Earth-centred Universe

This chapter is about the oldest view of the skies, a view that is still very relevant.

Whatever Copernicus may have said about the Earth and all planets going round the Sun, the fact is we view the heavens from the Earth. What do we see when we look up? Mostly clouds and the Sun during the day; at night, stars, the Moon and more clouds. The clouds we'll wish away. The Moon we'll come back to. Let's look at the stars. They form a pattern in the sky that doesn't change from day to day.

As we've seen, there is no such thing as depth perception in visual astronomy. The stars appear to be fixed on a sphere a very great distance from the Earth. This distance is so far that the pattern of stars looks the same wherever you are on the Earth. The stars are visually on the **celestial sphere**.

One way this can be appreciated is by comparing stars that move towards the horizon with terrestrial objects. If you follow a high flying plane by eye or with binoculars then when it is overhead you see it 'full on' from underneath but as it moves towards the horizon, then it's apparent shape changes as you see it more and more side on. The plane not only appears smaller near the horizon but its shape looks a bit different. The star patterns on the other hand don't change in either size or shape as they move towards the horizon. This is a good visual test that stars appear on the 'celestial sphere' and for visual purposes are effectively 'at infinity'. Of course, in reality they are not at a mathematically infinite distance, just at immensely large distances.

Take away the Sun and Moon and you are left with the stars. Look up and you will see the same arrangement of stars every day of the year. Because of the rotation of the Earth, stars that go below the horizon will rise, reach a maximum and set, exactly the same day after day. How long does it take for the stars to rotate around once? If you have a clock, you'll find they do this every 23 hours 56 mins 3.4 secs (23.934 hours), which is the length of the **sidereal day**. This is the true rotation period of the Earth. The background is called the fixed stars. Living on the Earth is a bit like living on a roundabout and trying to describe the outside world as you see it! For over a century, time itself used to be measured by reference to the stars. You wanted to know if your pocket watch showed the right time? You needed a small telescope to observe the stars, or know someone who had.

If the stars go around like clockwork, why don't you see the same pattern of stars in the same place at the same time every night? Because we set our clocks by the Sun, which appears to move through the fixed stars. We time the length of a day to be the interval of time between the Sun appearing successively in the same direction. The direction particularly chosen is the North-South line, called the **meridian**. This gives the length of a **solar day**, which is 24 hours on average. The solar day differs from a sidereal day by about 4 minutes.

Sun's motion in the sky

Digression to next slide: Sun's Motion in the Sky explaining the difference between the solar day and sidereal day. The sidereal day is the time taken for the sky to roll round once. Because the Sun moves backward through the sky (i.e. in the opposite direction to the motion of the stars), the Earth must roll a little longer for the Sun to come round to the same position. Hence the solar day is longer, on average by 3 min 56.5 sec, making the mean solar day of course 24 hours. Over a year, the difference between sidereal and mean solar time is exactly 1 day. This is as it should be because it takes a year for the Sun to travel once around through the stars. Looked at from the Copernican view, this is obvious because the Sun is fixed and the Earth orbits once a year, which we would now say is the basic reason why the Sun appears to move through the stars. There are 366¼ sidereal days in a year. **Return to first slide: Earth - centred Universe**.

Stars are faint. Even when they all shine together you can't read by starlight. The stars around the position of the Sun are not going to be seen, because we are blinded by the Sun. The stars we actually see are the ones that are in broadly the opposite direction to the Sun. In that direction, the Earth is shielding us from the blinding sunlight. If you were on a place with no atmosphere, in principle you would see stars pretty close to the Sun, merely by blocking out the Sun with a finger. Whether you would or not in practice would depend on how dark your visor was. Because the Earth's atmosphere scatters the bright sunlight even when there are no clouds, virtually no stars are visible between dawn and dusk. Go out of the lecture theatre and look up. It may be near mid-morning but the stars are all there. You just can’t see them.

