symbols ♈, for the first point of Aries, and ♎, for the first point of Libra. The **line of nodes** is just the line connecting these two nodes. As we have seen, this line precesses around the ecliptic once every 26,000 years or so.

Likewise the Moon goes around its orbit, which is inclined to the Earth's orbit. There will be just two points on the Moon's orbit that intersect the plane of the Earth's orbit. In the Earth-centred view, the Sun's apparent orbit around the Earth becomes the ecliptic so there will be just two points in the Moon's path across the sky that intercept the ecliptic. These points are called the **nodes** of the Moon's orbit and often labelled N and N′. N is the ascending node, where the Moon's declination is getting larger and N′ is the descending node. The nodes play a key part in determining when eclipses occur, as we'll see.

Nodes in the Earth-centred view are points on the ecliptic. The Sun's nodes are where the celestial equator and ecliptic intersect. The Moon's nodes are where the track of the Moon in the sky intercepts the ecliptic.

What phase the Moon has at maximum declination depends on the position of the Sun relative to the Earth-Moon system. How big the greatest and least declinations are depends on the orientation of the orbit with respect to the Earth's orbit **and** the Earth's equator. This is because declinations are measured from the celestial equator, which is above the Earth's equator. The tilt with respect to the Earth's orbit is fixed but with respect to the Earth's equator it is not, because the direction of the tilt precesses around in a time as short as 18.6 years. Another way of saying this is the line of nodes NN′ precesses in 18.6 years. The animation on the next slide may make this clearer

The Moon's inclined orbit

The slide shows the inclination constant in one particular direction. The line AC is drawn through the Sun parallel to the line of the Moon's orbit that lies in the plane of the Earth's orbit (the line N´N). The line AC is relevant to determining when eclipses occur. A further complication is that the orientation of this inclination rotates in space, more or less keeping the value 5.15°. This is discussed in the next slide. (I'll not introduce any more of the real life complications, since the picture is already complicated enough. Tycho Brahe determined the extent of some of the further complications, such was the precision of his observations and his understanding of what was going on). The perpendicular to the plane precesses, just like the Earth's rotation axis precesses. Let's look more closely at this precession.

Precession of the nodes of the Moon's orbit

The Earth's axis remains fixed in direction and tilt on the timescale of 18.6 years that the Moon's orbit spins around. It is therefore fixed with respect to the Earth's orbit, making an angle of 23.5° to a line perpendicular to the orbit. Viewed looking down on the Earth orbiting the Sun, the Earth's axis will however change its angle to the Moon's orbit, sometimes making a greater angle than the angle to the Earth's orbit, sometimes a smaller angle, as the Moon's orbit spins around in 18.6 years.

Our reference to where objects are in the sky is the celestial equator, which is of course perpendicular to the Earth's axis. Declinations in the sky are measured with respect to the celestial equator. To find the ecliptic, take this plane and twist it up by 23.5° about a line through the Sun's nodes ♈ and ♎. To find the Moon's orbit, we need to first find the ecliptic and then twist the ecliptic plane by 5.15° degrees about the line joining the Moon's nodes N and N′. This is not so easy to imagine! The next slide shows two special cases, drawn when the line of the Moon's nodes coincides with the line of the Sun's nodes.

Precession consequences

When the ascending nodes of the Sun and Moon coincide, hopefully it's obvious that the tilt of the Moon's orbit adds to that of the Earth's orbit, making the total tilt of the Moon's orbit relative to the celestial equator 23.5° + 5.15° = 28.65°. When this happens, only every 18.6 years, then the Moon travels around the sky even higher than the Sun. 9.3 years later, the reverse happens and the Moon's orbit only reaches a declination of 23.5° - 5.15° = 18.35°. I haven't shown what happens in between times. You need a good 3D drawing package or some 3D models!

In summary, the Moon goes around its orbit about 13 times faster than the Sun goes around its apparent orbit and the Moon's orbital nodes precess over 1000 time faster than the Sun's nodes precess, which makes the Moon's motion conspicuously complicated.

Lunar Eclipses

The basic phenomenon of the lunar eclipse is simple enough: the Sun, Earth and Moon are in a line, resulting in the Moon passing through the deep shadow of the Earth. The full shadow region behind an object is called the **umbra**. From there, the entire Sun is blocked out. The partial shadow region is called the **penumbra**. An eclipse is said to be **total** if the Moon is completely in the umbral shadow and **partial** if it is only partly in the umbra. A penumbral eclipse when the whole Moon passes through the penumbra only merely dims the light of the Moon a little and is scarcely noticeable if you just look up at the Moon.

In principle there is little difference between the phenomenon of night-time and that of total lunar eclipses. At night it gets dark because we're in the Earth's umbra. Lunar eclipses are a brief experience of Earth's night for the Moon.

View of an eclipse from behind the Earth

This shows the textbook figure of an observer in umbral and penumbral regions looking back at the Sun.

Eclipses of the Moon always occur at full Moon. They are visible from all points on the Earth that can see the Moon. The maximum duration of totality is about 1¾ hrs, though 1¼ hours is more usual. An eclipsed Moon is coppery red, due to refraction of light into the shadow area and Rayleigh scattering of the blue light out of the light path.

In the past few years I've expanded the notes on eclipses to the extent that they now contain more than I want to spend time on in the lectures. I've done this partly because eclipses have played a very significant part in civilisations for thousands of years, from the archaeological evidence alone, particularly in respect of early civilisations. They are therefore an astronomical phenomenon that has played an important part in cultures around the world. Secondly, their timing and the details of their appearance are not simple to understand and I wanted to give a better idea of what is going on than can be found in basic textbooks. First, though, let's look at some recent total lunar eclipses.

