Astronomy 2012

Course Introduction

See the handout

Prologue

What's in this Universe beside ourselves and all we see around us on Earth? One of the main purposes of this course is to give some answer to that question. Since one of the first rules of science is 'use your eyeballs' and I'm going to begin with a few comments on vision.

On vision

As you know, an angle is the amount you have to rotate a line from pointing in one direction to pointing in another. Small angles are a measure of *width*/*distance* away. '*Width*' can be the diameter of a planet or moon, the distance between two features on a single object, the gap between two stars or any other two objects for that matter, and so on.

Our eyes can only register the angular size of objects, with the angle measured in degrees, or minutes and seconds of arc for smaller angles. For objects close to us, we can use the stereoscopic effect of 2 eyes to estimate distance. This option is irrelevant in astronomy. Eyes determine only angular size.

When we look at the Moon, we see a circle about 0.5° across. When we look at the Sun we see a circle of almost exactly the same size. It's quite reasonable to think that the Sun might be a lot closer than the Moon. It's a lot brighter and hotter. Objects moved further away get duller and cooler. How might ancient folk have deduced that the Moon was actually nearer than the Sun? [Perhaps because it moves across the sky more quickly or because of eclipses of the Sun by the Moon]. Thanks to knowledge only just over 2000 years old, we know that we are actually looking at a moon that's 0.27 of the Earth's diameter at a distance of around 384,000 km (the distance varies by about 20,000 km). The Sun, which is a full blown star, is 400 times the Moon's diameter and 390 times as far away as the Moon. This knowledge is only a few centuries old.

Angular measurement

Kuhn's diagram emphasises that angles measure separation in direction of view.

On angles

You should be able to recognise the subdivision of one degree into minutes of arc and seconds of arc. These units are still widely used in astronomy. You should be able to convert minutes and seconds to fractions of a degree, using the fact that there are 60 minutes in a degree and 60 seconds in a minute. Basically, divide the seconds by 60 to get fractions of a minute and divide minutes by 60 to get fractions of a degree. Many Casio calculators have a standard button that does this for you. The standard symbol for a minute of arc is a single tick ′ (e.g. 1.5′ for one-and-a-half minutes of arc) and a double tick for seconds of arc (e.g. 4.5″ for four-and-a-half seconds of arc). You should now know what 23° 1.5′ 4.5" stands for, if you didn't before.

Example on angles

Work out the angle subtended by Saturn (currently high in the evening sky).

The eye

Our eyes have limitations on every aspect of their performance. As far as seeing detail is concerned, if I were to hold up these notes, probably only some in the front row coud read the print. Why is this? Even if you have perfect lenses in your eyes, the width of the photoreceptors on the back of the eyeball limits what we can distinguish. If the light from a single letter on the sheet falls on just one photoreceptor at the back of your eye, you won't be able to tell which letter it is. This limitation produces an 'angular resolution' of about 0.01° or about 0.5′ arc. This measures how far apart two points must be to see them as separate. In visual terms, a person with the sharpest eyesight could just tell if someone at 100 m distant was holding up 1 or 2 fingers together.

This limit to the detail we can see has serious implications in astronomy. For example, it limits how well we can tell two separate stars apart. Even more importantly, one of the effects of only being able to see angles directly is that as you look at objects further and further away you'll only be able to see larger and larger objects. It's the same as the effect of the seagull and the plane. If you look out of the window you'd expect to be able to see a seagull 100 m away but not at 5 km distance. If you see something that appears as big as a seagull at 100 m but is actually at 5 km, then it has to be as big as a plane.

Our view of the Universe gets coarser and coarser the farther away we look. We can't even see all the larger planets in the solar system with our naked eye. Even with a very good telescope it's hard to spot a body as big as 1000 km in diameter at the edge of the solar system. If we are to see objects, then they need to be bigger and bigger (and brighter and brighter) the farther off they are. This is a fundamental truth about our vision of the universe. Who knows what's lurking in the ever increasing spaces between visible objects at larger distances. Little green men? Perhaps. Science fiction is riding high in books, TV, drama and films, thriving off our imagination of what might be out there. See some recommended books on the course web page.

Slides: the eight planets and beyond

From set *The Solar System*. Initial number is place in cassette; (n) is slide no. in set.

