Cosmic Evolution:

The Birth, Life & Death of Galaxies

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The Sky at Night

In this International Year of Astronomy, we celebrate the 400th anniversary of Galileo turning his telescope to the skies. What he saw revolutionized our understanding of our place in the heavens, and set us along the road of astronomical discoveries that continues today. Following Galileo, generations of astronomers scanned the sky and slowly the nature of our Universe was revealed. At first it was thought that the Universe was a simple place, and that the Sun was but one of an infinite number of stars that filled an infinite heavens. Even to the naked eye, it is apparent that this could not be the truth as that stars are not simply scattered over the sky, but tend to lie in a band known as the Milky Way.

Intensive detective work at the end of the 1800s and early 1900s uncovered the true nature of the Milky Way, showing that the Sun lives with many others (roughly 250 billion) in an "island Universe". Rather than being a shapeless 'blob', the Galaxy possesses beautiful structure, with the majority of stars lie in

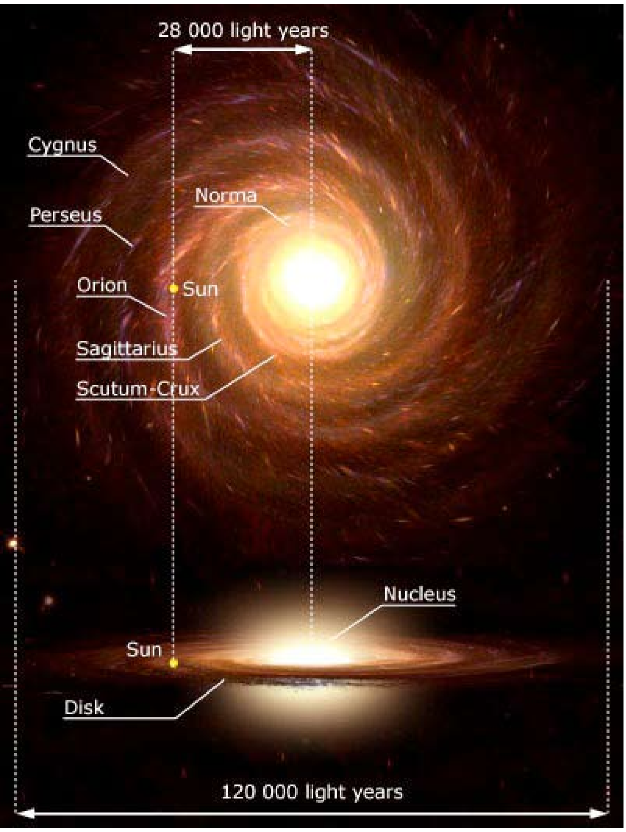

Figure 1: The structure of the Milky Way viewed from above (top) and the side (bottom), showing the galactic disk, with spiral arms, orbiting the central bulge.
ESA

a disk, with pronounced spiral arms, orbiting a central ball of stars known as the Galactic Bulge. The scale of the Galaxy[1] is staggering (in human terms), and the disk is 100,000 light years[2], with the Sun located roughly 28,000 light years away from the Galactic Centre, buried deep in the disk which is 'only' 3000 light years thick (Figure 1).

Using the Doppler shifting of light, astronomers were eventually able to determine the velocities of stars and gas within the Galaxy, directly measuring the rotation of the disk. We can use Newton's famous laws of motion and gravity to calculate the expected Galactic motions, assuming that the only mass present is what we can see. The results were, to say the least, shocking, with all the stars in the disk moving around the centre of the Galaxy at a little over 200km/s, far faster than our naïve expectations. Astronomers were led to the conclusion that there must be more mass out there than we can see, much, much more. In fact, the vast majority of the mass (~95%) must be this "dark matter", which emits no light but whose gravitational influence holds our Galaxy together; exactly what this dark matter is remains a major outstanding problem in astronomy.

The Universe of Galaxies

As astronomers were unravelling the structure of our own Galaxy, their observations revealed it was not alone in the cosmos, but is just one of billions within the observable Universe. Surprisingly, right next-door to us, at the cosmologically small distance of two million light years, is the Andromeda Galaxy, almost a twin of our own, being similar in size and possessing its own beautiful spiral disk and bulge of stars (Figure 2).

Observations of our local patch of the Universe also reveal the Milky Way and the Andromeda Galaxy are not alone but are accompanied by a host of much smaller 'dwarf' galaxies, containing between a few million and few billion stars. Unlike the larger galaxies, these dwarfs do not possess the grand spiral disk structure, but are usually amorphous blobs, roughly the same shape as a rugby ball, or even possess no real structure at all. Two of the closest of these dwarfs are actually visible to the naked eye as the Large and Small Magellanic Clouds that can be seen in the night skies of the Southern Hemisphere. In fact, there are almost fifty of these dwarf galaxies accompanying the Milky Way and Andromeda in a family known as the Local Group.