Lunar eclipse of Jan 2000

The *following two slides* show views of the lunar eclipses of Jan 2000 and Jan 2001, taken by me in my garden with a 35 mm camera. These are related to the track of the Moon through the Earth's shadow.

Lunar eclipse of Jan 2001

This eclipse was cut off in my location by the edge of our house and hence the photo sequence doesn't run until the end of the eclipse.

The following eclipses

If a lunar eclipse takes place when the Moon is below the horizon, it stands to reason that we won't see it. This happened in 2002. In 2003 there were eclipses in May and November but they were both clouded out in Aberdeen. Likewise the lunar eclipses of 2004 were clouded out. Again, there were no total eclipses in 2005 and 2006. The slide shows the track for the penumbral lunar eclipse in 2006. You would hardly notice a penumbral lunar eclipse.

March 2007 eclipse

The total lunar eclipse in March 2007 was one of the best that will take place for a long time. It was around midnight and hence the Moon was at its highest in the sky. There were no clouds and a brilliant view was had from Aberdeen.

2008 total lunar eclipse

Scheduled, as I wrote these notes, for Feb 21st in the small hours of the night. Clouds again hid the view. You can keep your own diary of future lunar eclipses. The September 2015 eclipse when totality was after 3 am occurred when the Moon was nearer the Earth than usual. It was visible in many places, though interrupted by cloud in Aberdeen.

When do eclipses occur?

Why don't we get an eclipse every month? Good question. Something is wrong with the earlier simple diagram. Actually, two things are wrong. First, the relative sizes and distances are not to scale. Secondly we must include the tilt of 5.15° of Moon's orbit relative to the ecliptic. The Moon can be above or below the plane of the Earth's orbit around the Sun, as we've discussed. This produces complications. Sometimes we get no eclipse, sometimes a partial eclipse, sometimes a total eclipse.

Explanations of eclipses can either be described from the Earth centred viewpoint in terms of where the Sun and Moon are relative to the ecliptic or from the viewpoint of someone looking at the Sun/Earth/Moon system from outside. I'll look first at the Earth-centred view and then at the outside view.

Second look at the Moon's orbit

This is a reminder that the line of nodes of the Moon's orbit is the line through the Earth that connects the two points where the inclined Moon's orbit lies in the plane of the Earth's orbit.

The most important fact to keep remembering is that the Earth's shadow is always close to the plane of the Earth's orbit. Hence the Earth's shadow is located in the sky close to the ecliptic and in the opposite direction to the Sun. Hence the Moon must be close to the ecliptic if we are to see an eclipse and of course in the right part of the ecliptic, the part opposite the location of the Sun. Now the points on the Moon's orbit that lie in the ecliptic are the nodes N and N′, introduced earlier. Hence to get an eclipse you need two conditions to be true.

1) First, the *line of nodes* must point in the direction of the Sun.
2) Secondly, the Moon must come through one of the nodes at the time when the line of nodes is correctly oriented.

Let's look again at the animation of the Moon's orbit. AC is parallel to the line of nodes of the Moon's orbit. Only when this line points to the Sun, or almost so, is there any chance of an eclipse. At other times of the year, the line of nodes is parallel to this direction but it doesn't point at the Sun. You can see this in the animation.

When do eclipses occur?

The second slide with this title shows as best I can the Moon's inclined orbit in a few positions as it approaches the part of the orbit where its nodes are aligned with the Sun. The slide shows that with the Earth in its first position the line of the Earth's shadow is off to the side of the direction NN'. If the Moon comes down heading towards the descending node N' then it will pass above the shadow and no eclipse will take place. The Sun, Earth and Moon might appear to be in a line but they are not. Only when the line of nodes NN' points back to the Sun can there be an eclipse and only then if the Moon comes past at the right time.

There is a little slack in the system because the shadow of the Earth at the distance of the Moon is bigger than the Moon by a factor of about 3. Hence the alignment of the nodes and the Moon crossing the node don't have to be precise. The next slide is a side view of the situation as seen from behind the Earth. That might make it clearer.

The eclipse season

In the earlier eclipse diagrams taken from a NASA supported web-site, what is shown are the Earth's shadow regions sliding along the ecliptic (on the diametrically opposite side of the ecliptic from the location of the Sun) and the Moon sliding on its orbit in the sky that usually doesn't pass directly through the centre of the Earth's shadow.

The slide tries to show the point of view illustrated by the previous slide but from the viewpoint of looking from the Moon's orbit back towards the Earth. Imagine yourself looking towards the Earth from just outside the descending node N´. Initially the Earth's shadow is to the left of N´. In due course the shadow passes through N´. Now where is the Moon in its orbit? Is it within the shadow region or not? If it passes totally across the shadow region then there will be a total lunar eclipse. Because the Earth's shadow is quite wide where the Moon passes through, the Moon doesn't have to pass through its node exactly when the node line points to the Sun. If the Moon comes down a few days early or late the umbra is wide enough that it will cause at least a partial eclipse of the Moon. In fact for about 24 days at a time there will be some eclipse of the Moon if the Moon comes by the node. However, in most cases it will be the scarcely noticeable penumbral eclipse. The total eclipse 'season' is much shorter. This happens twice per year and there are therefore from the animation typically 2 lunar eclipses per year, approx 6 months apart but a bit less for a reason we'll see, but they may not be total eclipses. Exceptionally there may be none.