1 **Earth** (6) the more we see of the rest of the Universe, the more we appreciate home. It's been said more than once by those who have been into space that you really appreciate what a beautiful planet we live on when you have left it.
2 **Mercury** (2) too near the Sun to be seen most of the year; very hot facing the Sun, cold on the far side; Mariner 10, one of the first planetary probes of the 1970s, showed Mercury to have a general appearance like the Moon. There were no further close-ups of Mercury until the first pictures from the Messenger probe were returned in Jan 2008.
3 **Venus** (3) Earth's sister planet, named after the Goddess of Love but in fact a hell-hole; the atmosphere is so thick that pressure at the surface of Venus is greater than at the bottom of the North Sea; the atmosphere is mainly asphyxiating CO_2, with high clouds of

H_2SO_4; the temperature on the surface is high enough for pools of molten lead to sit happily, if there were any lead.

4 **Mars** (8) Mars is a pretty small dot in the sky to the naked eye – about the size of a golf ball seen at half a kilometre distance. Is Mars the most desirable piece of real estate in the rest of solar system? In some places the landscape is fantastic, there's 150 million square km of land, as much as all the continents on Earth put together, unlimited building materials, vacant possession with no sitting tenants, reduced gravity for softies. Or is it a just another dead rock circling the Sun; arid, dusty, cold enough to freeze carbon dioxide, oxygen free, life free, liquid water free, almost atmosphere free and too far from the Sun to warm the cockles of anyone's heart? You can decide when I tell you more about Mars later in the course.

5 **Jupiter** (10) the giant of the solar system; not far off being a miniature solar system itself with many diverse moons in orbit and a net output of energy in excess of the radiation it receives.

6 **Saturn** (13) another gas giant, with a stunning, complex ring system that continues to cause wonder the more we find out about it.

7 **Uranus** (16) a giant, not visible to the naked eye; generally smooth and mysterious, particularly so because it is the only planet lying on its side, so to speak, with its poles close to being in the plane of the solar system.

8 **Neptune** (19) the last gas giant whose features we have only recently begun to see.

9 **Pluto** (22) now designated as a dwarf planet. Completely invisible to all except powerful telescopes; back to small, almost moon like planets; in fact Pluto is smaller than our Moon. No doubt Pluto will have some surprises in store for us when we see it more clearly, which we hopefully will when the 'New Horizons' probe finally reaches Pluto.

From *School of Physics collection*

10	**Comet West**	there is more in the Solar system than planets; 1976
11	**Halley's comet**	famous as the comet that returns every 76 years, but its re-appearance in 1986 disappointed

Clusters and Galaxies

12	**M11**	A young open cluster rich in stars, around 5600 LY distant.
13	**NGC 5139**	ω Centauri, the largest and brightest globular cluster in the sky (not visible from Aberdeen) about 17,000 LY.
14	**M31**	Andromeda Galaxy, our sister galaxy around 2.4 MLY, part of our Local Cluster of galaxies.
15	**NGC 253**	Spiral galaxy similar to ours, almost edge-on, at distance of 10 MLY; particularly dusty, in the constellation of Sculptor, not visible from Aberdeen.
16	**M104**	The Sombrero Galaxy, a dusty spiral galaxy exactly edge-on, in Virgo, containing many very old stars
17	**NGC 2442**	A barred spiral galaxy.
18	**Trifid Nebula** (12)	M20, in Sagittarius; about 40 LY across; enough material to form 1000s of stars; some have already formed and are causing hydrogen gas in the cloud to glow red; some light escaping from the side, blue being reflected by dust; dust itself so thick in dark lanes as to obscure light.

19 Part of the lagoon nebula called the **giant twisters**. In Sagittarius, about 5600 LY. A place where stars are born.

20 **Helix Nebula NGC7293** (15) The nearest so called 'planetary nebula' to us at about 400 LY, about size of moon but very weak; inner light from ionised oxygen, outer from H and N. Nothing to do with planets but it is the remnant of an exploded star.

Purpose of a telescope

How can we see more? The telescope is today's answer. Telescopes have one dominant lens or mirror, like the eye, but they differ from eyes in two particularly important optical respects.