Looking into the deeper Universe, we see that not all large galaxies are spiral, and most are actually larger versions of the spheroidal

1 Our galaxy is usually known as the Milky Way or simply the Galaxy.

2 A light year, as the name suggests, is the distance that light covers in a year. As light travels at 300,000 km/s, this corresponds to roughly 9460000000000 km, or 9.46×10^{15}m in scientific notation).

Figure 2: A montage of galaxies, with our nearest neighbour, the Andromeda Galaxy appearing at upper-left, a large elliptical at the upper-right, and several dwarf galaxies in the lower panels. While the elliptical and the dwarfs appear to similar, they are hugely different in size. To see the huge diversity of galaxies, visit Galaxy Zoo (www.galaxyzoo.org).

Adam Block/ NOAO/AURA/NSF; Canada-France-Hawaii Telescope & Coelum; NASA, ESA and C. Conselice

blobs we see in the vicinity of our own Galaxy. These 'elliptical' galaxies possess a huge range of sizes; while the dwarfs are a million times smaller than the Milky Way, the largest, the giant ellipticals, are a hundred times more massive (Figure 2). Just like the Milky Way and Andromeda, most galaxies live in groups with a few other large galaxies, and many more dwarf galaxies, but the giants are found in the centres of huge agglomerations of large galaxies, numbering hundreds or thousands, known as galaxy clusters.

So, galaxies do not live alone, and are found to reside in groups and clusters, although these galactic families are not strewn randomly throughout the Universe. Cutting-edge instrumentation, like the 2dF spectrograph at the Anglo-Australian Telescope in Coonabarabran, has allowed astronomers to measure the distances to a large number of galaxies and produce a map of the Universe, showing that galaxies are spread through the Universe on a sponge-like structure, clusters joined by filaments of galaxies and groups, with huge,

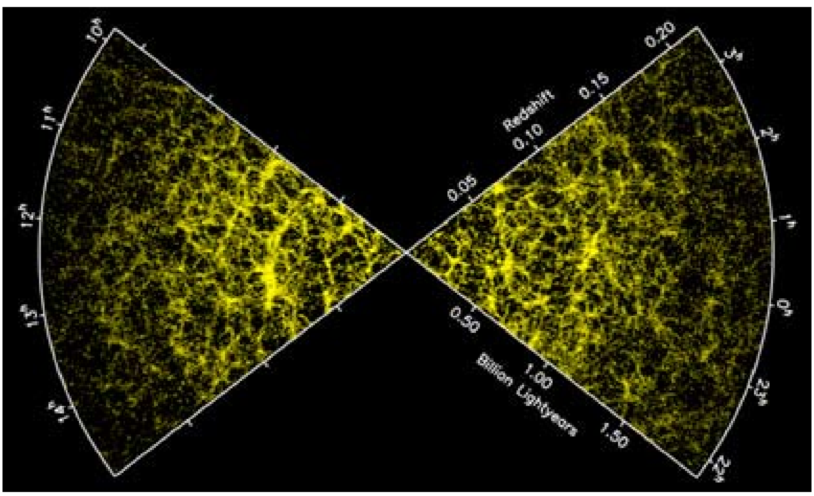

Image courtesy of the 2dFGRS Team

Figure 3: The results of the 2dF Galaxy Redshift Survey, which measured the distances to more than 200,000 galaxies out to a distance of roughly two billion light years. We sit at the centre of this picture, and it is clear that the galaxies are laid out on a fine structure of clusters, filaments and voids.

almost empty voids, some being more than 300 million light years across (Figure 3).

Clearly, the Universe is not a higgled-piggledy mess of stars and matter, but contains rich structure of well-defined objects, the galaxies, laid out in rich patterns of knots, the clusters and groups, and voids. Immediately, we are faced with a difficult question; astronomers have determined that the Universe began almost 14 billion years, in the cataclysmic event known as the Big Bang. Soon after its birth, there were no stars or galaxies, only a smoothly distributed gas and dark matter, so where did all the rich structure we observe today come from?

Out of the Dark Ages

Understanding exactly what kicked off the Big Bang still remains one of the biggest outstanding questions in astronomy, but we do know that during the very initial stages of the Universe, a rapid burst of accelerated expansion, known as 'inflation', fill the Universe with a smooth distribution of radiation, dark matter and hot gas. Vitally for the evolution of galaxies, inflation blew up tiny, microscopic energy fluctuations (due to the weird action of quantum mechanics on the smallest scales) that resulted in tiny differences in density scattered through the Universe, seeding it with the birth sites of galaxies.

