Cosmology 5 – Dark matter and dark energy, the Universe revealed

We are lucky. We are alive and perceptive at a stage in the life of the Universe when there's a lot going on. A couple of generations of typical stars like the Sun have come and gone before our solar system was born. Great clouds of matter have formed and are still swirling through space. Galaxies of stars have formed, tugged at each other, collided and aggregated. Beautiful structures like our Milky Way galaxy litter the cosmos. They won't be there for ever. Indeed, star formation has passed its peak by some way, and is declining in the Universe.

Our place

We may be located at an apparently random place in the Universe but if you look around on almost every scale you'll see that we could be in a lot worse a place. We could be on a world that's permanently covered in cloud or haze. Take Venus or Titan, to name two nearby examples. How much would we know of the Universe then? Instead of being about 8 kpc from the centre of the Milk Way, we could have been much nearer the centre, either enveloped within interstellar dust or exposed to high levels of electromagnetic radiation from a variety of mechanisms, or too near a massive star that blew its heart out in a supernova explosion. In fact the more you look around the Universe, the more it becomes apparent that it's not a great place for life. Almost every part of the Universe is either too hot or too cold, debris is whistling round at tens and even hundreds of km per second, impacting whatever comes in its way, electromagnetic radiation and other hazards all make life unimaginable in many parts of every galaxy. What fraction of the Universe is like the Earth with blue skies, sunny beaches, heather clad mountains, productive fields and forests? A precious small fraction. In fact, so far we've found nowhere else. There can't be a much stronger incentive for looking after the Earth.

This is a suitable place for a digression that I may not cover in the lectures. I used to wonder, as you probably do, 'why haven't we seen evidence for other intelligent life in the Universe?' If you're a believer in abduction by aliens using flying saucers, then the question is a non-starter. For most of us, though, it's a good question. My take on it is both physical and philosophical.

First, the physical reasons. It's only in the past few decades that mankind has realised what an enormous place the Universe is - enormous but almost empty: empty of matter and empty of energy. The universe at large is not a place where the complexity of life thrives. It is mainly a cold, dark and empty place except in isolated and widely separated regions. The stars are too hot for life, too hot in the most part for even molecules to exist. Active life, which I take it is a pre-requisite for intelligence, can potentially exist in narrow shells a few light minutes across around stars, where the temperature is about right. Stars themselves are typically light years apart. It is possible that other civilisations can launch intelligent life away from its origins in these habitable shells, but life sustaining capsules need adequate energy to travel for large amounts of time in the cold and dark of space. However that may be, in short the gigantic vistas of space and the low density of matter in space both dictate that advanced life that develops separately is likely to be a very long way apart.

Secondly, there are issues of time as well as space. Any kind of life was never going to form early in the history of the universe. The elements from which life is built simply didn't exist. The very atoms of life such as C, N, O, P, S, Fe, Mg and a bit more of the periodic table in small amounts were not present in the early universe. They have taken billions of years to form in reasonable quantity, generated during the evolution of medium-sized stars. The elements that might make up ‘artificial life’, such as Si, Ge, As and Al, if our present day electronics technology develops far enough in this direction, have been no quicker to appear. It will have taken billions of years for the most primitive life to start in the Universe.

As we know from the one example we can probe into here on Earth, it also takes billions of years for intelligent life to form once primitive life has arrived. There are traces of cellular life on Earth 3.5 billion years old. Life that understands the astrophysics of the Universe is less than a century old. For a start, we need to be orbiting a singleton star that lasts a good few billion years, and stars much more massive than the Sun don’t do so. We also know that for quite special reasons the Earth has enjoyed an unusually protected history and been spared an assortment of potentially common cataclysmic occurrences that could have wiped out life in several ways. I’m thinking of instabilities in our star the Sun, of an enormous impact by another body, of the supernova explosion of a nearby star that would have bathed the Earth in deadly radiation, or simply a tumbling of the Earth’s spin axis over many millions of years that would have caused potentially life exterminating climate changes. We have been spared all these and so it could well be that the appearance of intelligent life in the 4.6 billion years of the Earth’s existence is a fast-track time for natural evolution. Don’t be surprised if aliens are not living next door. We’ve almost certainly done well to get this far this quickly.

Finally, there are some more ‘philosophical’ reasons why we may not have seen intelligent life. First, we may not recognise it when we see it. It may be on a nanoscale; it may be gigantic. We humans have a good imagination but every generation fails to see what later generations think of as ‘obvious’. More likely, intelligent life may not want to communicate with us. What would be the point? When you see a baby in a pram you know that your own experience of life and your knowledge of the universe is vast compared with its. Do you stop and try to pass your knowledge on? No, it’s pointless, and you really don’t speak the same language. The baby will grow up, evolve and learn about the universe in the fullness of time. Maybe intelligent life feels much the same when it has detected the birth of mankind’s civilisation and awareness that we are probing the universe. In evolutionary terms, alien life may already have adapted to challenges we’ve never faced yet and be living a totally different kind of existence. Perhaps I’ve watched too much Star Trek, where the ‘prime directive’ is that ‘there be no interference with the natural development of any primitive society’. Star Trek is fiction but the code may be a good one for evolved life forms. One can’t help feeling that when mankind as we know it leaves the Earth, it will be to create colonies and the ‘prime directive’ will be nowhere to be seen.

On reflection, I’m not surprised we haven’t seen alien life. The astronomical distances and the harshness of space as an environment almost preclude travel for sentient beings. Perhaps the best that can be done is to send the seeds of life into space. Seeds, though, don’t include encyclopaedic knowledge and they need to be absorbed into the local surroundings when they arrive to grow and develop. After that, they are no longer alien.

A huge range of possible alien scenarios have been explored by science fiction writers, some seriously, some just for the adventure. I’ll leave you to browse. Now let me return to the topic of the lecture.

In the last chapter we left the Universe a bit less than 1 million years old, having cooled so that light could now travel almost unimpeded between the matter. The Universe was about

1/500th of the size it now is and filled with cooling electromagnetic radiation that has now become the cosmic microwave background we measure. The universe was pretty well uniformly filled with thinly spread out matter and with radiation. When did the first stars and galaxies appear? Not for quite a long time, perhaps 200 Myr. Now the physics gets complicated. There are a few things I haven't told you about whose existence can't be hidden any longer. One of them is 'dark matter'; the other is 'dark energy'.

How much matter?

Radiation and matter are two forms of the energy of the Universe. I said a while back that the density of the Universe has been found to be such that the Universe is geometrically 'flat'. This meant that it has just the critical density to expand for ever. In cosmological jargon, $\Omega_0 = 1$. However, when the amount of matter as we see it is added up, the density barely comes to 1% of that needed to make $\Omega_0 = 1$. Let's put it another way. If you took all the matter we know about in the Universe, not only the Earth, the solar system, and all the stars in our galaxy but include all the galaxies we estimate exist and pull them apart, atom by atom and spread the result over all the space we know about, what density of would there be? It's clearly not zero. The figure works out at barely 1 atom per 10 cubic metres. Compare that with the density needed to make $\Omega_0 = 1$, given earlier as the critical density of about 5 atoms per m^3. The conclusion is that there must be much more matter around than we can see.