In brief, there are at least two mental pictures you can have. One the Earth-centred view of what happens in the sky with the Moon sliding past the location of the Earth's shadow on the ecliptic. The second is a Sun-centred picture of the Earth travelling around its orbit and the

Moon orbiting the Earth, which is the basis of the diagram on this slide. You can choose which picture makes most sense to you.

The eclipse year

This is not the full story. Because of the Sun's influence on the Moon's orbit (and the equatorial bulge of the Earth) the line of nodes rotates, as has been mentioned. The line of nodes rotates once every 18.6 years. It does so in such a direction as to shorten the interval between eclipses. The eclipse year is 346.62 days (19 days shorter than the calendar year).

I have to confess to having to think hard about this myself. If you've sussed it out, and not everyone in the class will, you can see that when the Moon's orbit is tilted so that the Moon travels up to its greatest declinations, then the line of nodes must be in the general direction of the equinoxes and hence a lunar eclipse will happen near the equinoxes. The situation of the Sun's nodes and Moon's nodes coinciding was drawn a number of slides back. This was the case in 2006 when the Moon at its greatest declination could be seen very high in the sky and could be seen to set north of north-east in our part of the world. Unfortunately the Moon was at an unfavourable place in the orbit in the spring of 2006 so there was only a penumbral eclipse. Again, when the tilt of the Moon's orbit is such that lunar declinations will rise only to a minimum, about 9 years later, lunar eclipses will take place near the equinox. In between times they will shift backwards through the year so that they take place, or potentially do if the Moon makes it round to the nodes at the right time, near the solstices about four-and-a half years later.

The Saros

The pattern of eclipses doesn't repeat every 346.6 days, because this isn't a whole number of synodic months and hence the Moon is in a different part of its orbit even if an eclipse does occur after this period. For a repetition of similar lunar eclipses, you have to have a whole number of eclipse years and a whole number of synodic months. Does this ever occur? Yes, it does. The eclipse cycle repeats in 223 synodic months or 19 eclipse years, which is 18 years $11^1/_3$ rd days. [29.531×223/19 = 346.60]. In other words, after this time, the Sun, Moon and Earth are almost back in the same relationship to each other. This period is called the Saros and was discovered by the ancients (a truly impressive feat). Eclipses that occur a Saros apart are said to be in the same Saros sequence. Each Saros sequence has been given a number, which you'll find in eclipse prediction tables.

The Saros involves $^1/_3{}^{rd}$ of a day. In each Saros there are on average 71 eclipses (43 of the Sun and 28 of the Moon; a ratio ~ 4:3). This means that there are about 70 Saros sequences of eclipses on the go at one time. An even more precise repetition of eclipses occurs every 3 Saros, with the Earth rotated into the same orientation too. This is the repetition period particularly relevant to solar eclipses, because solar eclipses are localised on the Earth and not seen by everyone who can see the Sun.

Eclipses of the Sun

The Moon gets between Earth and Sun. The observer on the Earth is now in the shadow of the Moon, or would be if the shadow from the Moon reached the Earth. Sometimes it doesn't quite do so. The shadow varies in length because of the variable distance of Moon and variable distance of Sun. The length of the umbra is typically 377,000 km, slightly shorter than the average distance to the Moon. A **total solar eclipse** occurs only if the Moon is closer than average to the Earth.

The area of Earth covered is a patch seldom more than 250 km across. The patch moves because of both the Moon's motion and the Earth's rotation. *See the animated slide*. The Moon's shadow moves at ~3200 km hr^{-1}. It usually passes over one place in less than about 4½ minutes for a person right in the centre. The maximum duration of totality is theoretically about 7.5 minutes with the present orbital parameters of the Moon, but eclipses lasting longer than 5 minutes are not very common. There will be 11 this century.

Most of Earth will not see a given total eclipse, although the eclipse can be seen along a path across the globe. Put another way, a total eclipse of the Sun in any part of the world is a rare phenomenon. The average time between total solar eclipses occurring in one place is about 375 years. Well over 90% of places on the globe will have experienced a total eclipse in a 1,000 years, but some places need to wait even longer than this.

If the Moon is too far away we get an **annular solar eclipse**. If the penumbra reaches you, we get a **partial solar eclipse**. The **penumbra** is larger than the Moon's diameter by a factor of about 28 at the distance away of the Earth from the Moon and hence the area of the Earth from which a partial eclipse of the Sun can be seen is large. Therefore partial solar eclipses are much more common than total eclipses from any one place on Earth. It is unusual not to get at least one every decade in a given place.

The (partial) eclipse season depends on size of the Earth and the size of the penumbra region of shadow (contact for lunar eclipse). It is about 36 days. The Moon's synodic period is ~29 days, so 1 or sometimes 2, eclipses per eclipse season occur, which means up to 4 solar eclipses per eclipse year somewhere on Earth. Most are partial but there are about 50 total eclipses per century. The appearance of a total eclipse is spectacular, as we'll see on some 35 mm slides, for the normally invisible corona of the Sun becomes visible.

The corona would not be visible if the Moon were closer to the Earth than it is now and a total eclipse of the Sun would be impossible if the Moon were much further away. You may remember that the Moon is gradually drifting away from the Earth. The effect is significant on a time scale of millions of years. When dinosaurs first roamed the Earth, the Moon was always bigger in the sky than the Sun. During the time that dinosaurs evolved, the first total eclipse as we know it would have occurred. It so happens that we are about in the middle of a period of some 300 million years in which total eclipses of the Sun will take place, the angular size of the Moon exactly matching that of the Sun. After another 150 million years, the Moon will be too far away for this to happen.