Pictures from space confirm that what I’ve said is true. If you look up the SOHO probe web-site (on our astronomy links page) then you’ll see images of the Sun taken by a probe that is sitting all day, everyday, between the Sun and the Earth. One of the on-board instruments is called LASCO and it looks at the outer regions surrounding the Sun, deliberately screening off the Sun itself by a metal disk held on the end of a rod inside the instrument. LASCO’s pictures show this rod and the disk, with the size of the Sun marked out by a white circle. Outside the area of the metal disk you can see the stars even though the instrument is looking quite close to the Sun. The difference between us and the probe is that it’s not swamped by the scattered light from the atmosphere, because the probe is one and a half million km out into space, away from the Earth. On the slide you can see two easily recognised groups of stars that are quite high in the evening sky early in the year, the Pleiades and the Hyades. When the image shown was recorded near the end of May, they are close to where the Sun is in the sky, in the constellation of Taurus, and of course are no longer visible in the evening or at night. On the SOHO web-site you can see the stars close to the Sun now, for LASCO’s pictures are normally recorded and posted every hour.

Constellations (*2 slides*)

People since pre-recorded history have drawn fanciful patterns in the sky grouping the almost random clusters of the stars together. Such a fanciful pattern is called a **constellation**. Different cultures have drawn different patterns. Now there is an internationally agreed set of constellations used by astronomers around the world based on European traditions. Most of the constellations have Latin names, bright stars within them have Arabic names (e.g. Rigel, Mizar, Alcor, Aldebaran, etc.). All these names go back a long way in time and we still keep them, to preserve continuity with past cultures and as a reminder that our ancestors studied the stars long before we were born. Indeed, some of the main constellation names go back to well before Roman times, embodying snakes, lions, bears, fishes and what Agnes Clerke, a very well-informed 19th century writer on Astronomy, called “a menagerie largely stocked from the banks of the Euprhrates”. Associated with many constellation names there are stories or symbolism, most of which modern astronomers have forgotten or never studied.

The entire sky is divided into 88 constellations that have agreed boundaries. At this level a constellation is just an irregular area of the sky. Any stars within a given area are said to lie in that constellation. The brightest stars within the area of a constellation define an associated figure. The older constellations define mythological figures or artefacts; in addition there are more modern constellations defining objects like the microscope and telescope. In diagrams, the key stars in each constellation are often joined together by lines forming a stick figure, supposed to represent the named character or object. These stick figures are often barely recognisable as the objects they represent. For example the constellation of 'Canes Venaciti', or the hunting dogs, just beneath the Great Bear (Ursa Major) in the northern sky, is just represented by a single line joining the only two brightish stars in that constellation. These stars represent the eyes of the two dogs. You have to imagine the rest of the dogs! There are 'full art' representations of the figures in some texts and on the web. These figures mainly originate in the Middle ages. They certainly help to see what our ancestors were on about. Looking at the stars in constellations like Ursa Major (great bear), Orion (the hunter), Draco (the dragon), Taurus (the bull), it's not easy to spot the figure in the star pattern. It's worth learning to recognise a few of the more prominent constellations.

To this end, explore the Stellarium software. There's a copy on the CD accompanying the 5th edition of our textbook and the software is also in the Physics folder on the computer classroom desktops. (Go to the College icon 'Physical Sciences', then the School icon 'Natural and Computing Sciences' and then to the discipline icon of 'Physics'). You can switch on the constellation names, the constellation stick figures and even the 'full-art' figures. You can alter the direction you are looking in, the time of day, the location on Earth where you are, your field of view, whether the atmosphere and ground are included, and so on.