Once inflation ends, the Universal expansion settles down to a more sedate rate. However, the very slight density differences imprinted by the rapid expansion begin to play their important role, and the dark matter and gas begins to move under the action of gravity, flowing into the denser regions. Just after the Big Bang, the gas is extremely hot and is a sea of electrons and nuclei (a plasma), but the expansion of the Universe allows the gas to cool and form normal atoms of hydrogen and helium. The radiation released in the Big Bang also cools to longer and longer wavelengths and, if we could visit the first half a billion years of the Universe, before the first stars would have formed, it would be completely dark with no sources of light; astronomers have labelled this period of the Universe's history as 'the Dark Ages'.

The Universe continues to expand, and the gas continues to cool, and it begins to pool into the denser regions, eventually reaching the densities needed for it to fragment and collapse into the first generation of stars. These stars, comprised of only hydrogen and helium, are massive and burn brightly, lighting up the Universe for the first time. But this early stage of the life of the Universe looks very different to today, with small pockets of bright stars lighting up the densest knots of dark matter, and there is nothing that we could identify as a 'modern-day' galaxy. So what happens next?

While the bright, first generation of stars are visually the most significant things in the early Universe, the irresistible pull of gravity has continued its work, with the denser regions pulling in more and more dark matter and, associated with it, the first generations of stars. These stars evolve quickly and explode as violent supernovae, throwing their gas, now enriched with the heavier elements generated in their cores as part of the process of nuclear fusion, into interstellar space. This gas forms the fuel for subsequent generations of stars, and eventually, after several generations, will form stars like our own Sun.

The Power of Gravity

Even with the birth of the first stars, the Universe is still a relatively simple place, with pockets of stars scattered through space, so how are astronomers to understand the complex flows of matter that would lead to the formation of a galaxy like the Milky Way? This is a tricky question as the motions of matter under the pull of gravity can be very complicated and is effectively unsolvable with paper and pencil[3]. Faced with this, astronomers have turned to a new approach to tackle the problem of the

3 Those familiar with the application of Newton's laws of gravity and motion to the movement of planets will know that we can write out the mathematical form of an orbit (an ellipse with the Sun at one focus). This two-body problem (the Sun and the planet) is easy to solve, but adding one more mass makes the problem intractable and we can't simply write out the orbit of three-bodies without make lots of simplifying assumptions. Given this, it's easy to understand why it is difficult to work out the orbits of trillions and trillions of bits of mass in an expanding Universe.

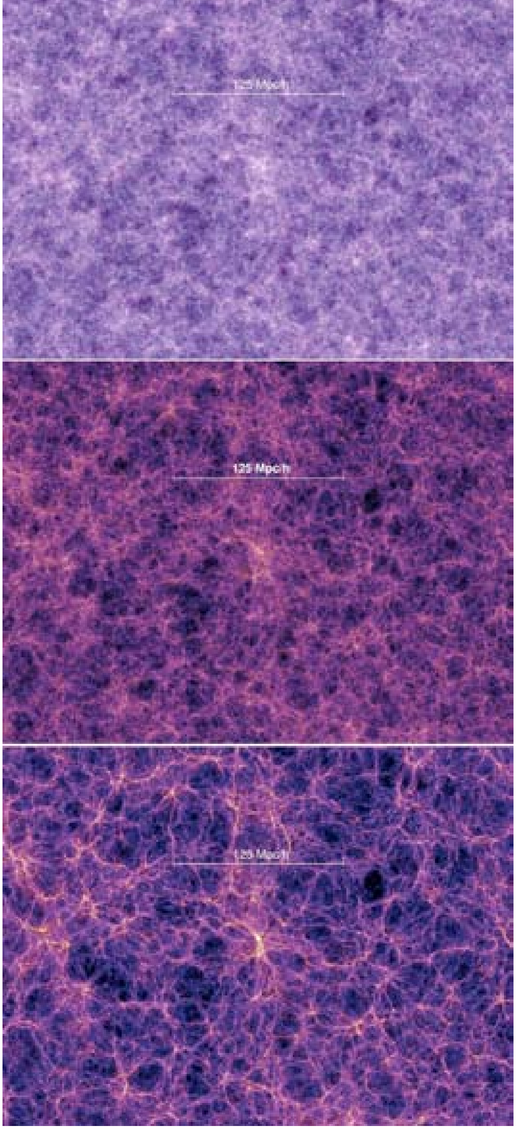

Figure 4: Three 'snapshots' of the numerical evolution of a cosmological volume, starting from the early Universe (top) to the present day (bottom); the box size is roughly one billion light years across. As the Universe evolves, more structure becomes apparent as matter flows into the denser regions.
Nicholas Martin & Rodrigo Ibata (Observatoire de Strasburg)

evolution of matter in an expanding Universe; basically they build their own Universes within a computer, sit back and let gravity do its magic.

What is required to build this 'numerical simulation' of the Universe? In principle it's quite simple (but, of course, in practice it's not).