There appears to be a large amount of dark matter in the halo of our galaxy, and in other spiral galaxies. This matter has been christened MACHOs, **ma**ssive **c**ompact **h**alo **o**bject**s**, as a play against the concept of WIMPs that I'll introduce shortly. Some machos can be detected by gravitational lensing, an effect mentioned in chapter 3 of these notes that arises in General Relativity from the ability of massive objects to deflect light. Unfortunately, fewer machos are detected by this method than should be for the amount of mass that's known to be present in halos. More on this shortly.

What's in the dark?

If we throw in what we know of invisible baryonic matter (protons, neutrons and such like particles are called baryons by the particle physicists) such as brown dwarfs, interstellar dust etc., then we come to about 4%, or as the cosmologist would put it, $\Omega_M = 0.04$. Surely someone has made a mistake in the arithmetic? No they haven't. Well, what about the radiation then? The Universe we know is matter dominated so you won't be surprised that the energy density of the radiation is much less than 4%, in fact less than 0.01%. What makes up the 96% of the energy density that we're missing? Dark stuff. You mean like soot, clinker, dead stars and such like? No. That is all made out of baryons and whatever most "dark stuff" is, it's not made out of atoms like we are. Just when the story of the creation and evolution of the Universe seemed to be going well are we forced to say that the Universe must be full of stuff we've never seen and which doesn't really come into our day-to-day physics, or even our laboratory physics? In a word, "yes".

Stuff we can see has an immediate reality. It takes more mental effort and an appreciation of the value of diverse evidence before we're convinced of the existence of something we can't see. If you look around this room, you think you can see everything in it. You are wrong. There are a good many things you can't see, from the IR, microwave and radio electromagnetic radiation filling the room, the neutrino flux, the cosmic ray flux, the radiation from the granite walls, the microbes and viruses we breathe in every moment, the sound waves that cross the room as I speak and indeed the air we breathe in. A room 10 m by 10 m by 4 m high contains 400 kg of air, and we can't see any of it, though we can get an inkling it is there from our sense of touch if you wave your hand around. So we do get used to believing in the existence of things we can't see but it's not nearly so immediate as with visible objects. Are there things in space we can't see but we think we can feel? Cosmologists and astronomers have identified two different kinds of dark stuff. It's a topic you may research into if you become an astronomer. Two things we can't see are called **dark matter** and **dark energy**. They are different.

Dark matter is felt by the force of gravity but it doesn't show up in our telescopes, instruments that aid our sight. If I drop an apple to the floor and measure its motion, then the motion is exactly consistent with the size and mass of the Earth that's attracting the apple. Gravity moves stars as well as apples, and clusters them into groups. We can work out from the dynamics of star motion and the law of gravity how much gravity must be present to cause the observed motion of stars that we do see. Gravity itself is caused mainly by mass, i.e. matter. Hence we can work out how much mass is responsible for the observed motion of stars.

Newton's law of gravity

Before telling you the result, I should just remind you what Newton's force law of gravity is. General Relativity tells us that this law is an approximation but it's an approximation that is more than good enough for almost all applications. Gravity is the force of attraction, F, between two masses m_1 and m_2 a distance r apart, measured from the centres of the bodies. In the simple formula usually quoted and given here, r is normally much bigger than the dimensions of either body. In the special case of the bodies being spheres, it doesn't matter the size of their radius in relation to the distance apart of their centres.

$$F = G\frac{m_1 m_2}{r^2} \tag{5.1}$$

Gravity is the force that m_1 exerts on m_2 and vice-versa. Gravity is a double-ended pull, at either end of the line joining the two bodies. G is a constant that gives the strength of the pull; in SI units $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}. In the case of spheres, the gravity produced beyond the surface of a sphere is the same as if the sphere were a massive particle located at its centre. I have said quite a bit about gravity to our astronomy class last year so I'll not say any more here.

Mass in a galaxy

How much mass, then, is responsible for the motion of stars in a galaxy? Starting from home base, the motion itself is found by measuring in detail the velocities of the stars in our own galaxy over the whole range of distances from the galactic centre to the edge. This is largely done via the Doppler effect. You know from Kepler's law that the further a planet is from the Sun, the slower it orbits. The same is expected to be true of stars in a galaxy. It's not quite as simple as Kepler's law because the further out one looks the more mass there is within the orbit of a star around the galaxy. However, the speed of stars beyond the Sun is expected to be slower than the speed of rotation of the Sun around the galactic centre. The measurements show otherwise. From about 2 kpc out from the centre, the speed of everything orbiting around is much the same. The slide shows the rotation curve and the deduction that more mass is needed than we can see, distributed throughout the galaxy, to explain the observed rotation.

NGC 3198

Evidence of rotation curves obtained for many galaxies give the same result. The slide shows the evidence from the galaxy NGC 3198 where the radio emission from hydrogen atoms can be traced out several radii beyond the optically visible galaxy. Dark matter is not just lurking unseen in the corners but actually is present in greater amounts than visible matter.

More evidence

When galaxies are studied as a whole the conclusion is that the ratio of mass, M, to light given off, L or luminosity, is about 20 times what our Sun produces. i.e.

$$(M/L)_{galaxies} \approx 20 \times M_\odot / L_\odot$$

($M_\odot$ is a symbol meaning the mass of the Sun). Your 'first thought' may be that galaxies contain lots of massive stars. This isn't true, and wouldn't solve the problem even if it were true, for massive stars emit huge amounts of radiation. When you look at stars more massive than our Sun they all have a smaller ratio of (M/L) than the Sun because they have very big luminosities. "Maybe galaxies contain lots of dim stars that we can't see", you may say. You are now looking in the right direction to increase (M/L). When we look at the stars near us we do see lots of dim stars that we would miss if they were further away. Locally $(M/L)_{local} \approx 3 \times M_\odot / L_\odot$. The dim stars are not enough to account for the high ratio of mass to luminosity associated with galaxies. There must be other 'stuff' around that we can't see. In a nutshell, to account for the large ratio of M/L in galaxies compared with our Sun both the average luminosity must be less than our sun **and** there must be more mass around.

In the Coma Cluster, there exist huge regions of gas hot enough to emit X-rays that can be imaged by X-ray telescopes like Chandra and Newton that were launched in 2003. These gas clouds are so large and so hot that they could not be held in place by the gravitational attraction of the visible matter we can see in this cluster of galaxies. This is yet more evidence for matter over and above the stars. Indeed there is evidence that hot gas is commonly present in galactic clusters in large amounts, totalling in mass more than the stars in the galaxies. 'Hot' really is hot – some 10 million degrees at the cool end and at least 100 million degrees at the hot end. The larger the cluster, the hotter the gas.

The conclusion of astronomers is simple. The stars are moving under the influence of more matter than we can see in our telescopes. The number of observations and deductions required to make this statement with confidence is considerable but all the evidence points in the same direction. One future mission to keep an eye on is the EUCLID Mission, due to be launched around 2020, one of whose aims is to measure the large-scale distribution of dark matter through its gravitational lensing of distant galaxies. EUCLID is another of the giant survey missions, aiming to record some 2 billion galaxies from the pristine conditions beyond the Earth's atmosphere at the Lagrangian point L2.

