Cosmology 1 – the introduction

Study Physics, and see the Universe!

This course, more than any other we offer, will give you a view of the Universe. Cosmology is our attempt to understand the Universe as a whole. We not only want to understand what we find now but also we want to understand what it was like in the past and what it will be like in the future. Aspirations don't really get any bigger. You won't be surprised that there is no definitive cosmology to which all of mankind subscribes. These lectures, then, describe an unfinished story. What is astonishing is that, in the last few decades or so, science has made huge contributions to the subject, taking cosmology out of the realms of mere speculation and making it a subject with predictions that can be tested and parameters that can be quantified. There are sound reasons for believing that the age of the Universe is 13.8 billion years, that the Universe is expanding, that the matter with which we are so familiar, the contents of the periodic table, constitute only about 4% of the Universe, most of the rest being cold dark matter and dark energy; that all the matter we are made from except the hydrogen atoms was synthesised within stars that existed before the Sun, and so on.

As we grow up we become more familiar with the ways of the physical world around us. Thinking of a few examples: we accept that matter comes in the form of solids, liquids and gases (and plasmas); we think we know that if two clocks at the same place show different times, then something is wrong with at least one of the clocks, not that time can have two values at once, and so on. In fact most of us in our teens get set in our ways of looking at the world. Cosmology, along with other areas of modern physics, gets stalled brain cells moving again. In cosmology there are reasons to ask questions you haven't asked before, to think of ideas you haven't thought before. A few examples of such questions are: "Does space have to have three dimensions or are there hidden ones?"; "Why is there so much space in the universe?"; "Can space really be curved?"; "Does the concept of the beginning of time make sense"? Actually, it's very easy to ask questions that science can't answer ("Does God exist?") and so the trick is to ask meaningful questions that can be answered. You will be amazed at what science **can** say about the Universe. One side effect of opening our minds to new ideas and new questions is that we become more ready to think of new concepts and use our imagination in other subjects too. *Too much learning facts*, as someone once said, *makes Jack a dull boy* – and Jill a dull girl, too! Stretching our understanding and imagination makes us more creative. I recommend cosmology for this reason among others.

To make a serious point: one most important power of modern science is that it not only enables you to make deductions about nature but it gives strong guidance on what you can't know. Heisenberg's Uncertainty Principle is one obvious example of the limitations imposed on knowledge. A much simpler example is that if you know that you need four quantities to deduce the value of something through a mathematical relationship and you know only three of them, then you can't make the deduction from that knowledge alone. The concepts of logic are now well formalised, effectively codifying how to make a reasoned argument that stands up to scrutiny. Physics, Mathematics and Logic are central to modern science. They empower it and also set the boundaries of testable knowledge. I personally have a lot of faith in modern science, because of the way it has been set up as verifiable, self-limiting and self-correcting. All my experience tells me that nature obeys the precepts of Physics, Mathematics and Logic and hence a valid cosmology, which is trying to explain the Universe at large, must be consistent with everything we have discovered about these disciplines. Astrology, for example, is inconsistent with modern knowledge and should be ditched, as I wrote in much more detail in last year's astronomy course.

Cosmology isn't a subject that was invented by science. It was invented by our long-gone ancestors who wanted the big picture. Some form of cosmology is built into all the religions we know about. In all religions there are more things in the Universe than the animate and inanimate objects of our immediate surroundings. There are Heaven and the Underworld, Gods benevolent and malevolent, or at least angels and devils, a creation story and a continuation story. These concepts have not been clumsily bolted onto everyday experiences but have been well integrated to make a story with some internal logic that describes everything that is – the Universe as a whole.

It's been said before that some scientists too have been guilty of inventing if not religions then systems of belief that they hold whatever the evidence. They start off as dispassionate observers trying to understand the universe at large. Augmented by received 'wisdom' they draw up plans and specifications on how it all works and gradually become convinced that the universe must follow their own schemes. Any evidence to the contrary is deemed as flawed, unsound or mistaken. They end up treading the path from observer to would-be God. As I'm sure I'll repeat, nature does not have to follow anyone's working, no matter how authoritative. It does what it does and we observe and try to understand.