Take a box that represents a large chunk of the Universe, say 300 million light years on a size. Fill this box with particles that represent the distribution of matter in the Universe, with more particle in regions which are more dense, and less in the voids, and arrange the particles to represent the almost smooth distribution of mass in the early Universe. Then all we have to do is to turn on the laws of physics, including gravity and the universal expansion, and let it evolve. Typically, state-of-the-art simulated Universes require billions of particles and can run for months on supercomputers.

The results of these numerical simulations are no less than spectacular (Figure 4)! In the initial stages, we can see the matter in the Universe smoothly distributed throughout the Cosmos, and as the Universe expands, the density of matter steadily falls. However, something interesting starts to happen and we can see clumps and bumps appear in the matter distribution; it must be remembered that these simulations represent a huge volume of the Universe today and each of these lumps contain masses which are billions times the mass of the Sun. The expansion continues and we can clearly see mass flowing into the denser regions, with the knots increasing in size. Intriguingly, a pattern emerges and the clumps of matter are not isolated but are connected through filaments and sheets, with these bounding huge areas of low density.

In these pictures, the matter distribution we see represents the dark matter evolution, but as it is the dominant component of matter in the Universe (making up 90% of all matter) it is this component that dictates the motion. As gas and stars will follow the dark matter, where we have high concentrations of dark mark matter we should expect high densities of stars and gas, so the tightest knots in the simulations represent the sites of galaxies, and where these are grouped together, at the intersection of the filaments and sheets, represent clusters of galaxies.

Examining the final stages of the Cosmic evolution, we can compare the distribution of galaxies in our synthetic Universe to that on the sky (Figure 3) and we see and the results are pretty

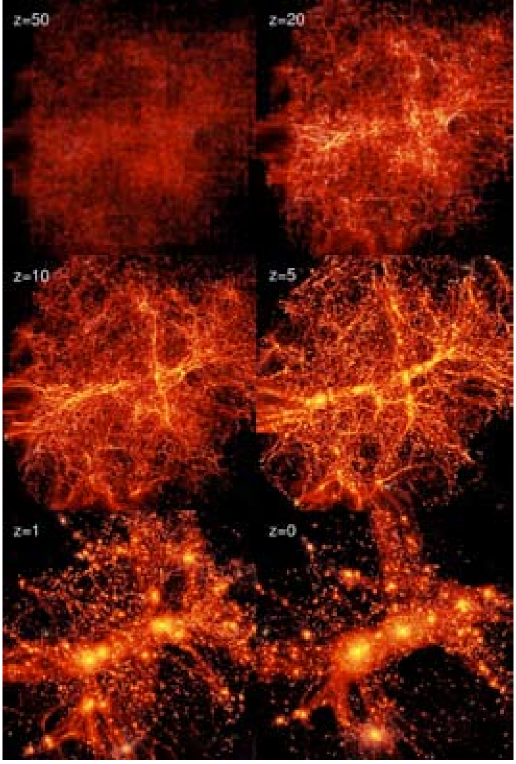

Figure 5: A computer simulation of the formation of the Local Group of Galaxies. The upper-left panel shows an early stage of the Universe, when matter was quite smoothly distributed and shows no structure, but as the Universe ages and we move down the picture, we can see structure begin to form. By the final panel, representing the present day, there are several large lumps which are the large galaxies like our own Milky Way, as well as a myriad of smaller galaxies buzzing around.
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impressive; our synthetic Universe possesses clusters and groups of galaxies, distributed along a spongy surface, interspaced with huge voids, precisely what we see in the actual distribution of galaxies seen in large scale surveys. This is quite amazing!

Remember that to make our synthetic Universe, we simply set up our initial matter distribution (with very slight bumps and wiggles which were due to the inflation of quantum fluctuations in the very early stages of the Universe), and allowed the action of gravity to evolve it over billions of years.

Violent Upbringings

Seeing how well our synthetic Universe represents our observed Universe gives us a warm and fuzzy feeling, but what does it tell us about the growth of an individual galaxy like our own Milky Way? Instead of looking at a huge volume of the Universe, we can focus our numerical simulations on the growth of a volume similar to our own Local Group, and within that we can watch the individual galaxies grow (Figure 5).

Initially, the situation looks similar to our large cosmological volume, with dense knots forming within an overall smooth background, but this entire region represents just one small region of slightly higher density within the evolving Universe. Quickly, a large-scale dense region forms due to the flow of matter, and it is this that will become the modern-day Local Group. The region is now filled with a myriad of dense knots of matter, buzzing around in the gravitational field like angry flies, but it's also apparent that the number of small flies is dropping as some larger concentrations of mass emerge. Just what is happening?