Simulation of solar eclipse

The animation gives an idea of the effect. Slides showing the real thing will follow in a later lecture.

Chromosphere - This is seen as a bright red flash lasting a few seconds during total eclipse. It is a region around the Sun's photosphere some 2000-3000 km thick. The red colour is caused by the emission of light by atomic hydrogen; it is much dimmer than the photosphere, but still bright.

Corona - Temperature increases to $>10^6$ K; it extends several 10^6 km with great irregularity.

Prominences can reach 10^6 km, ejecting material at speeds of 1500 km s^{-1}.

Annular solar eclipse of May 2003

You can read about my expedition to observe this eclipse in Orkney on the course web-page.

Eclipse Atlas

World map after Koupelis & Kuhn.

The Moon's surface

The Moon has no atmosphere - it is almost waterless, barren and desolate. How do we know the Moon has no atmosphere?

- sharp occultation of stars
- clarity of view – lack of haze and clouds
- no spectroscopic observation of elements that might make up an atmosphere
- expect it, with an escape velocity from the Moon of 2.4 km s^{-1}.

There are very small He/Ar traces, the products of radioactive decay of elements in the lunar rocks.

The Moon looks as if it is a cold place orbiting in the wastes of space. In fact the Sun's heat blazing down on the Moon's surface un-dimmed by any atmosphere makes the lit surface of the Moon searingly hot. During lunar daytime the Moon becomes hotter than the hottest desert on Earth. Frying eggs on a moonrock is 'on', though I'm sure it's never been done. At night time it is as different story. Think of the coldest starry night you have ever experienced. A lunar night is colder and more starry. With no atmosphere, you will see the stars shine rock steady as the temperature drops to colder than the coldest arctic waste. The space suits of astronauts don't just protect them from the lack of atmosphere but keep them at the right temperature in hostile surroundings.

The back of the Moon was first photographed in 1959. Many of the features at the back of the Moon are named after Russian people and places.

We see 59% of Moon's surface from Earth (more than half) because:

a) Moon's orbit is inclined to the plane of the Earth's orbit and hence we can sometimes see on top a little (over the N pole) and sometimes underneath the S pole.
b) Moon's orbit is elliptical and hence it moves at a variable speed in orbit around us because of Kepler's laws, though it rotates uniformly. This causes what is known as longitudinal libration.
c) The inclination of the Moon's rotation axis of 6° to the Moon's orbit.

The Moon's surface is very heavily cratered, though it also contains comparatively smooth areas called Maria (originally because it was speculated they might be seas). I said above that the Moon is 'almost waterless'. There is now good evidence that some polar craters never received any sunshine. The temperatures there in permanent shadow remain as cold as 25 K (nearly -250° C). These places have acted as cold traps, freezing any water that has come their way by cometary bombardment or other means over millions of years. Radar measurements suggest that there is a few metres of ice in places on and close to the surface, which may not sound much but it adds up to many hundreds of million tonnes in total. With the aid of electricity obtained from solar cells located in sunlight, this could potentially be converted into a lot of hydrogen and oxygen fuel by future generations. Indeed people are now talking about water mines being established on the Moon within a decade or so. Talk and artists' conceptual pictures are easy. Reality is much more difficult. At a temperature of -250°, electronics won't work and combined with a vacuum pretty well everything that moves at ordinary temperatures will be rock solid. It will be tough call to mine water in these circumstances. But at least we know now that in a few special places the Moon is more than rocks and dust.

The KE to form craters

Mountains of the Moon are not formed by crustal motion, as on Earth, but by impact craters.

Consider the impact of pretty small asteroid or piece of solar system debris such as a large meteorite 1 km cubed:

$$KE = \tfrac{1}{2} mv^2 \quad .$$

$$\text{mass} = \text{density} \times \text{vol} = 3000\ \text{kgm}^{-3} \times 10^9 \text{m}^3 = 3 \times 10^{12}\ \text{kg}.$$

$$v = 20\ \text{km s}^{-1} = 2 \times 10^4\ \text{ms}^{-1}.$$

Therefore the KE = 6×10^{20} J.

$$1\ \text{megaton TNT explosion} \equiv 4 \times 10^{15}\text{J},$$

therefore the KE ≡ 150,000 megatons explosion, which can vaporise ~ 50 × mass of the impacting body.

The impact energy is enough to melt the surface rock, allow the meteorite to penetrate the surface, sweeping the material aside like a stone falling into water and then there is a rebound of material outwards just like a giant explosion.

At an impacting speed of 2.8 km s^{-1}, the KE of a mass is enough to vaporise the complete mass of water, rock and meteoric material. At only 2 km s^{-1}, 1 kg has as much KE as a kg of TNT exploding. Gravitational energy is very large, making atomic bombs feeble in comparison.

Forming craters

Diagrams from NASA show how the crater is formed by explosion and rebound of vaporised material.

Characteristics of craters

Impacting meteorites penetrate the surface and create an explosion of material. Crater floors are lower than surrounding rocks; larger craters have small central cones; craters are circular whatever the impact angle.

Maria have been formed by large basaltic lava flows emerging from cracks. There are almost no maria on far side of Moon

The surface of the Moon is being powdered and turned into glassy rocks by a bombardment of 'countless small meteorites' through the ages.