1. the longer the focal length of the lens or mirror, the larger the image. See the illustration. The focal length is the place where a lens or mirror forms the image of a far off object. All astronomical objects are 'far off'.
2. the bigger diameter the lens or mirror, the more is its light gathering power.

Demo of large lens. Would this lens make a good telescope objective? "No". Its focal length is too short. In addition a big lens needs to be very well figured so that the image formed by the outer edges coincides exactly with the image formed by the centre. This moulded lens is not nearly good enough.

In astronomy, the second of the numbered effects above is more important. It can also make a larger difference. A big modern telescope might have magnification of ×1000 relative to the eye; but an area of over 10^6 times that of the pupil of a night-adapted eye. The big modern telescopes therefore collect as much light as several million people looking at the night sky; the telescopes have better light detectors than our eyes and are located where the finest views in the world of the stars are obtained. What they see in the Universe and what they have found far surpasses anything our ancestors could have experienced. Due to turbulence in the atmosphere for a site like Aberdeen, ×400 is a good achievable magnification. Any more magnification just produces a dancing image with no more visible detail. Images of stars are typically spread out over a good many seconds of arc by the air above us in Aberdeen. In a very good observing site they may be as small as 0.5 seconds of arc, and there are ways of making the images even better. Above the atmosphere, the clarity of vision is perfect, as the Hubble Space Telescope has shown, and the size of images is limited only by the telescope's optics (to something like 0.05″ arc). I'll show pictures from the HST later.

Images through a modest telescope may dance in front of our eyes or on a monitor screen but astronomical ground-based photography is improving these days in ways our predecessors can only have dreamed of. There are modern image collection techniques used on professional telescopes known as 'adaptive optics' that allow the light path within a modern telescope to be altered to compensate to a fair degree for the dancing images caused by atmospheric turbulence. The results are impressive. I'll show some modern astronomical pictures during the course. Even amateurs can get results that are as good as some of the professionals of the past, using CCD images and suitable software processing.

When national observatories were first set up, they were erected in places like Greenwich and Paris. 130 years ago, to reduce atmospheric limitations of 'seeing', observatories were built in places like Pic-du-Midi, the Jungfrau and Mt Wilson in America. Nowadays, observatories are built on the highest and driest places available, such as the top of Mauna Kea in Hawaii or the high Andean plateau in Chile.

Modern telescopes (3 slides)

Examples of large modern facilities in Hawaii and the Andean plateau in Chile.

Telescopes need to be in unheated surroundings to avoid additional atmospheric shimmer of the image caused by rising heat from the telescope hall and dome. It is modern instrumentation that has enabled today's big telescopes to be located at the very best observing sites in the world. These are the highest and driest places on the planet that have some accessibility. You can't sit in the seriously sub-zero temperatures of a night at 4000 m altitude wrapped in a thick coat peering into the eyepiece of a telescope. At least you can't do it for more than a few minutes. Today's computer controlled telescopes with electronic read-out of the images are huge machines designed to operate in conditions no astronomer could tolerate. Indeed, you don't even need to be on-site to use the highest and largest facilities in the world. All that is needed is technical support on-site

Extra large telescopes (ELTs)

In the first decade of the 21st century many of the leading observatories had telescopes 8 – 10 metres in diameter. These are very large pieces of kit, expensive and along with their guidance and other operational hardware and software and their attached instrumentation were at the forefront of technology when they were built. This next decade, though, will see at least 3 'extra large telescopes' constructed, pushing hi-tech even further but more importantly being built to answer fundamental questions in astronomy that are beyond the existing instruments. Extra large telescopes have a greater collecting area, allowing much fainter objects to be recorded, and a greater resolving power, allowing finer detail to be seen in images. Both these advantages are needed to further explore extra-solar planets and the dusty disks around stars, to see individual stars in more distant galaxies that will enable more detail of galactic evolution to be unravelled, to allow measurements to be made on many more far-distant galaxies and hence give more observational evidence on how the early universe developed (since very distant galaxies are seen very far back in time) and there are any more goals.