From the street-lit suburbs of a town or city, even a clear sky shows broad starless patches. Whole constellations are invisible. Isolated stars shine through the glow above you, flagging the locations of the more conspicuous constellations, if you can identify the individual stars from their height above the horizon and compass bearing. You can see a lot more stars if you raise a pair of binoculars to the apparently starless patches. In the winter, though, one constellation cuts through the haze better than any other. It is the conspicuous figure of Orion, the hunter. Look towards the south later in the evening and there he will be, with his glistening belt represented by 3 bright blue stars, all stunningly more luminous than our Sun but in reality a huge distance away. You won't see his bow or his club from within the town lights but the appearance of Orion signifies in our latitudes the end of the summer season of long evenings and the onset of long, starry winter nights. Not far below Orion is Sirius, the brightest star in the whole sky. Its brilliance is often dimmed as far North as we are by the added haze that's always near the horizon. Looked at through binoculars, Sirius twinkles with a rainbow of colours through the haze. If you want to identify just one constellation in the sky to begin with, make it Orion. He will become the friendly figure of the winter sky that you will never forget.

Moving away from Orion, the constellations of Gemini, Auriga and Taurus are all nearby. Looking towards the North, it's worth identifying Ursa major, Ursa Minor and Cassiopeia. That gives you two areas of sky that you can work out from when you're away from the street lights and want to identify a few more of the traditional star patterns in the sky.

A sheet given out when you make a visit to the planetarium will help you find out what's where in the sky.

The Celestial Sphere

Movement we see in the night sky is of course because of the rotation of the Earth. The Earth's rotation axis points closely but not exactly at the **Pole Star**. This therefore remains almost fixed. Other stars rotate around in circles, whose radii increase the further we get from the pole star. The fixed points on the celestial sphere are called the **north celestial pole** and **south celestial pole**. Half-way in between we have the **celestial equator**. All the stars on the celestial equator are directly above the Earth's equator. The stars that pass overhead at Aberdeen all have the same celestial latitude as Aberdeen, namely 57° N (or, as astronomers say, a declination of +57° as I'll explain shortly).

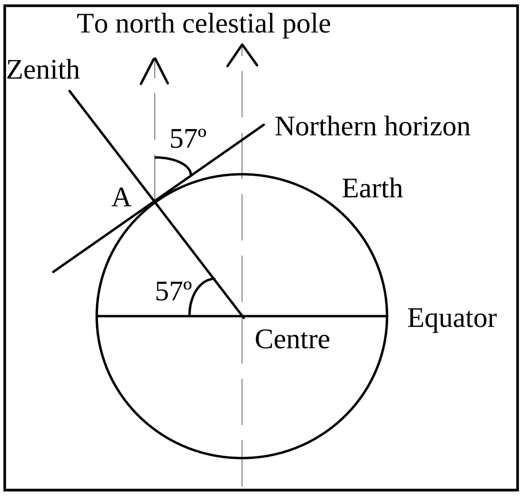
Motion of the Sky

In Aberdeen, stars around the north celestial pole never set. They go round in **anticlockwise circles**. You can demonstrate this very well yourself by looking at the sky with the Stellarium software and speeding up time.

(*Perhaps demo by student halfway up class rotating arms to show that the description 'clockwise' or 'anticlockwise' depends upon which direction you are looking in.*)

Pole Star above the Horizon

How high above the ground is the north celestial pole? Distances across the sky are measured in angles, not km. See the diagram.



Notice on the diagram how the **latitude** is the angle between the equator and the place, measured from the centre of the Earth.

Angle between a horizontal line pointing northwards and the north celestial pole at Aberdeen is 57º, the latitude of Aberdeen. For Edinburgh it would be 56º, London 52º and so on.

The pole star gets lower in the horizon the further South you go. Anyone who has been to the Mediterranean for a holiday and looked up at the stars will recognise how low the Pole Star appears and how you can see in the opposite direction other stars not visible from as far North as Aberdeen.

Quick angular estimates using your hand as a rough and ready ruler:

Moon's diameter	0.5º
Finger at arm's length	2º
(Fist or) flat hand at arm's length	10º
Extended fingers (to thumb)	20º
2 outstretched hands together	40º

Demo to class on finding the altitude of the Pole Star

Constellations on the Ecliptic

[*Helpful to have an Earth globe and a celestial globe*]. Looking from outside the Earth, you see the Earth moving in an orbit around the Sun once a year. Viewed from the Sun, the Earth moves round in front of the stars. Viewed from the Earth, however, the same situation appears as the Sun going round once a year in front of the stars. That's the first point to note. The Sun appears to travel through a succession of constellations. You can't see this directly, of course, because you can only see the stars that are in the opposite direction to the Sun. We don't think about it but the stars are still there during the day, twinkling unobserved.