The idea that people have held through most of the centuries since Galileo is that the round craters were produced by volcanism. Volcanic craters look different, for they are generally on top of conical mountains. The clinching piece of evidence, if one were needed by the 1960s, was that craters on the Moon occur in a complete spectrum of sizes from the tiny to the enormous. Volcanic craters don't have such a spectrum of sizes. The final evidence came in the 1960s when close-up pictures from orbiters and landers first showed surface features down to the detail of small rocks.

There *has* been volcanic activity on the Moon, resulting in molten lava pouring out of fissures in the surface and covering large areas of cratered terrain. This lava is darker and denser than the surface rock and forms the maria. Moon lava was much more fluid than the lava we are used to on Earth, more like car engine oil in texture.

When the Moon finally slowed its rotation rate so that one face pointed towards the Earth, the face that did so was generally the region where the lighter crust was thinnest, and there was more dense rock beneath. It is this side of the Moon that faces the Earth. When the Russian space probe Luna 3 returned the first blurred pictures of the far side of the Moon in October 1959, they found virtually no maria and almost all craters.

Man on the Moon

When Kennedy pledged in May 1961 that the US "*should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the Earth*", no American had even been into orbit. It was a genuine gamble. When Armstrong first set foot on the Moon on 21st July 1969 it was a world-wide media event the likes of which seldom happen. Who hasn't heard of Neil Armstrong and Buzz Aldrin some half century later? I was in Washington DC at the time and remember the impact it made, not just because it was a high-risk and symbolic spectacle but because it was front-page news that did not have any immediate connection to a war somewhere in the world. Yes, the Apollo program had its roots in the cold war but this was a media event that grabbed people's attention around the world without tanks rolling into cities, a battleship fleet steaming across the ocean, helicopters dropping napalm, missiles being rattled or images of that ilk we had all got used to. The sixties may be remembered now as the age of the Beatles and mini-skirts but it was also a time of violence and social change. I remember it as the age of anti-war, demonstrations, particularly CND (Campaign for Nuclear Disarmament) protests in Britain and anti-Vietnam war protests in the USA; the rise of civil-rights and black-rights riots in the USA. Against this backdrop of civil and military violence, the Moon landing programme was truly seen at the time as a symbol of hope for a brighter and different future.

I recall looking up past the soaring pillar of the Washington monument into a cloudless evening sky at a first-quarter moon, a familiar tilted semi-circle hanging over the bustling city. It was hard to believe that men were on the Moon but I felt privileged to be alive on a special day in the history of mankind. Mankind had taken its first extra-terrestrial step. No long program of exploration followed, no base-camps were set up on the Moon but that day will be in the history books for many centuries to come. The succeeding Moon landings brought back sacks full of rocks from various sites and did a bit more, before the program was terminated in three and a half years. The final landing left the footprints of astronauts Cernan and Schmitt on the Moon in December 1972. Not a lot of people have heard of them now.

The Moon program may have fizzled out in the early 70s but it was the beginning of the exploration of the rest of the solar system, an exploration that is still very much alive and well. Imagine yourself living on a desert island 1 km across. The nearest island to you is 30 km away. It's only a few hundred metres across but since time immemorial your ancestors have been able to see it. Now, at last, your generation have built a craft able to take a few people there. Of course you jump at the chance. It's a risky journey, there and back, but the few explorers who can be sent bring back photographs of the landscape, some measurements of the surroundings and a few sacksful of rocks. You know by now that the next island beyond is a staggering 5000 km away at the nearest. You know it's comparable to your island in size but very different. What do you do? Dream about getting there and wonder how it can be done. That's space travel for humans. The dream is on. My guess is that the dream will become reality in your lifetime. Mars awaits.

Digression – space tourism

Many people have more achievable dreams and *space tourism* is a reality today. Several million dollars - I don't know exactly how much but it's not a lot of money to a good many people these days - will get you a flight to the International Space Station. Anousheh Ansari was the first women to make the trip, in September 2006. She is an Iranian who has spent her adult life in the USA and made a good deal of money in the telecommunications industry. Interviewed in the December 23/30 2006 edition of the New Scientist she said *You go up there thinking, I'm an American or I'm an Iranian, I live here or I work there. But then you go up there, and none of those things seem important any more. You see one planet. You see how small and fragile it is against the background of the universe, and you tell yourself, wow, this is my home, not Texas or Houston or Dallas. It affects your behaviour – you can't help that. That's why I think it's important for more and more people to fly into space.*

The interview runs to a couple of pages. The impact of her trip is a reaction not only common to space tourists but to the professionals as well. Yuri Gagarin, the first human to orbit the Earth (in 1961: yes, I remember the headlines at the time) said simply, *it's beautiful.* Valentina Tereshkova, the first woman cosmonaut, piloting the Vostok-6 craft in June 1963, said afterwards *Only there, in outer space, do you understand how great are the things that unite us and how petty are the things that separate us.* Mike Collins, one of the 3 astronauts on the Apollo 11 trip that took Armstrong and Aldrin to the surface of the Moon, recalled that when looking back at the disk of the Earth from a greater distance away "*the over-riding sensation I got looking at the Earth was: my God that little thing is so fragile there.*"

What has changed in recent years is not only the advent of government-run projects accepting private finance in exchange for a ride in a spacecraft but a blossoming private space industry that shows every sign of being able to get people into orbital and sub-orbital flight of its own accord. *Spaceport America* may sound like a comic-book creation but is a real development in the New Mexico scrub that has already attracted hundreds of millions of dollars. It's one of several such developments. Wealthy, very wealthy, businessmen on either side of the Atlantic are spending their money with a good chance of success of achieving commercial flights in the next few years and a modest chance of success that they will actually make millions more dollars when income exceeds expenditure. Space tourism is the 'application' that is driving this development. Keep you eye on *NewSpace*, the phrase covering the entrepreneurial space industry. Firms involved include Virgin Galactic, Bigelow Aerospace, XCOR, SpaceX and a good few more. It's not entirely private enterprise either. The China Academy of Launch Vehicle Technology is interested in developing space tourist capability.