Looking a little closer, it can be seen initially that a couple of small lumps, of roughly the same size, crash together, and this smashing merges the two into a single, larger lump. This resultant larger lump now has a stronger gravitational field, and its tidal influence reaches further, capturing and disrupting more small lumps. Over a period of time, these lumps (which become the sites of modern-day galaxies) dominate their local environment, and by the final stage of this scenario is much of the mass has flowed into several large features, representing large galaxies like the Milky Way and Andromeda, as well as a sea of smaller clumps of dark matter and stars, the dwarf galaxies like the Magellanic Clouds.

While the overall picture appears to be quite rosy, there are a few issues that have dogged astronomers over the last decade, the main being the missing dwarf galaxy problem. With a glance of the last frame of Figure 5, we can see that there are many hundreds of dwarf galaxies orbiting the large galaxies, and so we should expect to see many of these in the vicinity

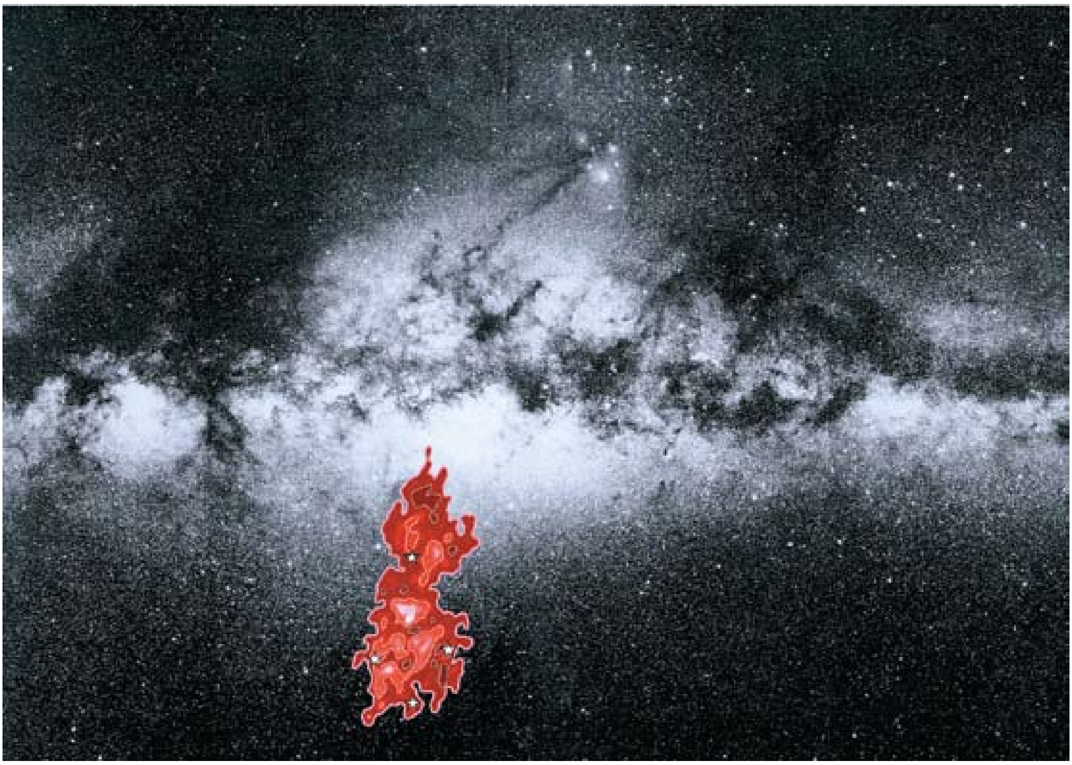

Figure 6: The black and white portions of this image are photographic images of the central bulge of the Milky Way; if you go out on a clear night in the Southern Hemisphere, you can see that this covers a huge area of sky. The brown smudge is the Sagittarius Dwarf galaxy, which is actually on the far side of the Galaxy and crashing into the disk. The dwarf is invisible to the naked eye and can be only imaged by identifying its stars as being separate from those in the Milky Way. *Rose Wyse/John Hopkins University*

of the Milky Way. Over the last few decades, we have surveyed the sky to unprecedented depths, and the conclusion is that the expected population of dwarf galaxies is just not there, with only one tenth the number predicted by the numerical simulations. This puzzle is not fully resolved, but many think that these dwarfs are actually out there, but in their formative stage, early bursts of star formation blew all the gas out and after the first generation of stars, there was no remaining material to form the next generation. With no stars, this leaves the dwarfs as invisible, dark matter lumps, buzzing around but unseen; whether this is the case or not still waits to be solved.

If we examine the growth of a galaxy like our own Milky Way in detail, we can understand how it has cannibalised smaller systems during its growth. Initially, when all the knots of matter are the same size, the collisions between any two are quite violent, and the lumps crash together to form larger lumps. However, once the proto-galaxy has become established, becoming the local dominant mass, the situation changes. As small masses get too close, the tidal gravitational force on them increases, with stars and dark matter being stripped from their outer edges. The closer they get, the more material is ripped off, until their orbit brings them as close as possible before taking them away to larger distances. Soon, it is on its way in again, and again the process of tidal stripping begins anew, with more material being ripped off. The process continues for several orbits until the little galaxy has completely boiled away.

