International Year of Astronomy 2009

Schools Projects for Autumn Moonwatch

Project 2: Exploring the phases of the Moon

Suitable for all ages, and for naked-eye or telescopic observing.

The Moon can be a very bright object in our skies – so bright, in fact, that it can often be easily seen during the daytime too. However, the Moon doesn't shine by itself; it merely reflects the Sun's light. This means that as the Moon orbits the Earth, different fractions of its surface are illuminated by the Sun. Sometimes we see only a thin crescent; other times we see half of the Moon's disk; sometimes we see the whole disk Illuminated. We call this changing pattern the **phases of the Moon**.

Figure 1 shows how the appearance of the Moon changes over the course of one month, as the illuminated part of its disk first grows (or *waxes*) and then shrinks (or *wanes*).

The **Scottish Solar System** events calendar provides the dates and times for the lunar phases of **New Moon**, **Full Moon**, **First Quarter** and **Third Quarter** throughout the autumn and winter of 2009/10.

Figure 2 shows how these different phases correspond to different relative positions of the Earth, Moon and Sun, as the Moon orbits the Earth each month. You can also download movie animations of the changing phase during each quarter of the Moon's orbit.

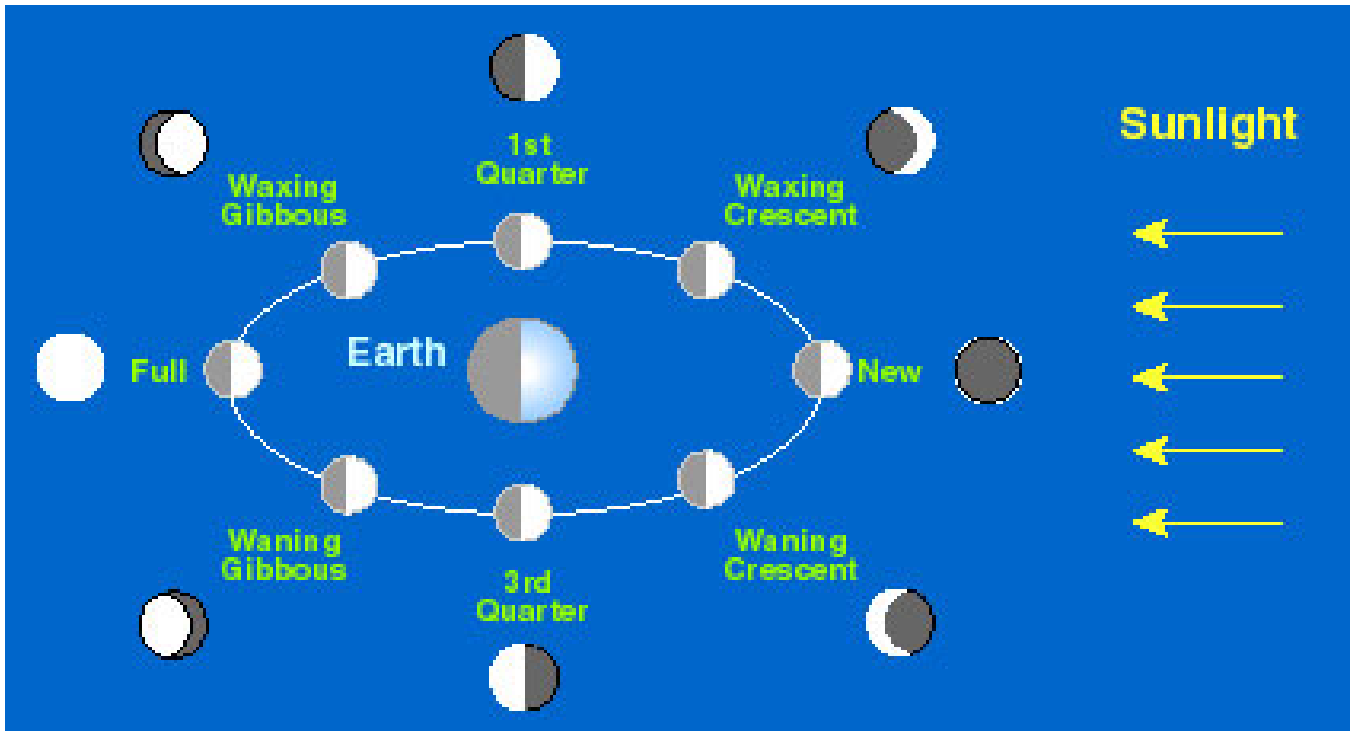Fig 1. Changing phases of the Moon

University of Glasgow

Fig 2. Relative positions of the Earth and Moon at different times of the month, showing how the different amounts of sunlight illuminating the Moon's disk lead to different observed phases of the Moon.