Returning to the Apollo flights, let me recommend as an interesting read Andrew Smith's *Moondust: in search of the men who fell to Earth* [Bloomsbury Publishing plc, London, 2005, ISBN 07475 7779 X]. The author is a journalist who sought out all the living astronauts who had walked on the Moon. Nine out of the twelve were alive when he undertook his mission, including Neil Armstrong and Buzz Aldrin. I wonder if any will still be alive when mankind returns to the Moon. I'll leave you to read the story but the subject gets us back to the Moon itself.

More Moon facts

- The Moon's albedo is the same as volcanic rock, namely 0.07.
- At 'half Moon' i.e. first-quarter where the Moon appears as a semi-circle, one might without thinking expect it would produce 50% of the light of full-moon. It doesn't, it gives scarcely 10%. The 50% of the Moon that we see is illuminated at ever shallower angles towards the terminator. On a big scale craters form huge shadows; on a smaller scale every boulder in the sunshine shadows a bigger swathe of the surface behind it. The intensity reduction is a measure of the roughness of the Moon on all scales.
- The huge temperature changes during the lunar night and day imply that the surface of the Moon must be a thin layer of very poorly conducting dust.

Before landing a man on the Moon, NASA (and the Russians) needed to know more about the lunar surface than could be deduced by telescopic observation from Earth. Three successful *Ranger* missions out of several launched between 1961 and 1965 returned close-up views of selected areas of the Moon before crashing into the lunar surface. Boulders were seen sitting on the lunar surface, on top of the covering of moondust, confirming that it was thin and that the ground beneath was capable of supporting a spacecraft – pretty vital information that telescopic data hadn't furnished for sure. The *Rangers* were followed by five successful *Lunar Orbiter* reconnaissance missions in 1966 and 1967 that mapped the whole Moon at 100 metre resolution and five successful *Surveyor* missions in which landers covered further sites from 1966 to 1968. The *Surveyor* probes not only took pictures but dug into the surface (the proper word for alien soil is the *regolith*) and analysed it physically and chemically. NASA's efforts were paralleled by a barrage of *Luna* probes from the Russians. Luna 9 was the first craft to make a soft landing on the Moon, in early 1966, and return a wide-angle view of the surface. Maybe the event should be remembered better, because it was the first controlled landing by mankind on any body outside the Earth. The Russians had had an impressive track record by then: first satellite launched (1957, Sputnik 1), first man in space (1961, Yuri Gagarin), first woman in space (1963, Valentina Tereshkova), first 'space walk' (1965, Alexey Leonov). These 'firsts' were followed by the first robotic lunar rover (1970, Lunokhod 1) and the first space station (1971, Salyut 1) but the Russians generally clouded their development program in military secrecy. Today they are rightly very proud of their space heritage and their continuing launch program. To return to the moon landings, by the time the Apollo astronauts finally blasted off with the intention of landing, a huge amount more was known of our nearest neighbour than when Kennedy first committed to landing a man on the Moon.

In parallel with this reconnaissance endeavour, the Americans had initiated the *Mercury* manned flight missions in 1959, intended to put the first man into orbit. In the event John Glenn's orbital flight was trumped by Yuri Gagarin, to the detriment of American pride. The single person *Mercury* capsule was succeeded by the 2-person *Gemini* craft before the 3-man Apollo capsule was developed. As the 1960s wore on the Apollo programme proper developed the basic procedures of manned space flight. Apollo 8 took astronauts round the back of the Moon. Apollo 9 tested the lunar module in Earth orbit and Apollo 10 saw astronauts orbiting the Moon pretty close in, testing manoeuvrability strategies and of course the safe return-to-Earth procedures. That was all the practice NASA was going to get before committing Armstrong, Aldrin and Collins to Apollo 11.

The pictures taken by orbiters and landers, though, don't convey quite the same sensation as being in a truly alien place with black sky, grey powdery ground whose dust clung and compacted thanks to electrostatic charge, no water, no air, no wind, no clouds, not a hint of plant or animal life. Gene Cernan, the last man to walk on the Moon, said in an interview: *as soon as you hit the surface the dust is gone, the engine is shut down, there's no noise; you are magically in another world. It was the ultimate quiet moment in my life. Pure silence*. Charlie Duke, the 10th astronaut to walk on the Moon, commented that being on the Moon was like being on '*the most spectacular desert you could ever imagine*'. Dave Scott, the commander of the 4th Apollo lunar landing mission, after experiencing the lifeless, waterless desert landscape of the Moon with no atmosphere put it that "*the Earth is truly an oasis*" and Alan Bean, the 4th man to walk on the Moon, said the same thing, in effect, "*we are living in a garden of Eden*". Almost 40 years after his few days on the Moon he added "*since that time I've not complained about the weather one single time; I'm glad there is weather*."

All of the pictures, many tens of thousands of the Moon in close-up, allowed a much more detailed morphology of the Moon to be deduced by geologists, piecing together some of the four billion year history of the features now seen on the Moon. What has made the story hugely more complete though, and much more convincing, has been the analysis that took place for many years after the Apollo missions of the Moon rocks collected by the visiting astronauts.