MACHOs

'Dark matter' is our name for that 'stuff' we can't see that's gripping stars on a cosmic scale. You might think that what we can't see is most likely to be large numbers of black, dead stars drifting around in space. After all, it's hard to see coal in a coal cellar if your only illumination is feeble starlight. However, astrophysics tells us that this can't be the case for the universe isn't old enough to contain black, dead stars. Put another way, the embers of stars take longer to cool than the Universe is old. What might dark matter be? Enter the two candidates, MACHOs and WIMPs.

'MACHOs' (**MA**ssive **C**ompact **H**alo **O**bject**s**, as was mentioned earlier) is the name given to astrophysical candidates for dark matter made out of stuff we would recognise. The halo association is because it seems that much of the dark matter is in galactic halos. MACHOs were the contenders to account for all dark matter in the 1970s and 1980s but every candidate that has been thought of has been explored in some detail and gradually been crossed off the list of major suspects. The contenders do not seem to be present in large enough numbers. They will all contribute some dark matter, but not nearly enough to account for all that must be there. Here are some examples:

- red dwarves – super massive planets that don't have enough energy to light up by nuclear fusion but glow from energy released by gravitational collapse
- brown dwarves – low mass stars, say 0.1 to 0.9 $M_\odot$, of low luminosity that emit mainly in the IR
- white dwarves – spent stars around 0.5 $M_\odot$
- VMOs – very massive objects, say black holes that are known to be the final fate of very massive stars
- SMOs – super massive objects such as entire galaxies with low surface brightness
- cold clouds of mainly hydrogen
- primordial black holes – **if** large numbers were formed in the very early universe then they would still be around.

The final two contenders are being increasingly considered. However the evidence is in that only some 4.4% of the mass of the universe is baryonic, meaning it is made of neutrons, protons, etc. so most of the dark matter is 'something else', generally more diffuse. In one sense more like something that's distributed in the Universe as the air we can't see is distributed in this room. Non-baryonic dark matter isn't air of course, or any new kind of molecule. In fact it is a component of the Universe that isn't made out of the stuff we are.

You may say "wait a minute, postulating something with properties so different from the matter in our experience to explain the motion of stars is really no explanation at all. An explanation in terms of the unknown is no explanation." You are partly right but it is the way science extends its basic knowledge base. For example, radioactive β decay was 'explained' by Fermi in 1932 by his introduction of the neutrino, a particle with no charge, no rest mass that travelled at the speed of light but wasn't light. The neutrino was outside the science then known but it had to fit in with observation and with what was considered known, such as the laws of conservation of energy and momentum. Gradually more and more knowledge was built up about the neutrino and it became clear, for example, that there had to be more than one kind of neutrino and, indeed anti-neutrinos. The whole of neutrino physics was gradually fitted into what we see as legitimate particle physics and in the modern view of things the neutrino is a fundamental constituent of nature that we simply hadn't discovered before investigations were made into β decay. Nobel prizes have been won for neutrino physics in the last 20 years. Another example is the concept of quarks. We now believe that neutrons and protons are different manifestations of particles made of 3 quarks. Quarks are part of the stuff of nature at a level below that of protons and neutrons. No-one has ever detected a free quark. However, to fit in with the observed properties of neutrons and protons, the underlying quarks have to have such a well-defined and consistent set of properties that we are convinced that we can talk of them just as sensibly as we can talk of neutrons and protons.

23% of energy is non-baryonic dark matter - WIMPs

The current best estimate is that 23% of the energy in the Universe is non-baryonic dark matter. Astronomers and cosmologist have lots of 'good' ideas what this dark matter might be. The ideas are 'good' in the sense that they extend our current ideas of particle physics in the right direction but the ideas are not so good because they can't all be right and there is no clear front runner. In that sense, we are still struggling. Let's give the dark matter particle a generic name – WIMPs, or **W**eakly **I**nteracting **M**assive **P**articles. It's not always obvious when names given to particles by physicists are whimsical or have some implicit meaning. WIMPS sound whimsical but the name actually has some meaning. WIMPS are so called because they are imagined to interact via the weak force that is moderated by W and Z bosons. They are postulated to be massive because if they have no charge (which they must do to remain 'dark') are of similar mass to the bosons, say around 100 GeV, then as the universe expanded they will condense out to create a cosmic background, just like the backgrounds created by photons and neutrinos. The 'WIMP miracle', so called, is that the density of this background from theory is in fact close to the density of dark matter that is deduced from numerous different observations. The search for WIMPS that is taking place in several big experiments is not as outrageous as a search for the gruffalo or gremlins, creations of a fertile mind, but is looking for particles that would fit nicely into our well established understanding of the universe. The pity is that they have not yet been found by our particle detectors.

Neutrinos were a candidate for dark matter. We know that neutrinos have a very small mass and therefore will exert a gravitational force if enough of them are present; we can't see them and, indeed, they interact exceedingly weakly with ordinary matter; we know that there were a comparable number around to the number of photons in the early Universe. However, as we get clearer experimental evidence for their mass, we have found that this mass is not enough to account for the dark matter we need. Neutrinos are present but they are only a small amount of the dark matter we are looking for.

The WIMP picture of dark matter is that it forms a kind of atmosphere within a galaxy. The WIMP particles can weakly interact with themselves, enough to create an internal pressure that resists gravitational condensation. The density of dark matter that one needs to explain the rotational features of galaxies, for instance, is actually very low if that matter is spread throughout a galaxy. This makes sense because if all the matter in the stars in a galaxy were spread out into the volume of the galaxy it would occupy only a few molecules per cubic metre. Dark matter is supposed to be similarly uncondensed in the galaxy, occupying a huge, roughly spherical, shell within which the visible galaxy sits. So, in case you wondered, there *is* dark matter within the solar system according to this picture but its density is too thin to have any measurable effect on the observed dynamics of the solar system.

Search for dark matter

Can WIMPs be detected in other ways than by their large-scale gravitational influence? People are trying. An extension of the standard model of particle physics introducing a concept called *supersymmetry* predicts a second, more massive, family of particles than the ones detected by today's generation of particle accelerators. These particles can decay into each other, much as the particles we're familiar with can. However, the lowest energy particle can't decay into any others, for an obvious reason, so it is a contender for being a long-lived WIMP. The lowest energy particle is one of four 'neutralinos', neutral and very weakly interacting like a neutrino but not in principle impossible to detect.