Secondly, viewed from the Sun, the Earth's axis is inclined to its orbit by 23.5°. Standing on the Earth, the view is different. The Sun's apparent orbit in front of the stars is tilted at 23.5° to the equator. This track of the Sun is called the **ecliptic**. The ecliptic passes through rather well-known constellations. You may recognise most of them for they are constellations in the zodiac much mentioned in tabloid newspapers.

12 of the constellations of the zodiac through which the ecliptic passes have traditional (astrological) symbols to represent them. The symbols ♈ and ♎, shown in red on the slide, are still used by astronomers to represent the two equinoctial points on the ecliptic, which, curiously enough, are not now in the corresponding constellations.

Constellations on the Zodiac

Viewed from outside the solar system, all the orbits of planets around the Sun are fairly close to the same plane as the Earth's orbit. Viewed from the Earth, the planets and the Moon are therefore never very far from the ecliptic. In fact they are within a band 16° wide centred on the ecliptic (all except Pluto, that is, but the ancients didn't know about Pluto and it is now only a dwarf planet). This band was known to the ancients and called the **zodiac**.

Notice that the Sun moves back through the stars from West to East.

The ecliptic, inclined at 22.5º to the celestial equator, intersects the equator at two points. i.e. twice a year the Sun is on the celestial equator. This happens at the **equinoxes**. The Sun is nearer the north celestial pole in summer, gradually getting higher and higher until it is 23.5º at its maximum N of the celestial equator at mid-summer. See the lecture slide. The constellations the Sun travels through are Sagittarius (Jan), Capricorn, Aquarius, Pisces, Aries, Taurus, Gemini, Cancer, Leo, Virgo, Libra, Scorpius, Ophiuchus (Dec).

Sun's path along the Ecliptic

The sinusoidal curve on the previous slide is an artefact of mapping the ecliptic onto a sheet of paper. This animation shows what is happening. Remember that the Sun is travelling around a circle inclined to the celestial equator. When the constellations are unwrapped and drawn onto a sheet, the circle becomes the sine curve.

The Sun spends 44½ days in Virgo, and just 6.3 days in Scorpius. Each of the constellations on the ecliptic isn't of the same size but the ancient astrologers defined 12 signs of the zodiac, altered the signs' boundaries to make them all equal in length and set down between which dates the Sun is in each of the zodiacal signs. Unfortunately, due to the phenomenon of precession of the ecliptic, caused by the interaction of the Earth's orbit with that of the other planets, not taken account of by astrologers, the Sun is now not in the astrological constellation it is ascribed to at a given date but in one constellation behind. Thus when astrologers describe the Sun as being in Aries, for example, it is actually in Pisces. Ophiuchus is omitted by astrologers, presumably because there are 13 constellations on the ecliptic and only 12 months.

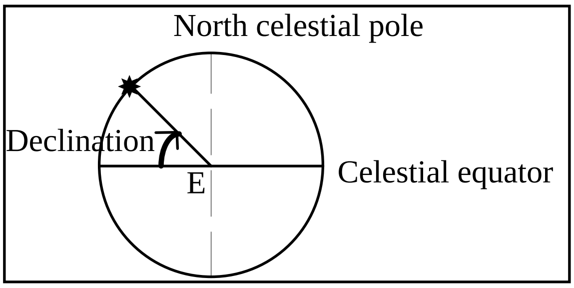
Locating Heavenly Bodies

The final topic of this rather numerical and spatial section is an important one. How do you locate the position of stars and other objects in the sky?