One feature of traditional cosmologies is that they have a participative element. Depending on which cosmology your society subscribes to you may attend large services, dress in special clothes or wear special decoration, join in public ceremonies or processions, eat special food or sing special songs and generally participate with many others in celebrating the existence of everything around us. It can be publically joyous or very personal. It will be a long time before society has comparable celebrations to marvel at the existence of the cosmic microwave background, the expanding universe, the Big Bang and many other features of the modern cosmological story. Meanwhile, a study of what is actually in the universe and how it came about will have to be a more cerebral experience and we'll save our communal celebrating for more immediate aspects of daily life such as the winning of sporting events, the commemoration of international events or simply that the banks are on holiday.

Scientific principles

Logic and self-consistency are concepts we cherish in our society. They are some of the foundations upon which science is built. Another foundation principle is simplicity of explanation consistent with all the facts. Einstein put it that '*everything should be made as simple as possible, but not simpler*'. This principle isn't limited to science. In Christian and Moslem societies people believe in one God rather than a pantheon of Gods each acting with a will of their own. That belief is understandable on the principle of the greatest simplicity, if nothing else. A less controversial example is that life is simpler if everyone around the world uses the same system of measurements. We don't have to. We have the brainpower and technology to convert between scores of different national systems but we try to use a single system on the principle of greatest simplicity that will achieve the ends. Where is this argument going? I want to introduce 3 foundation principles of science that have been responsible for the evolution of cosmology from a system of belief to a modern science. These are:

- logic and self consistency

- the principle of adequate simplicity
- the principle of testability

Actually there are other principles, too, embedded in modern cosmology but let me start with these three, for they apply to science as a whole. The final idea above, which is a key concept in distinguishing what is science from what is not, is that a scientific idea should produce testable conclusions. Modern cosmology is testable. A famous physicist of over 50 years ago, Lev Landau, once said that *Cosmologists are often in error but never in doubt*, a saying that has been used to taunt cosmologists on many occasions. Cosmologist used to be never in doubt because there were no ways of testing what they said. Now there are, as we'll see in this course. The bright light of testability has left only a very few ideas still in the spotlight. The rest have had to be swept off the stage.

Classical cosmology

I'm going to start a brief survey of historical cosmology by reminding you of the ideas of the classical era that were embodied in Ptolemy's *Almagest* and that most in the audience met in last year's astronomy course. The Ptolemaic view of the cosmos was not just a description of the planets but a view of the physical Universe as a whole. It embodied ideas widely held for centuries before Ptolemy and ideas that were embodied in the interpretation of Christianity that the highest church authorities of the Middle Ages defined as the only acceptable view. The astronomical ingredients were:

- the Earth was at the centre of the Universe
- the 7 planets, which included the Sun and Moon, revolved around the Earth in orbits that could be described with circular components
- each planet was contained within its own crystalline sphere
- out beyond the realm of the planets lay the stars, on the 8th crystalline sphere or firmament
- beyond the stars was the sphere of the prime mover, that kept the whole system in motion
- from Aristotelian philosophy, all earthly bodies were made of the four elements, Earth, Fire, Water and Air but the planets and stars were made of a fifth element, Quintessence
- in the realm of the planets and stars, nothing ever changes apart from the relative positions of the bodies as determined by the mechanism of the prime mover and coupled circular motions.

To these the Church added some theological ingredients such as

- God made the Universe in seven days
- the Sun was made for the purpose of illuminating the Earth by day and the Moon for illuminating the Earth by night
- and so on

Of course there were more details. I personally would like to tell you that these ideas represent long-gone history, like the Sack of Constantinople, the Battle of Hastings, the Crusades, the Hundred Years' War or the reign of Henry the 8th but unfortunately that's not the case. I'm sure you wouldn't have to look far to find someone who would say "What's wrong with these ideas?" Modern cosmology will tell you that everything is wrong with these ideas; every one has fallen to the idea of 'testability'.

Cosmology evolves

I laboured the point in the astronomy course how the Copernican universe placed the Sun at the centre, not the Earth; how Galileo's telescope showed that everything didn't revolve around the Sun or the Earth, for the Moons of Jupiter appeared to revolve around Jupiter. Tycho Brahe's reporting of a Nova Stella, or new star, showed that the heavens were not immutable and his calculations of the orbit of a comet showed that there were bodies further away than the Moon that came and went. Once people accepted that there were an enormous number of faint stars that were visible only with the aid of a telescope, then it became more obvious that one cause at least for the big variation in brightness of stars was that they were spread across a wide range of distances. The stars, then, are not all on a crystalline sphere.