If WIMPs can be detected individually, then we will know much more about them and there will be some hope of distinguishing between contending ideas of what they might be. This is the driving force for a number of experiments both past and present. The Boulby Mine in Yorkshire was the site of experiments that ran for several years but the last of them, the ZEPLIN project, closed in 2012. You may remember from last year's astronomy course that neutrino experiments are typically conducted down mines because neutrinos are very weakly interacting neutral particles that are hard to detect. Any such experiment needs the shielding provided by a kilometre or more of rock so that counters are not triggered by muons generated in cosmic ray showers. In addition, the mine must be carefully chosen so that there is very little background radioactivity from the surrounding rocks themselves. The Boulby Mine experiment, 1.1 km deep, had a similar philosophy to a neutrino experiment. The very hard part in such experiments is removing or accounting for all the background signals. Until that has been done, you can't say that you have detected something new. In fact the Boulby Mine experiments did not observe any WIMPS. The null results from ZEPLIN and other such experiments set limits on how weakly interactive WIMPS are, telling future searchers how sensitive the next generation of instruments must be to have any hope of success. I'll leave you to look on the web for more on this and related dark matter searching experiments, of which there are over a dozen. Look for names such as CDMS, EURECA, CRESST and DAMA. There are links on the course web page to two high-profile WIMP experiments. DAMA has created a big stir by claiming to have detected dark matter at a level that should have been seen by other experiments but hasn't. WIMP searches are part of the astronomy of the future, very different astronomy from peering through a telescope. WIMP searches are speculative science but the prize of discovering what no-one has detected before even though there's more of it in the Universe than all the matter we can see is enough to keep many groups going. As Martin Rees said in *New Perspectives in Astrophysical Cosmology* "Great galaxies could be just a puddle of sediment in a cloud of invisible matter ten times more massive and extensive".

Any more ideas?

Dark matter may be a gamut of particles. However, we are struggling to find experimental evidence for the existence of any particular kind of WIMP, apart from their gravitational effect. Several experiments connected with cosmic rays have detected a surplus of electron/positron pairs over the number expected. One school of theoreticians attribute this to the generation of such pairs by interacting WIMPS known as Kaluza-Klein particles, in which their mutual interaction is effected by a new force called, not surprisingly, 'the dark force'. There is some high-power physics behind this idea but there is also high-power physics behind the competing neutralino idea so that in itself doesn't count in its favour. What will count is if detailed predictions from the theories match observations. It seems to me almost a certainty that 'out there' there is a universe of almost but not quite hidden particles that interact weakly with the stuff all around us; a universe whose existence was not even suspected until cosmology changed from a speculative to a numerical discipline in the modern era.

If this generation and the next generation of astronomers can't make the idea of 'dark matter' work, then it will be abandoned for an idea that's more successful. On the bottom line at the moment are two key observations: 1) Galactic motion on a large scale implies more matter in the universe than we see in visible stars or can deduce from the known constituents of the Universe. 2) The Universe appears to be self-consistent and in a very large measure intelligible in terms of the physics that has been developed over the last few centuries. Therefore future extensions of our knowledge need to be consistent with what we already know. Dark matter may be unknown as yet but it needs to fit onto our present day knowledge in some intelligible way.

In passing I'll mention MOND (MOdified Newtonian Dynamics) because it's an acronym that you may come across in articles. MOND is an alternative idea of why galactic rotations don't tally with the mass we see in galaxies. It's not dark matter that needs to be introduced, the MOND people say, but a modified form of the law of gravity when working on a galactic scale or larger. MOND enthusiasts try to interpret the effects attributed to dark matter, particularly those of galactic structure, galactic collisions and galactic clustering as consequences of a modified gravity law (i.e. modified General Relativity). They have some success but it's fair to say that the weight of evidence is against this idea. Of course any future detection of WIMPS will kill MOND stone dead. Computer modelling of large scale galactic structures needs dark matter to form the kind of structures we now see, so much so that one can say pretty confidently that the universe would not be like it is today if dark matter wasn't present.

In one sense MOND isn't as radical as it sounds since if you look back at Einstein's general equation mentioned in passing in 'chapter' 3 of these notes you'll see it has gravity on the left-hand-side and the 'stress-energy tensor' on the right. Both dark matter and dark energy are modifications of the right-hand-side, leaving the left-hand-side unchanged. MOND is an attempt to change the left-hand-side and leave the right-hand-side unchanged, or at least get rid of dark matter. The interpretation of the two approaches is quite different and there are technical reasons why dark matter and dark energy are the better options.

[As a brief aside while updating these notes in 2013 I'll mention that the Boulby Mine is about to become the long-term host of the Boulby International Subsurface Astrobiology Laboratory (BISAL) that will no doubt feature in the scientific news in coming years. One reason for locating this facility in the mine is that its salt deposits are thought to be the kind of deposits that exist on Mars in which early life on Mars may have flourished and subsequent halophilic life may still be found. The Boulby mine deposits contain a variety of salt-loving microbes that may be derived from the salty sea in which the deposits originated in Permian times, 250 million years ago.]

The Anglo Australian 2dF redshift survey

This is one survey among several to map the distribution of galaxies in the Universe. The 2dF stands for "2 degree field" which is the width of the survey slices. The slide shows clustering of galaxies over one area of the sky. Each one of more than 100,000 galaxies in this survey had its spectrum taken and the red-shift identified. Hubble's law relates red-shift to distance and, of course, time, since most of the galaxies are far enough away to ignore peculiar velocities. You are seeing a map of some of the large-scale structure of visible matter in the universe. It's very clear from such images that the organisation of galaxies on a large scale is very different from the organisation of stars in galaxies. You would suspect that processes that are at least different in detail, if not in principle, are at work in these two different cases.

The detail you see here is a revelation of modern astronomy. Pictures like this weren't available even at the start of the 'space age'. By the mid 1960s, the best galactic red-shift survey contained only 1500 entries. Even the idea that there was a 'large-scale structure in the universe' that needed to be understood wasn't articulated. Over the 1970s, '80s and through the 1990s to the present day, modern observational techniques have developed and a picture of the universe on a large scale has began to emerge. That picture shows galaxies distributed in a way that reminds us of the walls of material in a froth, though not quite so connected as a froth. The walls have texture within them in the form of clusters and small voids. Some super-clusters of galaxies appear filamentary; within them are clusters that may be roughly spherical with protuberances, such as the Virgo cluster of which the Milky Way is one component towards the end of a protuberance. The voids may not be completely empty but are seriously under-dense. Surveys reporting this century have put a lot more detail into this quasi-cellular picture of the large scale structure of galaxies in the universe.

Part of the 'map of the Universe'

See this impressive visual aid on the web. There is a link on the course web page. The information comes from an independent survey to the 2dF image of the previous slide. The quasi-cellular structure is pretty obvious. How did it get that way?

Galactic clustering

Dark matter affects mass on a cosmic scale. It therefore influences the formation and evolution of galaxies. Galaxies exist on a huge scale in both space and time and hence the evidence we have to work with is essentially a snapshot of the Universe as we now see it. In one very important respect a snapshot of the universe differs from a snapshot you or I take with a camera. A snapshot of the universe contains information about earlier times in the Universe, if we look far enough away. For instance, if we can see objects that are about 4.5 billion light years away, and we can, then we are looking at objects one third back towards the creation of the Universe. Although we can't see any one galaxy or system of galaxies evolving, and in that sense our view is like a still photo, we can see what galaxies were like a very, very long time ago and compare their appearance to nearby galactic systems only a few tens of millions of light years away and hence 'modern' galaxies.

Now, we know that galaxies come in quite a range of sizes from small-scale, dwarf galaxies, to large ones like our own Milky Way galaxy or the neighbouring Andromeda galaxy. In the early universe, did small-scale galaxies like dwarf galaxies form first and then accrete to form large galaxies? Did large-scale structures form early on? The answer lies in the effect of dark matter on the visible matter we see composing galaxies.