[*Take in celestial globe*]

a) Cover the sky with constellations and find the constellation in which your point of interest lies. Some are large (Virgo, Ursa Major) and some small (Corona Borealis). The 88 constellations are listed in Koupelis & Kuhn's textbook. Their boundaries have been agreed by international convention (1930). This is like covering the globe with countries and saying which country a town is in. It gets some of the way but to be precise you need a map reference.

b) On Earth, which is nearly spherical, you can specify latitude and longitude. e.g. my home village near Aberdeen is 57º 4' N & 2º 6' W. Ulan Bator is 48ºN 107º E. Latitude is measured by finding the 'great circle' that comes up from the equator, passes through the place on the globe and goes on to the nearest pole. The angle round the earth from the equator to the place is its latitude. **Great circles** are circles whose plane includes the centre of the Earth (or sphere we're talking about). **Small circles** are circles on the surface whose plane doesn't contain the centre of the sphere. For example, all lines of constant latitude except the equator are 'small circles'.



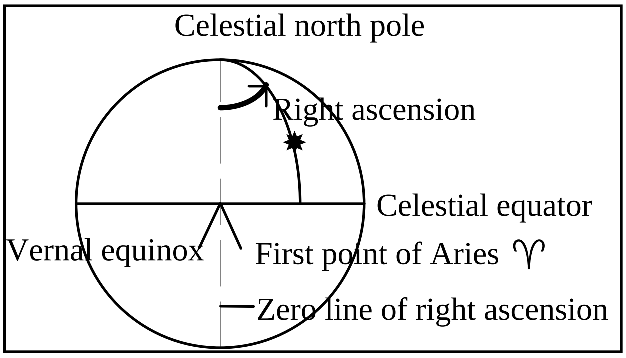
On the celestial sphere, we should also be able to specify latitude and longitude and this is exactly what is done.

Celestial latitude is known as **declination** ("decl")
Celestial longitude is known as **right ascension** ("RA")

Celestial latitude, aka declination, is easy - it is measured from the celestial equator. It is an angle. It is the angle from the celestial equator to the star or heavenly object, measured around a great circle that passes through the celestial poles. Just as on the Earth, lines of constant declination are small circles excepting the celestial equator, which is a great circle.

- +ve declinations are towards the north celestial pole
- -ve declinations are towards the south celestial pole

For longitude, or right ascension, we also need a reference circle to measure from. On Earth we use the Greenwich meridian, the line where East meets West (chosen in 1884 at an international conference). In the sky we use a circle that passes through the intersection of the ecliptic with the celestial equator. There are 2 intersections [*demo with celestial globe*]. See the next diagram.



The half great circle selected as the zero of right ascension is the one that passes through the place where the Sun in the sky is at the spring (vernal) equinox. This point in the heavens is traditionally called the 'first point in Aries' and represented by a ♈ symbol looking like a Greek gamma, supposedly representing ram's head and horns. ♈ is now in Pisces. Right ascension is celestial longitude measured from the reference great circle. It is always measured East. Like declination, it could be measured in angle, from 0 to 360º. In fact it is not.

Right ascension is divided into 24 (sidereal) hours, with 24 hours covering 360º, or 15º = 1 hour. e.g. Sirius has RA = 6 hours 45.1 min. The use of hours gives directly the *sidereal* time between the first point in Aries, or the zero RA line, crossing the N-S line and the heavenly body crossing. (The Earth rotates once in 24 sidereal hours). The average RA and declination of all 88 constellations is given in Appendix G of Koupelis & Kuhn’s textbook.

Claudius Ptolemy (about 150 AD)

Our description of the stars and their motion is all based on taking the Earth as a reference. This is not at all unreasonable. To help explain things one can build physical models of the celestial sphere - perhaps out of wire, so that you can see through to the Earth at the centre, or as globes. The classic **armillary sphere** was the name of the wire model. The celestial globe is the aid for geographers of the heavens.