What happens to the stars and dark matter that is ripped from the cannibalised galaxy? As it begins its demise, this matter moves along in the orbit of the dwarf, both infront and behind, and forming extensive tidal tails that can eventually wrap the entire galaxy. As time goes on, these tails eventually dissipate, and the stars and dark matter in the dwarf are completely mixed with that of the growing galaxy, and any memory of the cannibalised dwarf is completely erased.

Middle Age Spread

In the early life of our Milky Way, it must have consumed many small dwarf galaxies over a relatively short period, to establish itself with the Local Group. Initially, the dark matter, stars and, importantly, gas will be present in a roughly spherical blob, and once enough material has been accreted, the gas will cool and collapse to form the spiral disk that characterizes the Milky Way[4]. It is tempting to think that the growth of the Galaxy is now over and all we have to do is to sit back, relax and watch the stars age.

Returning to our simulated Universe we can see that this is not the case. While the Milky Way had a voracious appetite when it was young, it should not have given up the consumption of little dwarfs, and hence be still growing, even today. Is there any evidence of this when we take a long, hard look at our Galaxy? For a long time, the answer was thought to be no, and that the Milky Way basically looked like a sedately aging, large spiral galaxy, with no evidence of ongoing cannibalism; it looked like our home galaxy was as large as it was going to get, but things were about to change.

Over the last few decades, astronomers have turned a battery of new, sensitive instruments towards the sky, surveying large regions to unprecedented depths. Coupled with this has been the development of "multi-fibre spectrographs" that allow us to analyse the light from several hundred stars at the same time, providing not only important chemical information, but also stellar velocities through the Doppler shift. One of the first targets of study was our own Galactic bulge, with astronomers hoping to use the velocities of stars to give us a detailed picture of the overall distribution of matter in the central regions. This work was the subject of the PhD studies of Rodrigo Ibata, then at the University of Cambridge, and he used the 3.9m Anglo-Australian Telescope to obtain a large sample of stars over the bulge. At first, things appeared quite straight-forward, with the velocities of stars moving as we would expect, buzzing around the centre of the Galaxy, although as he obtained velocities for stars in the southern regions of the bulge, something quite unexpected happened; Rodrigo picked up another bunch of stars moving independently of those in the Galactic Bulge. Initially thinking little of it, Rodrigo continued to examine his data, finding this second population of stars was spread over a large region of the sky. Given the number of stars that he had detected, he was led to the conclusion that this second population must represent a small dwarf galaxy moving through the halo of the Milky Way, colliding with the spiral disk on the other side of the bulge to the sun. Scrutinizing old, large-scale photographic images of the region, a large, but very sparse population of stars, now named the Sagittarius Dwarf, was identified as the source of the additional stars; this interloper had been hiding in plain sight, but, being so diffuse, no one had noticed it previously. (Figure 6)

The discovery of the Sagittarius Dwarf galaxy resulted in a flurry of activity, with its ragged appearance confirming that it was slowly being dismembered by the stronger gravitational field of the Milky Way; in a few more orbits (each lasting roughly 750 million years) the Sagittarius Dwarf will have completely dissolved, its stars and dark matter completely mingled with those of our own Galaxy. But if this is the case, then we should expect there to be the long tidal streams of stars, representing material torn from the dwarf during its demise, to lie across the sky, although given

4 The process of turning an embryonic galaxy into either a spiral or elliptical is thought to depend on how much angular momentum (or spin) it has; those with spin give spirals, those without result in ellipticals. The amount of spin can be determined by the tugs from the environment that the young galaxy finds itself in, or due to the violence of the collisions it has undergone.

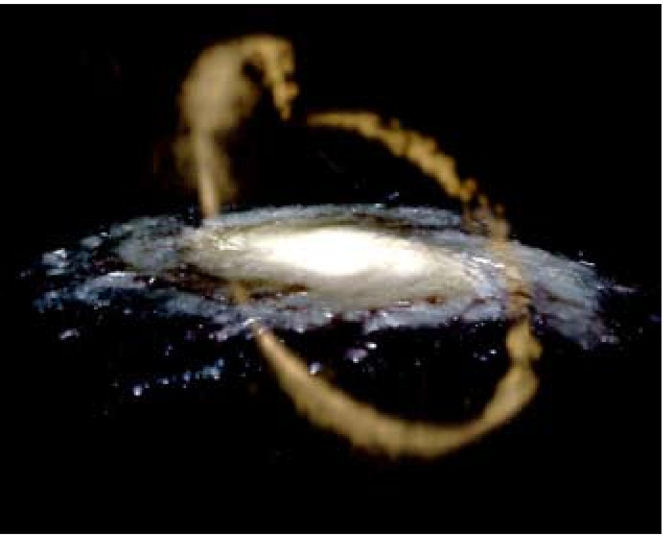

Figure 7: An artists representation of the Sagittarius Tidal Stream, the debris torn off the Sagittarius Dwarf as it is dismembered by the gravitational field of the Milky Way. The stream completely wraps the galaxy.
David Martinez (MPIA) & Gabriel Perez (IAC)

the faintness of the dwarf, we would expect the stream to also be extremely faint. In the ensuing years, dedicated detective work sought to isolate stars that could lie in the Sagittarius Stream, with a handful of bright 'Carbon stars'[5] possibly lighting up the stream's location.