Galaxies are a clustering of matter. Clustering began as density fluctuations in the early Universe. Some of these fluctuations grew under the clustering effect of gravity. The growth process is was not unlike the way a flat road acquires more and more potholes over the years if it is never maintained. A new road is never quite billiard-table flat. Slight small-scale undulations cause the wheels of passing traffic to exert irregular forces on the road surface, sometimes greater than average where a wheel encounters a slight uprise and sometimes less than average where a wheel is lifted over the back of a very small rise. The greater than average forces keep occurring in the same place, dictated by the little undulations. Gradually the road there is knocked more and more out of shape until a stone comes loose and a tiny pothole forms. The pothole quickly exaggerates the irregular force exerted by passing wheels and more stones come loose. The front edge of the pothole gets hit hard by a falling wheel and the rear edge crumbles away. The pothole gets bigger. People swerve around it and the traffic gets focused onto a smaller area of the road. More potholes form in the previous apparently smooth section of the road and potholes begin to coalesce into very big holes. You get the idea. The process is an inevitable result of the forces acting on the road.

The Universe is something of the same. The force in the Universe exaggerating the tiny initial irregularities is gravity. On a road, hopefully a workforce will repair the first potholes before they get really bad. You might think that no-one repairs the density fluctuations in the Universe caused by gravitational attraction. This is not quite true. A small clumping of matter increases the temperature of the matter in the clump as work is done by the gravitational force of attraction. The increased temperature means that the particles move faster and this tends to expand the clump, reducing the clumpiness. Small clumps tend to disperse due to this effect. It’s large clumps that grow, where gravity wins over the increased temperature.

In a static universe density fluctuations will necessarily lead to a collapse of matter. In an expanding universe, this isn’t so because the expansion of the universe is making matter separate on the very largest scales. If the expansion were too great or the density fluctuation involves too little mass, then condensation won’t happen. In a universe with very rapid expansion, there would be no galaxies, no stars, no planets and hence no intelligent life as we can conceive it. It was the astronomer James Jeans who first investigated in some detail the conditions under which an over-dense fluctuation of matter would lead to a condensation. The critical mass is known as the Jeans mass. For the parameters of the Universe at the time of recombination it was about 10^6 solar masses. This may sound a lot but is very small compared with our own galaxy, which includes more than 200,000 million solar masses of matter, excluding dark matter.

To come back to the question of whether small galaxies dominated in the early universe and have gradually aggregated to form larger ones or whether large ones formed first and have fragmented in time, the evidence favours the first idea.

Dark energy

After all the effort expended in explaining the origin of matter and dark matter, we believe that together they account for only just over a quarter of the mass of the universe. 73% is something we call ‘dark energy’.

Dark energy has been firmly put into the cosmological picture in the past few years. Look back in our lectures to where I mentioned the acceleration factor q_0 of the cosmic scale factor. The story I have given so far leads you to believe that the rate of expansion is slowing down, for the simple reason that gravity is an attractive force and works against expansion – slowly perhaps, but inexorably. Results measuring the acceleration parameter q_0 seem to show that it is *negative*. The parameter was defined so that a positive value was what was expected and hence a negative value means an increase in the rate of the expansion, not a decrease. What is going on?

This is a question that all cosmologists are asking. The beginning of the answer takes us back to Einstein again. Einstein himself showed that his equations were consistent with a collapsing universe or an expanding universe. He didn't like this and added an extra term that he called Λ and which has since come to be called the *cosmological constant*, in order to counteract this expansion or contraction and create a steady universe. In the 1920s, the work of astronomers Vesto Slipher, Edward Hubble and others convinced Einstein that the expansion of the Universe was real. Einstein took his *cosmological constant* out of his formulation of General Relativity, realising that it wasn't necessary to make General Relativity agree with astronomical observations. He described its introduction as *the greatest mistake in my life*. However, that's only the beginning of the story.

The cosmological constant has come back again, this time as a possible expression of dark energy that will account for the accelerated expansion of the Universe. Einstein chose the value of his constant to stop expansion. However, change the value of it and you have a cosmological constant that represents an expansive force that is unclustered at all scales, homogeneous throughout the universe. If it were too large in cosmological models, then there would be insufficient time for galaxies and their clusters to form, because space would expand too quickly. The cosmological constant effect has to match the observed expansion rate.

As I said earlier, the Universe appears to have the critical density to make it flat. Hence if we associate a density Ω_Λ with dark energy, then we have:

$$\Omega = 1 = \Omega_0 = \Omega_m + \Omega_\Lambda$$

There are also contributions from electromagnetic radiation and neutrinos to the total density of the universe Ω but we now know that these are very small so I haven't included them. Why does the sum of the two components written above just give the critical value Ω_0? Moreover, Ω_m scales as a^{-3} (a is the cosmic scale factor discussed in the second cosmology chapter) and hence surely Ω_Λ must scale the same way or it is an amazing co-incidence that the two just sum correctly to make the universe 'flat' at this moment in the history of the Universe. There is a real issue here for modern-day cosmology. If the cosmological constant Λ really is a constant, then there's no reason to believe that Ω_Λ scales this way. Hence Λ must vary with time rather than space and the issue gets complicated. What is going on over time is an unsolved problem but it seems clear that at the moment, in the relationship above, Ω_Λ is about 0.73 and Ω_m 0.27.

It is a feature of the maths of cosmology that if Ω departs slightly from unity at any time during the evolution of the Universe, then it will depart even more a little later. Hence if Ω is nearly unity now, 13.8 billion years since the Big Bang, it must have been incredibly close to unity earlier in the Universe. The figure quoted is that it can't have differed by more than 1 part in 10^{15} after 1 second and would have been closer still earlier. It's the gut feeling of most cosmologists that Ω must be identically 1. A somewhat different analogy is this. Suppose you stand next to a target and fire a bullet at it. Your gun could be pointing in a pretty wide range of directions and you'll still hit the target, so the fact that your target ends up with a hole in it doesn't tell you much about the direction of the gun. However, now take the gun 1 km away and fire. The fact that there is a hole in the target after you've fired limits the direction your gun must have been pointing to very high accuracy indeed. The cosmological 'target' is $\Omega = 1$ and the fact that the Universe is close to this after 13.8 billion years tells us that Ω must have been phenomenally close to unity a long time ago.

There's another special reason why cosmologists might expect $\Omega = 1$. If $\Omega = 1$ and the Universe is flat then the total energy in the Universe is zero. This may sound extraordinary because the Universe is clearly a violent, energetic place full of radiant energy and motion. It's also full of mass energy but that all adds up to no more than the negative gravitational energy between each mass in the Universe. It seems we live in a Universe of zero total energy. Perhaps the creation of the Universe was not such a remarkable event after all.