People made conceptual models, too and arguably the model with the greatest influence on civilisation has been the model that’s come to us through the Ancient Greeks. This was based on a recognition that heavenly bodies were intrinsically different from earthly bodies: they kept on moving regardless of wind, wave, weather, king and country. The Moon, planets, Sun and stars were all imagined on their own spheres, regions at different distances from the Earth. The Moon and Sun were planets (they all moved through the zodiac) and hence the Greeks had 7 planets. We have 7 days in the week as a result of this, one for each planet (we all know Sunday, Monday, from the Sun and Moon; Tue-Fri are now named after Viking mythology gods and goddesses). The Ancient Greeks were keen on qualitative observation but not so keen on measurement. Nowadays, measurement is an obsession in science, and rightly so. With more careful observation the Greeks refined their model of the heavens until it reached the complexity that was recorded by Claudius Ptolemy around 150 AD and written down in his book **Almagest** (a later title, after the Arabic for ‘the greatest’). The motion of Ptotemy's spheres seemed to describe what was seen. The stars really did rotate, not the Earth. As Plotemy said, if the Earth rotated, surely there would be a great wind on it?

The observed motion of the stars was simple. The planets, though, wandered amongst the stars, not at random but not quite along circular paths at a uniform rate. Ptolemy realised that the planets were not going round on simple circles and he incorporated circles on top of circles to explain the apparent motion. These secondary circles are called **epicycles**. The Ptolemaic model was getting rather complicated. Take two examples:

Epicycles for Mercury & Venus

Mars needed a substantial epicycle; the centres of the Mercury & Venus epicycles had to be between the Earth and the Sun. The animation shows the motion of these planets around their deferents. The deferents were circles in space around which the centre of the epicycle moved. Deferent circles weren't centred on the Earth. Yes, it gets complicated, and I haven't mentioned the equants.

Mars Retrograde Motion

See the animation of effect. The animation is on the CD that comes with Koupelis & Kuhn' book. So are almost all the other animations.

Epicyclic Explanation

Animation of epicyclic motion.

How does Ptolemy's model fare as a scientific model?

- Does it fit the data? Yes, it did fit the available data.
- Could the model make accurate predictions about the past, future or some other facts of the present that hadn't been used to build the model? It had some success but it was not tested with rigor, and we would not expect it to have been.
- Is it aesthetically pleasing? The basis was pleasing but it had become messy in its elaboration.

An Everyday Astrological Relic

Knowledge that was as ancient and long-lived as the knowledge in the model of the Universe has been built into the fabric of our culture. Let us look finally at the subject of the days of the week. Why are there 7? Imagine the situation today if a UN inter-governmental panel was formed to recommend a world-wide standard for the number of days in a week. The mathematicians would point out that 12 is much the most convenient number to subdivide into various equal portions; a committee of social scientists would point out that working 9 or 10 days continuously before each weekend would induce world-wide stress; the panel would divide into 4 main subgroups, each wanting a different number of days, and so on. Fortunately, the matter has been decided long before the days of UN panels. There are 7 days in the week, world-wide. Why 7? Because there are 7 planets in the sky. Again? Because there are 7 planets in the sky: the Sun, Moon, Mercury, Venus, Mars, Jupiter and Saturn. If any more planets are discovered, will the days in the week be increased? No! What order are these days named in? Not one you might have expected. See the slide. [Inscribe the 'magic heptagram' in a circle. On each vertex write the names of the 7 planets in the order of their supposed increasing distance from Earth. Start with the nearest (the Moon for Monday) and follow the lines of the heptagram and it leads you to the successive days of the week. Mystic nonsense of course, but typical of the way things were done a few millennia ago, ascribing bogus meaning to random facts – in this case the names of the days of the week, which could be called anything].

Another relic could well be the link between the astronomical year and playing cards.

- A pack of cards has two colours of cards, red and black corresponding to the days and the nights. The year is made of a succession of days and nights.

- A pack of cards has 4 suits. The year has 4 seasons.

- A pack contains 52 cards. There are 52 weeks in a year, plus 1 day represented by the joker.

- If each card is given a value from 1 for the ace to 13 for the King, the sum total is 364 + 1 for the joker, making 365, the number of days in a year.

Today's "strange but true" fact from the course!

JSR