There are many interesting projects relating to the phases of the Moon. Here we give four examples.

(i) Keep a "lunar phase diary".

Observe how the phases of the Moon change over the autumn and winter of 2009/10.   Draw sketches of the Moon's appearance, from naked eye observations or better still using a small telescope – just like Galileo did! (See Figure 3).

Compare your sketches or photographs with the predicted lunar phase. See for example:

http://stardate.org/nightsky/moon/

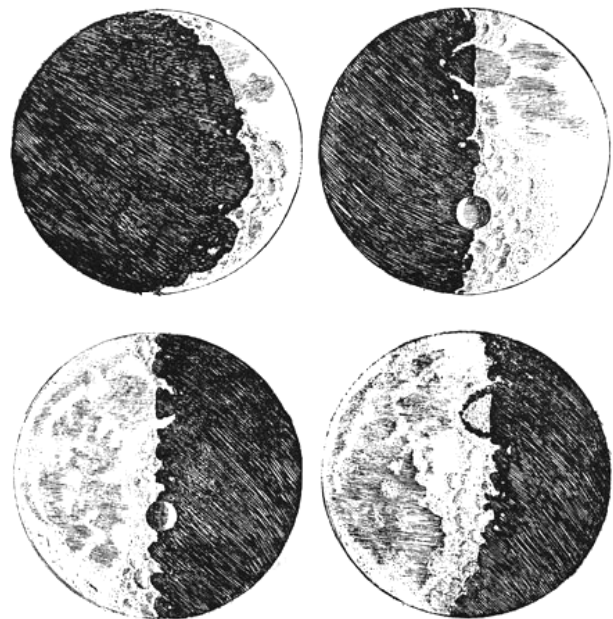How soon after New Moon can you catch your first glimpse of the crescent Moon?....

Fig 3. Some of Galileo's sketches of the Moon, drawn in the autumn and winter of 1609/10, as he recorded in his famous book the "*Starry Messenger*"

(ii) Track the daily motion of the Moon.

Since the Moon completes one orbit of the Earth per month, it appears to move about 13 degrees per night against the background stars. That means that every hour of the night the Moon appears to shift its position by about its own width – half a degree on the sky.

As a rough guide, if you stretch out your arm and hold up your thumb, it will cover roughly about two degrees on the sky – or about four times the width of the Full Moon.
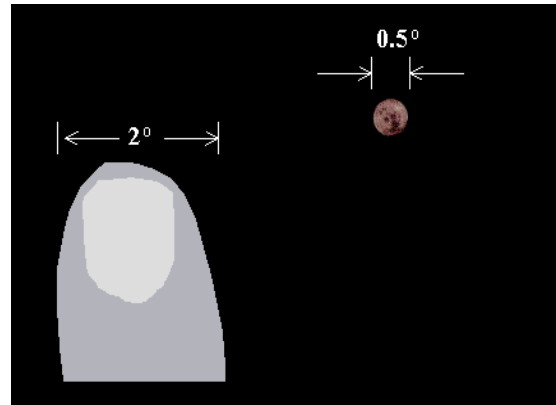

Fig 4. A rough "rule of thumb" for estimating angles on the sky: your outstretched thumb will cover the Full Moon about 4 times over.

By carefully observing the Moon's position against some nearby bright stars, can you spot how their relative positions change – even after just a few hours?


Fig 5. Tycho Brahe, at work with a giant quadrant at his Uraniborg Observatory, 1598

Measuring angles between objects in the sky can be done quite precisely, even with the naked eye. Astronomers like **Tycho Brahe** could measure the positions of stars to a small fraction of a degree, even before the invention of the telescope, using a device called a **quadrant**, which was rather like a giant protractor.

You can build your own version of Tycho's quadrant using e.g. a metre stick and a pencil

Suppose you want to measure the angle between the Moon and a star that lies near to it on the sky.

• First line up the metre stick with the Moon's edge, and hold the end of the metre stick up to your eye.