Coming back to dark energy, the situation is rather different than for dark matter. Particle physicists have plenty of candidates for dark matter but none from pre-existing physics for dark energy. Its existence came as a complete surprise to us. Perhaps it shouldn't have been because there is another simple argument implying its existence. In an earlier section of this course I said that if the Hubble expansion of the Universe was a constant then the age of the Universe was 13.8 Gy, very close to the current estimate. We know, though, that gravity has been reducing the rate of expansion as time goes on and hence Hubble's constant should have been larger in earlier epochs. If the Universe has as much matter in it as would make $\Omega = 1$ and no 'dark energy', then it can be shown that the age of the Universe is only 2/3rds of the value above, namely just over 9 Gy (9×10^9 years). This is significantly shorter than the age of the oldest stars, as deduced in other ways. Hence the age of the oldest stars is clear evidence that something besides matter is affecting the Universe's expansion. We call it dark energy. This wasn't obvious even as recently as the 1990s because Hubble's constant wasn't so accurately known then and neither was it as certain then that Ω was necessarily as close to unity as it is now found to be.

If you look at the 4 fundamental forces we find in nature then the two acting at nuclear level, the strong and weak forces, are both short-range and attractive. The other two forces in the Universe are gravity and the electromagnetic force, both obeying the inverse square law. The later can be either attractive or repulsive, so can any component of gravity be repulsive? Surprisingly, perhaps, the answer is 'yes' without tinkering with any basic physics. The gravity associated with mass is attractive but the gravity associated with pressure can be repulsive, quite within the description given by General Relativity. For this to happen the pressure must be 'negative', namely like a tension. Gas in a container exerts a positive pressure on the container walls. The very odd feature of Einstein's equations is that matter within the universe has a gravitational effect that slows the expansion whereas tension speeds the expansion. It's very counter-intuitive. The pressure exerted by ordinary matter has a negligible gravitational effect compared to the energy content of the matter but can dark energy be modelled by some kind of fluid under tension that exerts outward pressure on space-time? It may sound bizarre, but remember that Einstein's picture of matter is that matter is energy, a constituent of the Universe that distorts space-time. Dark energy, then, would seem to be something that has no mass component but exerts a lot of negative pressure, enough to accelerate the expansion of space. One version of this idea that is in vogue is the concept of *quintessence*, the old word for the stuff stars were made of, now applied to one of today's big problems. Quintessence creates negative pressure that is promoting the expansion of space, acting against the gravitational effect of mass that is slowing the expansion of space.

The traditional view is that a vacuum is an absence of matter and hence an absence of anything. Imagine a glass bell jar pumped out until there was a complete vacuum. Our ancestors if asked what was left in the jar would probably have said 'nihil', 'nada', 'rien', 'nothing'. They would be wrong in any language. A compass in the middle of the jar still points north, so there is a magnetic field there. A mobile phone in the jar would still ring if dialled; a GPS receiver will still display its whereabouts; a radio will still work, and so on. The modern view is that a vacuum is indeed an absence of matter but it is not an absence of everything. It's not a big stretch of the imagination to say that space can contain one or more fields. We know all this because we have detectors to show at least some of what's there. Do we have detectors to show all the fields that are in space? The particle physicists would have us believe that space contains a Higgs' field that particles interact with and the result we experience is that they have mass. In the very early stages after the Big Bang, it appeared that the Universe contained an 'inflation field' that expanded space very rapidly. Quintessence is essentially an inflation field that acts comparatively slowly, sufficient to provide the dark energy we now believe is present.

There is a second, rather different take on dark energy. If you look back at the expression Einstein gave to work out the curvature of space-time (given on page 2 of section 3 of these notes) and set the T term that represents the stress-energy tensor of matter to zero, then you have an equation that refers to the 'vacuum' – space-time with no energy and pressure in it. Take the Λ term over to the right-hand side and you can see that the curvature terms R are given by the Λ term. In effect, the Λ term becomes the simplest form of stress-energy tensor that controls the curvature of space-time. The negative sign implies that the term will cause an accelerating expansion of space-time, equivalent to an outward pressure, one in the opposite direction to gravity. Is this just playing with symbols or has the argument real meaning? In this interpretation, the acceleration of space is due to the cosmological constant term Λ.

Modern physics predicts and indeed can demonstrate experimentally that particles can be created from the vacuum state for very short periods of time before disappearing again. The effect is known as the Casimir effect, after the Dutch physicist Hendrik Casmir (1909 – 2000) who predicted it. In quantum physics the vacuum state is not just 'nothing' but is a source of virtual particles. This isn't mere speculation, for the force that arises from this has been measured experimentally. Perhaps we are finding through cosmology that 'the vacuum' is the source of dark energy that influences the expansion of space. I certainly can't tell you what dark energy is but the evidence that it exists is clear. Indeed, the visible universe would not be the size it is today without the presence of dark energy. The challenge for the physics community is to integrate the idea with conventional physics.

Analysis of the Universe

Our modern description of the universe at large is often referred to as the ΛCDM model (i.e. a model with dark energy(Λ) and cold dark matter(CDM). The 6 parameters in the basic model can be determined pretty accurately from the cosmic microwave background. Other probes such as large-scale galaxy surveys, supernova distance measurements and more both provide independent determinations of these constants and also allow more refined models to be explored. One such refinement is modelling dark energy so that it depends on the scale of the universe (the parameter a in earlier sections of these notes). So what numbers can modern cosmology determine for the Universe as a whole? Combining the results from measurements of the cosmic microwave background fluctuations (mainly WMAP as these notes are being written) with other large-scale information from surveys of various kinds tells us that:

$h = 0.685 \pm 0.01$	(equivalent to $H_0 = 68.5 \pm 0.6$ km s^{-1} MPc^{-1}) Hubble's constant. Mean value from 2012 WMAP and 2013 Planck Mission, though other sources quote 0.673
$\Omega_0 = 1.02 \pm 0.02$,	i.e. the Universe is flat, within experimental error of 2%
$\Omega_m = 0.27 \pm 0.04$,	i.e. only 27% of the density of the Universe is matter
$\Omega_b = 0.044 \pm 0.004$,	i.e. only 4.4% of the Universe is baryonic matter and hence 22.6% is dark matter
$\Omega_r = 4.902\times10^{-5}$,	i.e. the radiation density in the Universe is now pretty small. The CMB involves on average 4.11×10^{8} photons m^{-3} with an average density of 2.604×10^{5} eV m^{-3}.
$\Omega_\nu < 0.015$,	giving an upper limit to the neutrino density in the Universe
$\Omega_\Lambda = 0.73 \pm 0.04$,	i.e. 73% of the energy density of the Universe is dark energy
$q_0 = -0.60 \pm 0.02$,	i.e. the expansion of the Universe is accelerating, not decreasing.
$t_0 = 13.8 \pm 0.2$ Gyr,	i.e. the age of the Universe is 13.8 billion years

The ratio of baryons/photons is $(6.1 \pm 0.7)\times10^{-10}$. This tells us the asymmetry between matter and antimatter in the very early Universe.

The average mass of the three neutrinos is <0.23 eV, with 95% confidence. Most dark matter is not neutrinos.

The microwave background represents the Universe with $z = 1088 \pm 1$.

The time when matter and radiation density were equal was 54,500 years after the Big Bang, when the temperature of the Universe was 9000 K.