During the same period, the 2-Micron All Sky Survey (2MASS[6]) was mapping out a huge area of the sky in the infrared, identifying bright stars within the halo of our Galaxy. By zeroing in on the expected brightness of stars associated with any debris from the Sagittarius Dwarf, the expected tidal stream was revealed in all its glory, spectacularly wrapping around the Galaxy, from one pole to the other and back again. These results clearly show that the Milky Way is busy digesting the Sagittarius dwarf,

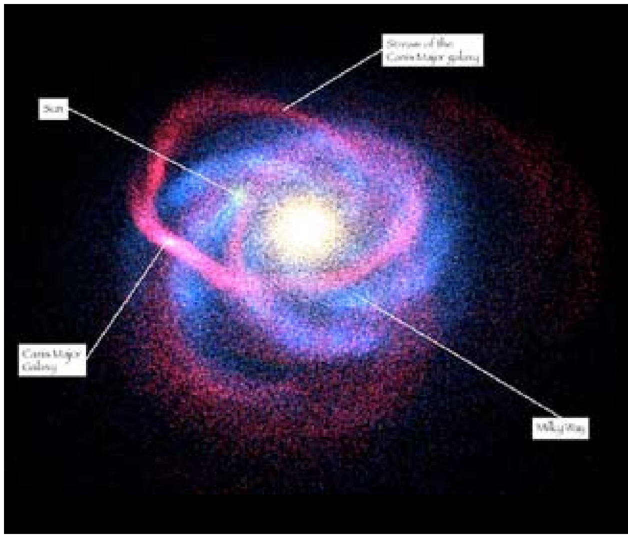

Figure 8: A computer simulation of the demise of the Canis Major dwarf galaxy. Unlike, the Sagittarius dwarf, this galaxy lies in the plane of the Galactic disk and its tidal streamers are completely threaded through the stellar populations of the Milky Way.
Nicolas Martin & Rodrigo Ibata, Observatoire de Strasbourg, 2003

growing by 100 million new stars in the process. (Figure 7)

The discovery of the Sagittarius tidal stream confirmed that our overall picture for the formation and evolution of galaxies is correct, with an early burst of feasting now replaced with a slow and steady munching on snacks that stray too close. But is the Sagittarius Dwarf all that the Milky Way is currently consuming? Our computer models say no, leading to a further search for evidence of galactic cannibalism in our own backyard. A detailed examination of the 2MASS view of our own Galactic Halo doesn't seem to show anything else as prominent as Sagittarius, but the picture changed as astronomers started to look closer to the disk of the Milky Way. Traditionally this area is difficult to study due to the huge number of stars, as well as gas and dust, that obscure the view. However, a team of astronomers, led by Nicholas Martin at Strasbourg Observatory, used the huge catalogue of stars produced by 2MASS to do just this, and found,

5 Giant Carbon Stars are old stars that have evolved into their Red Giant phase. Their atmospheres are cool and rich in carbon, allowing carbon monoxide to form. The presence of this molecule eats huge chunks out of the spectrum of light emitted by the star, making them easy to identify.

6 http://www.ipac.caltech.edu/2mass

in the constellation of Canis Major, nestled just under the disk, a small dwarf galaxy. This was extremely surprising as this little galaxy would be suffering greater gravitational stress than Sagittarius, and would also be being torn apart. The astronomers concluded that a huge ring of stars, known as the Monoceros Ring and circling the disk of our Milky Way, could be the tidal debris torn from the Canis Major dwarf galaxy.

The edge of our Galactic Disk, which can be warped and flared, is a messy place, and the interpretation of Canis Major as being a distinct dwarf galaxy is not universally accepted. If it is, however, then its future is slightly different to that of the Sagittarius Dwarf galaxy; its ultimate demise is not in question, but unlike Sagittarius, which is dumping its stars into our Galactic Halo, Canis Major's debris will be mixed with the stars in the disk of our own Milky Way. We are left, therefore, with one remaining question: was our own Sun born within the disk of the Milky Way, the child of previous generations of stars that lived their entire lives and died within the Galaxy, or are the Sun or its parent immigrants, brought in during the accretion of a now destroyed dwarf galaxy? As we develop newer instruments that will allow us to take the census of the velocities and chemical fingerprints of huge populations of stars, we may be able to answer this intriguing question.