All the extra large telescopes being planned and built this decade should see the light of the heavens early next decade (the early 2020s). The smallest will be the Giant Magellan Telescope (the GMT) built near the existing Magellan Telescope at Las Campanas in Chile by a collaboration of several American Universities, Australia and Korea. This will have the largest field of view of the ELTs (20 minutes of arc) but the smallest diameter at just over 22 metres (though it is not exactly circular). The next largest is the Thirty Meter Telescope (the TMT), to be added to the suite of telescopes already at the top of Mauna Kea in Hawaii and run by Caltech, the University of California, and international collaborators Canada, Japan,, China and India. The third instrument is the European Extra Large Telescope (the E-ELT), 39 m in diameter and located at Cerro Armazones not far from Cerro Paranal in Chile, the site of the 'Very Large Telescope' of the European Southern Observatory, who will build the E-ELT. We shall hear much more of these telescopes in the coming years but it will be the 2020s before the science from them begins to appear.

Telescope images

Suppose another sun, a star, is so far away that we can't see it as a disk with even the most powerful telescope but we can see light from it. This is in fact the case with all stars in the night sky. What does it look like? What it looks like depends entirely on the instrument we use to see it. Many people see stars as small ✸ or streaked spots. The streaks are put there by imperfections in the cornea or lens in your eye. In some telescopes, stars appear as ⌖ or as concentric circles. This is an artefact of the telescope optics, not caused by a design error but by the necessary consequences of the laws of imaging. All good telescopes have limitations set by the diffraction of light due to the wave properties of light itself. In short, all stars except the Sun are seen through telescopes as points of light, or what pass as points, because the nearest star beyond the Sun is 250,000 times the distance of the Sun from us, and most stars are very much further. In fact there are ways of deducing the diameter of stars without actually seeing their disk. We'll mention a few of these, in due course.

Units of distance

By the standards of everyday life, the Earth is big: 12756 km in equatorial diameter. Relative to the Earth, the solar system is very big. The average distance to the Sun is 150×10^6 km. The Sun is therefore greater than 10,000 diameters away. It's hard to appreciate how big such a distance is but 10,000 times the diameter of a tennis ball that you can put in your pocket is about 660 m, a long way compared with the size of the ball. Most of the solar system is a lot further from the Sun than we are. The textbook's analogy is that if the Earth is the size of a pinhead, the Sun is a basketball about 27 m away, a bit beyond the back of this room. Try making your own scale model: e.g. if the Earth is the size of a golf ball, how big is the Sun and how far away is it, etc? The diameter of the Sun and data for the 8 planets is given in an appendix of the textbook. Astronomers get tired of millions of this and that, like the rest of us, and have chosen better units of distance than km.

You might think that astronomers would use units like megametres or gigametres but no-one does. Astronomers use their own units. 1 Astronomical Unit (AU) is within a whisker the average distance between the Earth and the Sun. The AU used to be defined as this average distance but in 2012 it was re-defined to be an exact number of metres (149,597,870,700 which is almost 150 million km). Planetary distances are conveniently measured in AU. e.g. Mars is 1.5 AU from the Sun; Jupiter is 5.2 AU, and so on. The convenient distance unit for the solar system is the AU.

The AU is too small a unit to measure distances to the stars conveniently. Light takes about 8 minutes to travel 1 AU. The diameter of Pluto's orbit is 80 AU. It takes light or radio signals just over 5 minutes to get from Pluto to Earth or vice-versa. Light takes over 4.2 years to travel from the nearest star. Astronomers use **light years** to measure the distances to the stars. Even that doesn't get them out of talking about millions.

A light year is the distance travelled by light in vacuum for 1 year. Light travels at a speed of 3×10^8 m s^{-1}. In one light year it travels about 9.5×10^{12} km, another astronomical number.

If the Sun is shrunk to the size of a basketball, how far is the nearest star? It's about 7200 km distant – here to the mid-West of the United States. That's a lot of space in between.

Scale of the Universe

If you're well away from house lights and town lights on a dark moonless night, you will see a band of white light in the sky, like thousands of stars packed so close together that you can't see the individuals. This is called the Milky Way. The stars aren't really packed together, it's that we're looking edge-on through a disk-like conglomeration of stars that is our galaxy, the Milky Way galaxy. There aren't just a few thousand stars in our galaxy, which is all you can see with your naked eye in a star-studded moonless sky, but over 100,000 million, or 10^{11} - a truly astronomical number. Our galaxy is big. Most starlight comes from stars in our galaxy.