These figures represent knowledge about our Universe that no-one knew when any of us in this room was born. Cosmology has come a long, long way in the last 20 years. It's moving quickly and with some confidence. The numbers above will be refined a little as more data becomes available from the Planck Mission results and from galactic surveys. I'd never have thought 20 years ago that I could tell you with some confidence what kind of a universe we live in. In another decade I may be talking about cosmic strings or colliding branes but I suspect that none of that will change the underlying view these figures give us of the kind of universe we live in.

Clustering of mass in the Universe

Given the present size of the Universe, there is extraordinary little matter in it. There is less than 1 atom per m^3. If you were God creating the Universe would you just create this amount of matter? Would you at the same time create some 4×10^{8} photons m^{-3}? It doesn't seem to make a lot of sense from the point of view of purposeful creation. That's a personal view. An equivalent question is to ask why is there such an enormous amount of space 'out there'? It has taken astronomers four centuries after the invention of the telescope to realise just how much there is. If you were inclined, you could say that mankind has found it hard to believe that God created so much space.

Our physics tells us that for the first few hundred thousand years the matter in the Universe was very evenly spread around. However, after the decoupling of radiation and matter, the matter started clumping in one way or another. How did that happen? Solids and liquids around us have about 10^{28} atoms m^{-3}, representing a fantastic clumping of matter from the average density of 1 atom m^{-3}. How did we get to the present state of affairs, which is roughly this? On the biggest scale, matter is clumped into galactic clusters, interspersed with comparative cosmic voids. The spacing between clusters is only a few times the size of the clusters. This represents modest large-scale clumping. In the galactic clusters themselves the galaxies are typically separated by about 10 to 20 times their size. This represents stronger clumping. Within each galaxy, some matter is loosely clumped into clouds and other matter into stars, where the spacing between stars is of the order of 10^8 times the size of a star – it varies significantly in different parts of a galaxy. This represents huge clumping, indeed most of the clumping. There isn't much difference in clumping between the Earth and the Sun so we've now got to about 10^{28} atoms m^{-3}. Why this figure? It's not determined by astronomy at all but by the balance between electrostatic attraction between atoms and their quantum mechanical repulsion. That's another story. To explain why the Universe looks the way it does today on a large scale is what modern astronomy is trying to do.

Clues to galaxy formation

The story of galaxy formation is only just beginning to be written. There is an enormous amount of evidence still to be collected. This is going to be a major theme in astronomy over the next decade or more. We realise that dark matter plays a crucial part in the story. To bring a few threads together, let me comment that when you look through your telescope at galaxies, or someone else's telescope to get an even better view, you see stars and you see cold dust clouds in the arms of spiral galaxies. We now know that in addition galaxies contain even more mass in and around them in the form of dark matter and hot gas. We are seeing in our telescopes only a fraction of the universe. Imagine trying to work out what football was all about if one team and the ball were invisible to you. It would be hard to make sense of what you saw. You would need to analyse every clue you could find in as much detail as you could. So it is with observations of the heavens through a telescope.

Astronomers have one remarkable circumstance in their favour – they can see into the distant past. By far the most detailed picture of the Earth's past history has come from the geological analysis of the fossil record. Yet fossils are not the plants and animals themselves that existed in the past but replicas in stone. Imagine the extra information we would have if we could actually see life say 400 million years ago. When astronomers look at galaxies 400 million light years away they are see the very light, UV, IR or radio waves that were emitted 400 million years ago. 400 million light years is too far away to see individual stars, let alone planets or dinosaurs but seeing galaxies as they were is still highly informative.

Part of the evidence for galaxy evolution then is to look at how the Universe used to look in the past. Because our view of the distant past is also our view of objects that are spatially distant, all we can see optically of the very distant past are galaxies. Can we see back to the very beginning of galaxy formation? The answer seems to be: 'not quite'. The need to do so is driving the next generation of astronomical telescopes: the James Webb space telescope that will succeed Hubble, the outstandingly large telescopes that are now on the drawing board, hoping to gain international funding.

Much nearer home, one area that astronomers will be looking at is the abundance of elements in stars. This gives important clues as to where and when a star was born. For example, stars born in galactic halos that have a thin density of stars have much less iron in them than our Sun, which was born in a galactic disk that was full of material created in stars of an earlier generation. By looking at the 'metallicity' of stars, essentially the relative abundance of different elements in large numbers of stars in a galaxy, we can hope to mine the fossil record of the evolution of the galaxy. This can really only be attempted in detail for our own galaxy and its immediate surroundings, for even the Andromeda galaxy is so far away we can only resolve the brightest individual stars. However, from more distant galaxies we see light that comes from millions of unresolved stars and hence we can at least see average metallicities. Where are the old, low metallicity, stars in the Universe? Hot dark matter and cold dark matter scenarios predict different distributions. Here is a topic you can follow up in the literature.

If larger galaxies have merged from smaller ones, then the distribution of stars in the large galaxy and their speeds will be another form of fossil record highlighting the past history of the galaxy. This pinpoints the kind of large-scale measurements that astronomy is looking to make in the future. Radial velocities, at least, can be deduced from stellar spectra, and so can element abundances. Hence big-scale stellar surveys are needed to answer basic questions about galaxy evolution. To give you one example of what can come out of this kind of thing. Just in the last 10 years or so, a dwarf spheroidal galaxy that turns out to be the closest galaxy to us at only 40,000 light years distance (12.3 kpc) has been discovered in the constellation of Sagittarius. It wasn't seen before because it is largely hidden from sight by the dust in the Milky Way. However, with clever techniques, a tidal stream of stars can be seen extending from this galaxy to the Milky Way, showing how the large Milky Way is stealing matter from this galaxy during the process of making itself even larger. The Milky Way has not stopped aggregating other small galaxies.

Mapping dark matter

Mapping dark matter is a task for astronomy in the next two or three decades. Dark matter distribution is deduced through the law of gravity by observing the distribution of mass and the velocities of stars. I.e. we need stellar mass, stellar distances and coordinates and velocities. Mass we get from identifying stars on the Hertzsprung-Russell diagram, as was discussed in last year's astronomy course but which I'll mention again later on. 3D coordinates on a galactic scale need accurate distances on a galactic scale, which means a distance measuring programme even more sensitive than the Hipparcos survey, that went out to about 1000 light years. Spectra provide radial velocities but we really need 'proper motion' or transverse velocities as well. This also becomes a big technological challenge for stars a long way away. Stars may seem to move quickly. 10 km s^{-1} is an impressive speed on Earth but it is only 3.33×10^{-4} of the speed of light. An object only 1 light year away moving at this speed across our line of sight for a year will only change its apparent position by 3.33×10^{-4} radians or about 1 minute of arc. For a star only 25,000 light years distant, about as far away as the galactic centre, if you watched it for 1 year you wouldn't see it change its position in the sky by more than 2.75 milliseconds of arc, an exceedingly small angle.