In the eighteenth century, telescopes became powerful enough for people to realise that not all points of light are stars. Some apparent spots of light are 'nebula' or hazy objects. The telescope was showing the Universe to be a more complicated place. Einstein's dictum '*everything should be made as simple as possible, but not simpler*' highlights that the earlier cosmology was too simple. It was William Herschel in the late eighteenth century who, with the help of the widest telescope in the world making visible the faintest objects, first mapped out the distribution of stars in space and concluded that the Universe was somewhat disk-like in shape. He could not tell if the nebulous objects seen were within this disk or outside it, but he came down in favour that they were within it and the Universe of stars was disk like. He also placed our Sun near the centre, if not at the centre.

The astronomical view that we were close to the centre of a disk-like Universe prevailed for all of the nineteenth century. It took new technology and a new breed of astronomers to change that view. The new generation of very wide astronomical telescopes that were built in the first part of the twentieth century, accompanied by the new technology of astrophotography, showed conclusively that some of the nebulae were galaxies beyond our own collection of stars. The disk-like distribution of stars was real enough but it represented only the stars in our own galaxy. People realised that our galaxy, the Milky Way galaxy, huge though it is with a few hundred, thousand, million stars, was but little more than a point in a much, much bigger Universe. By 1920 the view was that our galaxy was about 10^4 light years across and the universe was a thousand times larger at 10^7 light years across. They still hadn't got it right. Our galaxy is about 10^5 light years across and the observable universe over 10^{10} light years across, more than 100,000 times as large in every direction as our galaxy.

Modern cosmology dawns

Cosmology as we know it is really less than a century old, some would argue barely half a century old. This is so not only because astronomy began to give us a realistic view of the Universe as a whole only after the twentieth century began but also because the second decade of the twentieth century saw the birth of Einstein's Theory of General Relativity. General Relativity is a theory about gravity, space and time. Gravity is the force that controls the large-scale structure of the Universe and hence without General Relativity it is not possible to have the kind of scientific cosmology we now have. I'll say some more about

General Relativity later but I want to cut quickly to what lies at the heart of modern cosmology.

How does cosmology work?

Modern cosmology is about applying the laws of physics to the Universe as a whole. That in itself is a huge step. You don't have to go far in this world to find countries where the laws of society are very different from our own, where the countryside and all the plants and animals in it look very strange. Yet we would say that these differences are superficial. Laws of society are made and changed by mankind; the plants and animals are simply an adaptation to local conditions of climate, soil and past evolutionary history. The laws of nature, we are quite sure, are the same the world over. It was Isaac Newton in the 17^{th} century who gave a convincing demonstration that the laws of physics extend beyond this world. He deduced that his law of gravity that explained the trajectory of projectiles on Earth would explain Kepler's laws of planetary motion if it extended out to the planets. Since Kepler's laws clearly work very well, there could be no doubt that the unifying idea, the law of gravity, must be true at planetary distances. If it extended to the planets, it should surely extend to the stars. So we have found. To take just one example, binary stars orbiting around a common centre of gravity obey Kepler's laws just as does a planet orbiting the Sun in the solar system. Hence the law of gravity appears to work across the Universe, as far as we can tell. Likewise, to take another example, the laws that control the spectra that light sources emit work not only in the laboratory but for our Sun as a source of light, for nearby stars and for every luminous body we can see, no matter how far away.

We can look back in time, too, and arrive at a similar conclusion that the laws of physics we have found out today seem to be the same ones that worked millions and even billions of years ago. Maybe you haven't thought about it before but when fossils several hundred million years old are analysed and the animals they represent are reconstructed, what we see makes perfect sense when we apply to them the laws of mechanics and biology that we know today. You can find fossilised wave patterns in sand and mud that are over a billion years old and they look identical to the wave patterns you can see at the water's edge on shores and estuaries today. The conclusion is that, unless we find evidence to the contrary, then we shall take the laws of physics that we have found on Earth and apply them to the Universe as a whole. We shall apply them to the Universe now and to the Universe in the past and in the future. That is the basis of modern cosmology.