You'll see from the diagram that the galaxy isn't the end of the story as far as size is concerned. 100 years ago many people thought it was. Our perception of the Universe has enlarged many million-fold or more this past century.

If there are all these stars around and, from what I implied yesterday, all this life, then why haven't we seen some evidence of other intelligence in the Universe? It's a good question. I've written at greater length about this and you can read it in one of the articles flagged on the blue panel on the astro web page. I think there are two important factors here. First, life and intelligence aren't the same thing. Life of some kind or another may develop quite easily but intelligent life that can bridge the stars is another matter altogether. We've seen on Earth that with a relatively stable, diverse and favourable environment for life, it has taken some 4 billion years for life that appreciates the universe at large to appear. That is close to one-third the total age of the Universe. Secondly, it's hard to grasp the scale of the Universe. It is a huge place and getting anywhere significantly far from home is going to be tough for any large organism. The evidence is that a Zephram Cochrane hasn't been born elsewhere and almost certainly won't invent the warp drive on Earth in 2061. Perhaps someone here can change their name and prove me wrong. Most of the class will hopefully be around to see. I shan't.

Stars in our galaxy

A slight digression to illustrate how big 10^{11} is. 10^{11} is about the number of stars in the Milky Way. Pick up a handful of dry sand on the beach and let it trickle through your fingers. You've just let go a very tiny fraction of 10^{11} grains. See the diagram on the slide. Now think of all the grains of sand on every beach on Earth. Throw in the Sahara and Arabian deserts, too. You haven't got nearly as many grains as the number of stars in the whole Universe.

NGC 6744

If you could travel 30 million light years away from our galaxy and look down on it then you'd see a sight pretty similar to our view of the galaxy NGC 6744 in the constellation of Pavo (the parrot). Maybe aliens in NGC 6744 have their own photo of the Milky Way and say much the same thing about it as we say about their home.

Hubble deep field view

The Hubble deep field picture was the picture of the decade in the 1990s. It is the first of three such pictures. It came about by an inspired look at the edge of the universe. The

Hubble telescope was pointed at a tiny area of sky in a direction which was thought to be free of interstellar dust and in which there appeared to be no stars; no stars because astronomers were looking passed the closer stars, through the gaps to the edge of the visible universe. The area was only as big as a grain of sand held at arms length. Outside the Earth's atmosphere, an exposure to the residual light was accumulated for some 10 days. What appeared on the picture astonished astronomers. Remember that the farther away we look, the bigger something has to be before we see it. If anything really distant is to be visible, it is likely to be a galaxy. What came up on the picture was not just one distant galaxy caught by chance but over a thousand galaxies never before seen by mankind. Galaxies so deep in space that we didn't know they would be there. Galaxies so far back in time in the Universe that many people hadn't expected so many to have formed when the Universe was so young. If this is repeated in all directions, the number of galaxies present is hugely greater than we thought before. Another picture taken in a completely different direction two years later produced a similar result, confirming that the first picture was not just a chance observation. Remember that a galaxy may contain some 10^{11} stars. With a single exposure, the Hubble Space Telescope enlarged our view of the Universe by 10^{20} stars. A third picture taken in 2004 with a 1 million second exposure showed galaxies even deeper in space and further back in time.

It's a big Universe out there, full of objects that mankind never imagined before they were discovered. How do we know all this? Through science. Not religion, not politics, not philosophy. Science is based on **observation**; it is based on the application of **intelligent thought** to the observations; it is based on **careful measurements**, on the reality check of **testing ideas through working out their predictions and consequences and comparing them with natural behaviour**; it is based today on **advanced instrumentation** and always on getting as close as we can to what we're exploring, which in astronomy means getting out there as far as we can, beyond the interfering effects of the Earth's atmosphere with satellites and close up to planets in the solar system with space probes. [Anyone interested in how science works can explore this theme more fully in the piece 'The Grammar of Science' linked in the blue panel on our web page].

Astronomy is an ancient study, but most astronomical knowledge is very modern. This is indeed a great time to be living, for new discoveries and perceptions are being made at an astonishing rate. I shall try to convey some of the achievements of modern astronomy and how these achievements have been built upon our prior knowledge.

JSR