Milli-arc second measurement technology is with us, as the Hipparcos survey demonstrated, and hence dark matter studies through this route are now possible. The GAIA Mission, launched by ESA in December 2013, will continue where the Hipparcos mission left off, measuring parallaxes to micro arc-seconds. It is estimated that GAIA should measure the positions, distances and proper motion of a billion stars over its 5-year life. It, too, will operate around the Lagrangian point L2. GAIA's results, if all goes well, will be a phenomenal increase in the knowledge of our surroundings. Dark matter is postulated to affect motion of the large-scale constituents of the Universe and hence we need to measure accurately the velocities of all the constituents of our local cluster, including the various dwarf galaxies that surround the Milky Way. Also, dwarf galaxies have the largest inferred dark matter content of any kind of galaxy and hence they are an obvious target for future measurements. This is one way modern astrometrics is going.

What is the history of our galaxy?

What sort of mass do you need to form a galaxy? The answer depends on the temperature, pressure and size of the system and is known as the Jeans mass after astronomer James Jeans who was active in the first half of the twentieth century. I mentioned earlier that the Jeans mass for the formation of early proto-galaxies is about 1 million solar masses. Star formation from a given mass isn't a very efficient process, in that only a fraction of the initial mass ends up in stars, about 10% if you are lucky. This makes early galaxies contain about 100,000 early stars. Our galaxy contains about 100,000 *million* stars, which means that it would need to be the end product of coalescing a million such small galaxies and star clusters. That's a lot to bring together in a modest time on the scale of cosmological evolution.

Modern observational astronomy is slowly filling in some of the story. It is now possible to look at many galaxies that are 10 billion light years away and hence 10 billion years in the past. The Universe in that era looks a different place but we see many rotating disk galaxies that would be like the young Milky Way. They contain about 20% of the mass of the Milky Way and star formation is taking place at typically ten times the rate it now is. Clearly much of the aggregation happened early on in the Universe's history. There is a lot of explaining to do to put together the story of how the Milky Way came to be the way it is. Stars in different parts of the Milky Way provide evidence that the last major merger was a long time ago. Not only that, the Milky Way may be a typical spiral galaxy but there are a wide range of galaxies out there and an evolutionary theory has to explain this diversity. The astronomy of the future will tackle this story.

Classifying galaxies

You'll find hand-drawn pictures of a few galaxies in astronomy books from the mid 19th century but it wasn't until the advent of astrophotography and the large telescopes of the early 20th century that the study of galaxies became a significant part of astronomy. Edwin Hubble did for galaxies what many people do when tackling a comparatively new field. He set out a classification scheme for what he saw. He classified galaxies into 3 main types, to which is added nowadays the fourth type, lenticular:

- **Elliptical.** These are given a number n according to the ratio of major (y) to minor axis (x) of the ellipse. Thus $n = 10(1 - x/y)$. E0 is a spherical galaxy, E7 the most elliptical. Ellipticals are the least common type. They tend to have high concentrations of old stars, little gas and dust and few active star formation regions.
- **Lenticular**. Type S0 introduced by astronomer Alan Sandage to describe a spiral like structure with a central bulge but no definite arms.
- **Spiral**, with sub-divisions of ordinary spirals (S or SA) and barred spirals (SB), and a classification of *a*, *b*, *c*, and *d* based on how tightly wound a spiral is. There are a few

more types too. Spirals are the next most common type but there are only 3 in our 'local cluster' (us, M31 and M33). There is some evidence that our galaxy may be a barred spiral but we are poorly placed to see the bar if it exists.

- **Irregular**, denote I**.** Many irregular galaxies show signs of being a collision between galaxies. Intergalactic collisions are relatively frequent because the typical separation of galaxies is only 20 times their diameter. These are the most common type, at least in our neighbourhood, comprising over 50% of galaxies but many are faint so that at large distances a census of galaxies under-represents them.

You mightn't be surprised that with technology available today we can now see a greater range of galactic types than Hubble saw. Indeed, imaging technology is now so good that you don't need a large telescope to obtain images of a wide variety of galaxies and an amateur with a CCD camera and a 250 mm diameter telescope can obtain impressive pictures. That said, you or I won't achieve the stunning images that you can find on the web these days.

Examples of Ellipticals, Spirals, Barred spirals

NGC 1672 is a composite image of a comparatively nearby (over 60 million light years away) barred spiral in the southern skies taken in the blue, green, IR and hydrogen. Unusually, the spiral arms join the ends of the bar. This kind of galaxy is rich in star-birth, with clusters of hot blue stars along the spiral arms embedded within glowing hydrogen.

Barred spiral galaxies are the most common kind of spiral. Some 75% of 'local' spiral galaxies are barred. In fact it's now thought that the Milky Way galaxy, our own galaxy, has a short barred centre but it's hard to see because of all the dust between us and the galactic centre. In general barred spirals have a fairly elliptical central region with the bar emphasised by dust lanes or a line of particularly bright, young stars.

Hubble's tuning fork diagram

This diagram is a nice way of showing the different kinds of galaxies in Hubble's scheme. The implication that galaxies evolve along the lines of the diagram is not now seen as true. Galaxies certainly do evolve, largely by collision and coalescence under the influence of gravity. However, their evolution is more complex than that shown in the diagram.

All types of galaxy are visible in the earliest views we get of the universe. Very old stars are present in all types of galaxy, which goes against Hubble's evolutionary hypothesis.

Why spirals?

The 'obvious' explanation is that spirals are the result of stars closer to the galactic centre moving faster than those further out, running ahead of them and creating a spiral structure with ever more turns. Some more thought shows you that this **isn't** what is happening. Our Sun has made about 20 revolutions around the galactic centre. If a wind-up mechanism has created spiral arms, then the galaxy should have many more spiral turns than it does.

A better view, but not one that explains all the features, is that the spiral arms are density waves in the galactic disk. The density waves are relatively stationary and stars move through these regions. As they do so, dust and gas is compressed and this initiates star formation, with a significant number of massive very bright stars making the compression regions shine out.

[An example of a density wave much closer to home is seen in an aerial view of a motorway traffic jam. On the upstream side of the centre there is an increasing density of traffic until the central jam is reached and then on the far side a decreasing density of traffic. Relative to the large-scale flow of traffic, the density wave moves only slowly]. In fact, in the galactic case there are almost as many stars between the arms as within the arms but they don't contain such a high proportion of young, bright stars. Look at a picture of a spiral galaxy and you'll see it's counterintuitive to say that there as many stars in the dark spaces between the arms as there are within the arms. It's just that the stars in the bright arms are bigger and brighter than the stars in the regions between the visible arms. It's an idea that was first proposed decades ago and is still the favoured view. What makes it a lot more plausible is the fact that the ratio of luminosities of the brightest to the dullest stars is about 10^{10}, ten thousand million in words. There are plenty of stars in our arm of the Milky Way that emit light at more than a million times the rate of a very dim star so it doesn't take a vast number of bright young stars to make a spiral arm stand out from its dark neighbouring regions.

Since spiral galaxies are pretty common and they formed fairly early on in the universe, you'd think that the general features of how they form and develop would have been sorted out by astronomers by now. In detail they haven't been, which leaves plenty of work for astronomers in the future. In fact what with dark energy, dark matter and the structure of the universe as a whole all in need of much more work, astronomers are not going to be out of a job in the near future. Looking over the areas that physicists are funded to do research recently, I was struck by the rise of grants going to astronomy and related disciplines like space science. It is an area of science that has yielded big advances in recent decades and looks set to continue this trend.

JSR