On physical constants

If cosmologists get to the state when their story unravels, when they produce conclusions that can't be right because they disagree with observations, then they will have to go back to their starting assumptions and their techniques and modify them. It hasn't happened yet that this basic assumption about applying the laws of physics as we know them has had to be changed. It is a very strong assumption because the laws of physics embody a collection of fundamental physical constants. You've met some of these in one context or another before. Examples of fundamental physical constants are, in no particular order:

- the speed of light c
- the fundamental electronic charge found on a proton or electron e
- the strength of gravity acting between two masses G
- the size of the quantum of energy of a photon, determined by Planck's constant h

- the energy a particle possesses by virtue of its temperature, embodied in Boltzmann's constant *k*

Physics has been very successful at finding relationships between different things. It has also highlighted areas where we've been unsuccessful in finding relationships, which essentially spotlights areas of our ignorance. Among the many things we don't know is why the physical constants mentioned above have the values they do. It's fair to say that we haven't a clue really. Do we know any reason why these constants even have to remain constant in time? The only reason is the application of the principle of simplicity. We assume they are constant unless we have to do otherwise.

If any one of these constants were different in value from what it is found to be, then the Universe would be a different place. By implication, our cosmology would be different. Would the universe be so different that life on earth as we know it wouldn't be the same or even exist at all? What are the pre-requisites for life? These are big questions that have received a lot of attention in recent decades under the heading of the *anthropic principle*. This so-called principle explores whether life as we know it could exist if the constants of physics were different from their known values and in its strongest form concludes that a Universe with such life as we now find must have constants very similar to the ones we find. I may come back to this later. Even in this form it doesn't tell us why the physical constants have the value they do, just that beings like ourselves will necessarily find that they do.

Einstein himself is quoted as saying *What interests me is whether God had any choice in the creation of the world*. He wasn't talking about the values of the physical constants in particular but about the laws of physics as a whole. He was speculating whether universes with other laws of physics could self-consistently exist. In his own efforts to unravel the laws of nature Einstein used his principle of adequate simplicity as a guide. *I tried to imagine the easiest way God could have done it* he once said. Of course science fiction writers have tried to imagine other universes for a long time but they have never had to put their creations to the reality test, or even to the computer simulation test: food for thought here.

That is a bit of a digression at the moment from the basic tenet of cosmology, namely that we can apply the laws of physics as we know them to the Universe as a whole.

Getting going

In addition, we need some contextual assumptions before we can get going. These assumptions say in essence that we'll start from the simplest viewpoint we can think of and only introduce complexity if it becomes necessary. There is another famous quotation from Einstein who said, "*The most incomprehensible thing about our universe is that it can be comprehended*". We might add that it seems to be understandable on the basis of some remarkably simple assumptions. While I'm quoting Einstein, I'll add another of his sayings "*Any intelligent fool can make things bigger and more complex… It takes a touch of genius – and a lot of courage – to move in the opposite direction*". In cosmology you will see that touch of genius and indeed the hand of Einstein himself through his Theory of General Relativity, which is essentially the framework used to understand the Universe as a whole.

The cosmological principle

What, then, are the further basic assumptions of cosmology that I've been leading up to?

- **The Universe on a big scale is isotropic** to a high degree. This means that it is the same on a large scale if you look in any direction. Clearly on a small scale it's not. Just look around you. Look from the Earth across the solar system and there is a planet here and another one there but not one in every direction; the Sun's in one direction and no other, and so on. On an even bigger scale, look towards the constellation of Sagittarius and you are looking through the great disk of the Milky Way towards the galactic centre, but towards the constellation of Coma Berenices, south of the Great Bear, and you are looking out of the plane of the disk towards the galactic north pole in a direction that is comparatively sparsely populated with stars. Even on the galactic scale, the Universe is not isotropic.

What is the scale of the Milky Way? The Milky Way is a disk about 25,000 parsecs across, a parsec (abbreviated pc) being 3.26 light years. The parsec is the unit of distance common in cosmology. The isotropy of the Universe is a concept applied on a scale of 100 Mpc. On that scale, the Milky Way and other galaxies are scarcely more than points. The observable universe as a whole is about 14,000 Mpc across, though that figure needs a bit of careful explanation. Cosmology is about applying the laws of physics on that scale. The idea takes some getting used to. On the scale of the universe, galaxies are but tiny aggregations of matter, a bit like molecules are tiny aggregations of matter in a gas seen by us. Well, perhaps galaxies are not quite that small. On a scale where the observable universe is unit distance (like 1 m), a galaxy of 25 kpc would be about 6×10^{-6} units, or 6 microns if the observable universe were scaled to 1 m. A galaxy would be about the size of a small speck of dust in a box 1 m cubed.