Rocks of the Moon

About 5% of Apollo mission costs went on science. The astronauts left behind more than their boot-prints and tyre tracks in the moon-dust, which rather spookily could still be there after mankind has been extinguished from the face of the Earth, should that happen. Thanks to the Apollo programme we have more geophysical data about the Moon than any other extra-terrestrial body, though we're catching up with Mars. The Apollo astronauts deployed heat-flow probes and gravimeters. They left behind magnetometers that measured the very weak magnetic field of the Moon. Seismometers pressed their ears to the ground to detect seismic waves from natural impacts, man-made impacts, a seismic mortar and lunar quakes. Lunar seismometers are not burdened by seismic noise from ocean waves, the buffeting of the ground by the weather, or shaking by traffic and building work! An analysis of their output has made it possible to get a reasonable idea of the Moon’s sub-surface structure. It has also provided valuable data on what is impacting the Moon, and by implication the Earth. The seismometers worked for years afterwards, until 1978 in fact. Several large optical reflectors that return an Earth-based laser beam were left on the ground so that changes in the Moon's distance from the Earth could be precisely measured and monitored. They are still working and have been part of a lunar ranging program that has measured lunar distance to an accuracy of about 30 mm for some 4 decades. There are reasons why this is worthwhile.

Another legacy of the Apollo missions was the value of mobility on the surface. Apollo 14 had taken a cart to help move equipment around but the final three Apollo missions, 15, 16 and 17, used the fully developed Saturn V rocket to lift double the load of the earlier missions. Included in these three missions was a lunar rover, a buggy big enough to take two astronauts and a substantial amount of sampling and retrieval gear a good way from the lander. In all, the 3 rovers travelled over 90 km on the Moon. The Russian lunar effort, which didn’t stop when the Americans landed on the Moon, included two robotic rovers, Lunakhod 1 and 2 that travelled a total of over 47 km under base control. Exploration without mobility is very limited. Nothing equalling this range has since been achieved on Mars in the succeeding 45 years and no mobility at all has been achieved by any space exploration landers anywhere else.

Over 2000 samples of Moon rock from 9 areas, with a total mass of over a third of a tonne, were returned to Earth. These samples came from both smooth and rugged lowlands, from dark areas of the Moon, bright areas and some lightly coloured red soils. There is, though, a bigger diversity of rocks on the Moon than the astronauts brought back. There was virtually no sampling of the mountains nor, of course, from the back of the Moon, which is visually significantly different from the face we see. All the Apollo landing sites were within 30° of the lunar equator. It’s not well known that 10 of the 12 astronauts who walked on the Moon left their Moon boots behind so that they could bring back extra rocks whose weight matched that of their boots. The last two astronauts there, Schmitt and Cernan, brought back their boots so NASA could examine them. In addition to the rocks brought back by the astronauts, 0.3 kg of Moon rock has been returned by three impressive Soviet automatic sample and return probes in the 1970s, sampling 3 new sites.

Research using the cache of moon rocks is still continuing. By dating the rocks using abundance measurements of products in naturally occurring radioactive decay chains, the cratering history of the Moon over the past 4 billion years has been established on an accurate timescale, and by implication the cratering history of other solar system bodies. The rocks have provided calibration for the substantial amount of in-orbit remote sensing of the whole Moon’s surface, the ‘ground-truth’ against which to interpret spectral and other orbital measurements. This knowledge has been applied to remote sensing of places where no landings have taken place, such as asteroids and the planet Mercury. The moon rocks have also been a key to unravelling the history of the Moon and its formation.

No rocks on the Moon are in the primitive state they were in when the Moon was formed about 4.6 billion years ago from primordial matter. All have been altered. However, the Moon’s geology is far simpler than the Earth’s, where the combination of plate tectonics, volcanism, weathering and the presence of seas have created sub-surface crustal structure more complicated than the multi-layers of flaky pastry. 3 dominant rock types are found on the Moon:

- Dark basalt, typical of the maria.
- High melting point anorthositic rocks rich in $CaAl_2Si_2O_8$. Most of the Moon is made of this to a depth of at least 40 km.
- A scattering of low melting point KREEP norite, rich in Potassium (K), Rare Earth Elements, Phosphorous and also radioactive Uranium and Thorium.

History of the Moon

Our ideas on the history of the Moon were speculative and more or less unprovable until mankind landed, looked, collected Moon rocks and took them home. The later astronauts didn't just pick up rocks from the surface but drilled several core samples at least 2 m deep. All these rocks give us many clues about the Moon's history and are now the crucial evidence under-pinning our modern views on the Moon's formation and surface development:

- Anorthosite is a light rock that separates out from a pool of molten rock at high temperatures (~1300°C). If there is at least 50 km thick of this on the surface, the Moon must have had at one time a molten outer surface around 200 km thick. For such a surface to stay molten, it must have formed pretty quickly (say in few thousand years). The heavier basalt type rock sunk to the bottom of this hellish ocean.
- Next, the norite formed under the Moon's crust and leaked out through volcanic cracks.
- An intense period of heavy bombardment seemed to follow, forming very large craters as planetessimals crashed into the Moon 4.2 - 3.9 billion years ago. For about 1 billion years afterwards, cracks appeared down to the upper mantle, still liquid, and floods of lava erupted into the large craters towards the end of the bombardment.
- Finally, quiescence under mild bombardment and cooling. The top 1000 km is now solid, leaving only a small shell of liquid mantle and probably a liquid, iron-rock core.