• Position the pencil along the metre stick, so that its tip appears to just cover the star.
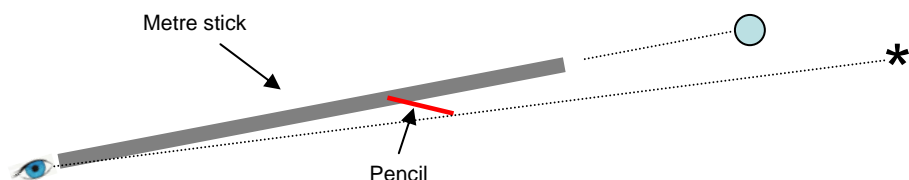
As the angle between the Moon and the star changes, so too will the position of the pencil. In fact some high school trigonometry gives a good estimate of this angle:

$$\tan(\text{angle}) = \frac{\text{length of pencil}}{\text{distance along metre stick}}$$

(iii) The Dark Side of the Moon.

When the Moon is illuminated as a thin crescent, shortly before or after New Moon, take a look at the 'dark' part of the Moon's disk. You can still see many features there, especially through binoculars or a small telescope.

Although this part of the Moon's disk is not lit up directly by sunlight, it is not completely dark since it also receives indirect sunlight reflected from the Earth – a phenomenon astronomers call 'Earthshine'.

Fig 6. An example of Earthshine. While the crescent Moon is illuminated directly by the Sun, the rest of the Moon's disk is illuminated by sunlight reflected first off the Earth.

There is good evidence to indicate that the amount of Earthshine is linked to the cloud cover on the daylit hemisphere of the Earth (e.g. the Pacific ocean, if we were observing the Moon from Scotland late at night) since clouds are good are reflecting sunlight.

During the autumn/winter of 2009-10, you could keep watch on the amount of Earthshine visible for the crescent Moon, carefully judging when it is stronger or weaker. You could even compare your results with weather maps of the Pacific to see if reflected light from clouds does indeed seem to have an effect.

Fig 7. The jagged terminator, due to mountains and highlands on the lunar dark side – the peaks of which are sunlit even when the valleys are in shadow

The dividing line between the parts of the Moon which are in direct sunlight and in shadow is known as the *terminator*.

If you look closely at the terminator through binoculars or a small telescope you will see that it is not a smooth curve but is jagged. If there are lunar mountains close to the terminator on the 'dark' side, the peaks of the mountains may be in sunlight even if their base lies in shadow.

The jaggedness of the terminator was one of Galileo's major discoveries from 1609, which he wrote about in the "*Starry Messenger*" (you can see this in Galileo's sketches, as shown in Figure 3).

Galileo realised the importance of this discovery as strong evidence that the Moon was an "imperfect" world, just like the Earth, contrary to Aristotle's teaching (and which was the prevailing belief in Galileo's day) that everything in the Heavens was perfect.

As a more advanced project, it is possible to estimate the heights of lunar mountains from the lengths of their shadows. See the links on the Scottish Solar System website for more details.

(iv) The relative size of the Sun and Moon.

It is commonly held that, before Galileo, everyone believed that the Earth was at the centre of the Universe. This is not strictly true, since more than 60 years before Galileo the Polish astronomer Nicolaus Copernicus published a model that placed the Sun at the centre of the Solar System – an idea that was already catching on before Galileo's telescopic observations helped to confirm it.

What is even less well appreciated is that *some* astronomers in ancient Greece already supported the idea of a Sun-centred model more than 1500 years before Galileo – all thanks to trigonometry!
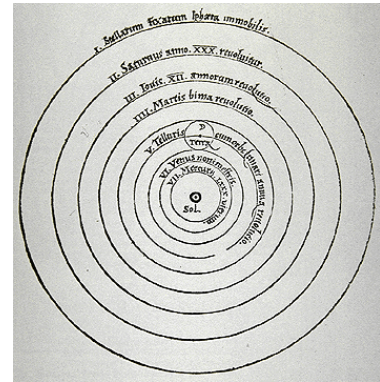

Fig 8. The Copernican Universe, in which the Earth and the other planets orbited the Sun, as presented in Copernicus' book "*On the Revolution of the Spheres*", published in 1543.

Fig 9. A total solar eclipse, when the Moon almost exactly covers the disk of the Sun.