- **The Universe is homogeneous**. This means that it is essentially the same everywhere. Again, the idea applies on the scale appropriate to the whole Universe. Homogeneity and isotropy are not quite the same thing. For example, if there were a uniform magnetic field running across the Universe, then it could be homogeneous, in that it is the same everywhere, but not isotropic in that the behaviour of particles moving along the magnetic field would be different from their behaviour if sent at right angle to the field. That would be a case of being homogeneous but not isotropic. If you imagine yourself at the centre of the Earth, then the Earth will appear almost the same along a path in any direction even though its composition and density vary with radius. This is an example of something (the Earth here) appearing isotropic from one point but not being homogeneous.

The two ideas of isotropy and homogeneity in 3D space are summarised by being given the name the **cosmological principle**. In other words, the cosmological principle states that there are no special places and no special directions in the Universe. It's an observational fact that the place we find ourselves in the Universe has no special properties. To expand on this a little: there are some observational tests that can be made on the isotropy and homogeneity of the universe at large. They all involve measurements that relate in one way or another to very distant objects; measurements like the number of galaxies of different magnitudes and their distribution in space, the diffuse X-ray background that originates from very distant objects, the microwave background that relates to the state of the Universe a long, long time ago. The evidence is sufficiently conclusive that the cosmological principle is incorporated as a basic premise of modern cosmology. The principle was essentially expounded by Einstein before there was much evidence for it but, like many of Einstein's other insights into nature, the evidence since he made his conjecture supports it. However, it's worth saying that the Cosmological Principle isn't a principle like the Principle of Conservation of Momentum, tried and tested in a million different circumstances. It is essentially an assumption, consistent with the evidence, that underpins modern cosmology. You'll realise that with this principle modern cosmology is quite different from most of the cosmologies of earlier centuries in which the Earth or the Sun occupied a very special place in the grand scheme of things, right in the centre. Modern cosmology says otherwise.

The background image is a section of the Hubble deep field picture of a tiny fraction of the sky taken south of the celestial equator. You can look at the fuller picture on the web.

Homogeneous and isotropic simulation

The last slide shows a small simulated 2D universe that is homogeneous and isotropic once you get past small-scale detail. The slide is used by Ned Wright of the University of California, whose cosmology tutorial you may find a helpful alternative presentation of some of the arguments I'm going to make in later sections.

Finally, I'll conclude this section with a few more quotations. Carl Sagan was a very influential populariser of astronomy in the years when satellites and space probes were beginning to show the huge range of knowledge that could be gained from extra-terrestrial exploration. He opened his famous TV series on 'The Cosmos' with the words '*The cosmos is all there is, or was, or ever will be*'. I can't do better as a fitting introduction to this course.

Articles in the media and TV programs can be very poor at distinguishing experimental fact, established theory and far-out speculation. 'Black holes' fall into the first category, 'wormholes' in space-time fall into the third category. Some ideas in these lectures sound 'far-out' when you first meet them so you'll have to take my word that I've tried to stick to concepts and facts in the first two categories and you'll need to use your growing experience when you read articles or watch documentary style programs to decide which bits of what you are presented with are which. You might expect the visuals of TV programs to be accurate but they are poor at telling you whether images are real or derived from computer simulations of the underlying science, or simply animations of an artist's impression. The bedrock of knowledge upon which science is based is experimental fact.

Re-enforcing this point, Sir Arthur Eddington, whom we'll meet later on, wrote in his book "The Philosophy of Physical Science": '*For the truth of the conclusions of physical science, observation is the supreme Court of Appeal*'. Einstein put it '*Truth is what stands the test of experience*'. Cosmology is no longer the subject of speculation of philosophers. Steven Weinberg, Nobel prize winner and one of the first successful popularisers of modern cosmology, commented at the end of his book "The First Three Minutes", when perhaps he was not feeling at his best, '*The effort to understand the universe is one of the very few things that lifts human life a little above the level of farce*'. Perhaps you'd prefer Stephen Hawking's observation that '*Scientific discovery may not be better than sex, but the satisfaction lasts longer*'.

On this note, I'm sure you'll be looking forward to our next section of scientific discovery. Our topic is "Expanding horizons".

JSR