For 3 billion years or so, the Moon's surface has remained much as it is now: a static relic of a violent past. Some big craters have been added, such as the spectacular *Tycho* with its bright rays, but looking at the Moon you are looking at the solar system of a long time ago. This has an important implication for the Earth because at least the first billion years of the Earth's history has more or less been wiped out by plate tectonic movement, mountain building and weathering. The Moon contains a record of the Earth-Moon system from that missing era if one is diligent enough to search and clever enough to read the signs. The relevance of the Moon to us is likely to be a topic of investigation well into the 21st century and a reason for a renewal of surface exploration moon missions.

[The diagram shown in the slides is based on pp 74-75 John A Wood in "The Solar System" Sci. Am., Freeman, 1975]

All the above shows that we know a lot more about the Moon than we used to. However, there's a limit to how much a few visits can tell anyone about a place. I think it was the Apollo 14 astronaut Edgar Mitchell, the last astronaut to indulge in a long lunar walk, who said "*When you land on the Moon, nobody's out there. You step [down] and you get out and there's two of you; you're it on this whole big place*". I have a lot of sympathy for astronaut John Young, one of the moon-walkers from the Apollo 16 mission, who said when interviewed "*we had 18 people up there for 12 days, so we don't really know beans about the Moon*". To put it in perspective, the comparatively simple story just given of the Moon's evolutionary history is based on observation of its landscape, examination of the rocks collected from a modest number of places and seismic data from several sites all on the near side of the Moon and not as far apart as is necessary to deduce detailed and accurate information about the interior of the Moon. You can't really know the full story of a body as big as the Moon from such a cursory exploration. You will hear a lot more in the coming decade about going back to the Moon. Indeed, Moon exploration has clearly restarted. In the recent years ESA, Japan, India and China have sent probes to the Moon, as well as several from NASA. The Chinese landed a rover 'Jade Rabbit' at the end of 2013 but it malfunctioned after travelling very little. It's easy to forget that the first lunar rover was an autonomous vehicle landed by the Russians in 1970. It clocked up over 10 km of roving. The Apollo rovers that astronauts rode on clocked up about 80 km. More than 50 years on as I re-read these notes, technology still has to recover the lunar exploration capabilities of the past.

[One fascinating aspect of prospecting for rocks on the Moon is that future discoveries might include examples of fossilised early life on Earth. Large impacts occasionally throw material between Mars, the Moon and Earth. Meteorites from Mars and the Moon are occasionally found on Earth and can be identified now we know what Martian and lunar rocks look like. It's not impossible that large impacts 1- 3 billion years ago threw rocks in the reverse direction, especially as the Moon was nearer the Earth then. If so, such rocks are likely to be still sitting at or near the lunar surface, unlike the situation on Earth where most early rocks have been subducted into the Earth by plate tectonics. The discovery of Earth fossils on the Moon would be dramatic news.]

None of this really addresses the fascinating question of where the Moon came from.

Origin of the Moon

- *Double planet theory* - difficult to see why Moon and Earth have different average densities (3300 and 5500 kg m^{-3} respectively)
- *Fission hypothesis* - difficult to see how fission could be induced; fast rotation and tides. Earth's crust has a similar density to the Moon
- *Capture theory* - need a third body. See the animation.
- *Aggregation of circulating matter round Earth*
- *Large impact theory* - body about a tenth the size of the Earth (as large as Mars) crashed into Earth ejecting enough into orbit to aggregate into the Moon. Earth has been spun up by off-centre impact? See the second animation on the slide.

The last theory is gaining widespread acceptance. The protoplanet that crashed into the Earth has been given the Greek mythological name of Theia, sister of Titan and amongst other attributes mother of the Moon goddess Selene. Of course there's no science in this but it deserves a name.

More on the large impact theory

The large impact theory takes on board the fact that the Moon's rocks are similar to common rocks in the Earth's crust, though generally lacking the ingredient of water. Overall, the Moon has a significantly lower density than the Earth, lacking such a large iron core.

Currently tidal forces are taking energy from the Earth's spin and making the Moon recede from the Earth at about 4 cm per year. Working back, around 4.6 billion years ago the Moon was a mere 20,000 km from the Earth, which itself was spinning around every 4 hours. An origin of the Moon early in solar system history, which is what the cratering evidence tells us, must address this scenario.

Astronomers are not keen on invoking very special circumstances, if a more commonplace explanation can be found. The chance of a large impact at the time when the large planets were forming in the solar system is not that unlikely. There would have been a good number of large planetessimals around, some most likely in quite elliptical orbits that could in principle intersect a lot of other planetessimals. In the outer solar system, Pluto has a Moon that is even larger in comparison to itself than our Moon is to us.

The main difficulty with the idea is the problem arising from Newton's law of gravity. Material thrown up either tends to fall back to Earth or keep going indefinitely, if it has a larger velocity than the escape velocity. Getting it to aggregate into orbit is not straight forward. One suggestion is that huge amounts of material may have been ejected as vapour. Whether this is likely or not depends on the equation of state for immensely heated and pressurised rock. Such equations are not well known, which inhibits computer simulations of the impact event and its consequences. Recent computer simulation work does seem to produce the Moon condensing from the ejecta over a few thousand years at a distance of about 20,000 km. This is strong support for the large impact idea. The impact would have heated the Earth to red or even white heat. Could we spot a glowing planet around another star that had undergone such a catastrophe?

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