It is a curious coincidence that the *apparent* size of the Sun and the Moon on the sky are very similar. We see this most vividly during a **Solar eclipse**, when for a few brief minutes the disk of the Moon almost exactly covers the disk of the Sun. We now know that the Sun is both very much larger *and* very much further away than the Moon is – the two effects together producing the coincidence of their equal apparent size.

The Greek astronomer Aristarchus (310BC – 230BC), for example, worked out the distance from the Earth to the Sun, using properties of right-angled triangles.

Aristarchus had previously worked out the distance from the Earth to the Moon using not *solar eclipses* but *lunar eclipses,* by studying the curve of the Earth's shadow on the Moon's surface. (For another method to estimate the Earth-Moon distance, see **Project 3**).

Aristarchus then used the phase of the Moon to estimate the Earth-Sun distance.

Fig 10. Curved shadow of the Earth creeping across the Moon's disk during a total lunar eclipse.

Aristarchus' method used the fact that the Moon is bright enough to sometimes be visible in the daytime (see Fig. 11). In particular, when the Moon is at **first quarter** (see also Fig. 2) it may be possible to see *both* the Moon and the Sun in the sky at the same time.

Fig 11. Daylight view of a first quarter Moon. (Image credit: Univ. of Illinois).

In Figure 2 we drew the Sun's rays arriving at the Earth and the Moon as parallel beams. This is not exactly true, as the diagram in Figure 12 shows.
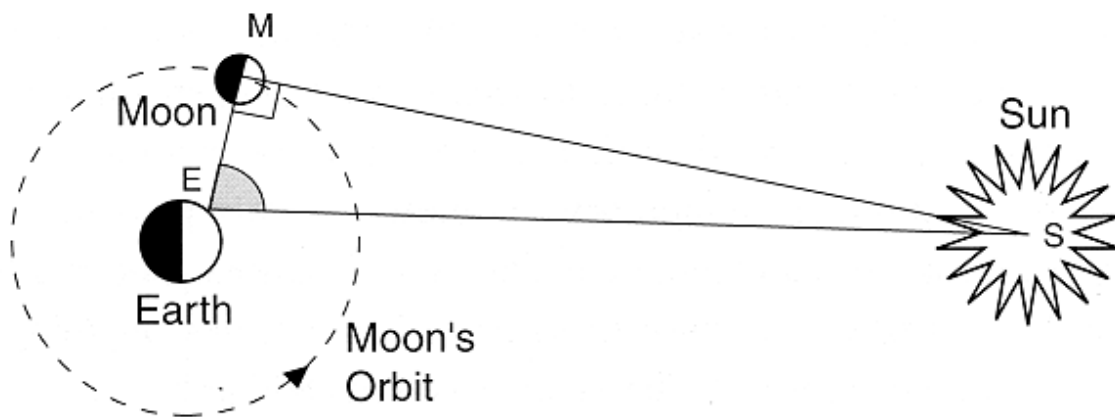

Fig 12. Simplified geometry of the Earth, Moon and Sun when the Moon is at first quarter. Note that the angle between the Moon and Sun, as seen from the Earth, is very slightly less than 90 degrees.

Figure 12 shows the Moon at first quarter, i.e. when exactly half of its disk is illuminated by the Sun. Because the Sun's rays are not exactly parallel when they reach the Earth-Moon system, the angle between the Moon and the Sun when the Moon is 50% illuminated is not exactly 90 degrees. (In reality this angle is about 89.85 degrees; Fig. 12 is not drawn to scale!)

We can, however, form a right-angled triangle, as shown in Figure 12, and use our measurement of the angle between the first quarter Moon and the Sun to estimate the distance from the Earth to the Sun. In fact, some high school trigonometry shows that

$$\cos(\text{Sun - Moon angle}) = \frac{\text{Earth - Moon distance}}{\text{Earth - Sun distance}}$$

Measuring the Sun-Moon angle is quite difficulty to do precisely, but Aristarchus' crude estimate was still good enough to tell him that the Sun was much further away than the Moon was. Since the Sun *appeared* to be the same size as the Moon, it must actually be much bigger than the Moon, and also much bigger than the Earth.

It made much more sense to Aristarchus to have the smaller body (i.e. the Earth) orbiting the larger body (i.e. the Sun). However his ideas were not widely accepted, for reasons which we discuss further in Project 3.