We Are Not Alone

The story is not over, and like the late-night telemarketer we have to face the fact that "and there's more!" While 2MASS was surveying the sky in the infrared, the Sloan Digital Sky Survey (SDSS[7]) was undertaking a similar project in the optical. Like 2MASS, astronomers scoured the images looking for new types of galaxies and structures within the Milky Way, especially the telltale signs of ongoing feasting, like the Sagittarius and Monoceros tidal streams. Again, the results were surprising, with one of the regions studied intensely being named the "Field of Streams" because of what it revealed. (Figure 9)

The Field of Streams covers a huge swathe of sky, with the disk of the Milky Way running along the right-hand side. Clearly visible in the picture are the Monoceros Stream, shown in blue at the right, and also the Sagittarius Stream which runs from right to left across the image; intriguingly the stream appears to

7 http://www.sdss.org

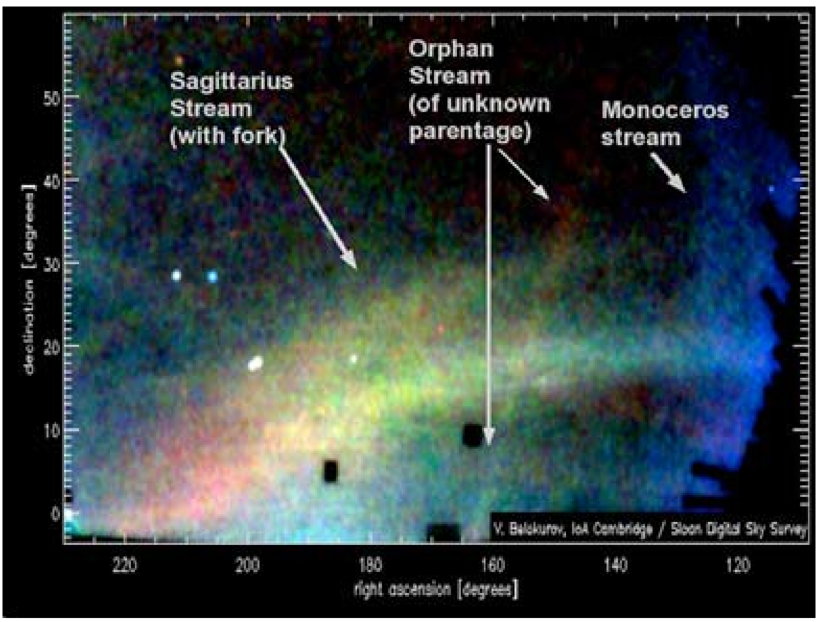

Figure 9: The Field of Streams, a small part of the Sloan Digital Sky Survey. In this field, which covers a quarter of the area of the night sky, the Sagittarius and Monoceros Stream are clearly visible, as is a previously unknown stream, named the Orphan Stream.

Vasily Belokurov, SDSS-II Collaboration split into two, showing that it wraps the Milky Way not once, but twice! Quite unexpectedly, however, running from the top to the bottom of the image was a completely unknown stream, named the Orphan Stream, the tidal debris from another disrupting dwarf. While this field remains the most spectacular, our ongoing large-scale survey of our Galaxy continued to reveal more and more evidence for ongoing, and ancient, accretion of our little cosmic companions, the dwarf galaxies within the Local Group, and showing that the Milky Way's growth appears to be far from over.

Our Bright, but Scary Future

It may seem that our Milky Way's future is pretty clear, gently chomping on any little dwarf galaxy that strays too close, and slowly growing old while retaining its stately spiral disk. The picture is not so rosy when we remember that the Milky Way is not the only large galaxy in the nearby Universe, but shares the Local Group with the Andromeda Galaxy, a spiral galaxy similar to our own. Every hour the distance between these two giants decreases by half a million kilometres; in roughly three billion years, these galaxies are destined to collide.

There is some uncertainty in the details of the collision[8], but the event is inevitable; we have to ask, therefore, what will happen in such a collision? Again, computers come to the rescue and we can smash together the Milky Way and Andromeda, over and over again, to understand the details of the collision. John Dubinski at the University of Toronto in Canada has undertaken a very detailed study of our upcoming galactic collision and collected together a series of beautiful images and animations to illustrate what will happen (Figure 10)[9].

As the galaxies approach one another, nothing really happens and both retain their spiral

8 While we know how fast Andromeda is approaching us, it is very difficult to calculate how fast it is moving across the sky. If this 'peculiar' velocity is zero, then we will suffer a head-on collision, with the collision becoming more glancing as its value is increased. We estimate the value to be less than around 100 km/s and so we expect the collision to be almost head-on, and hence quite violent.

9 http://www.galaxydynamics.org/

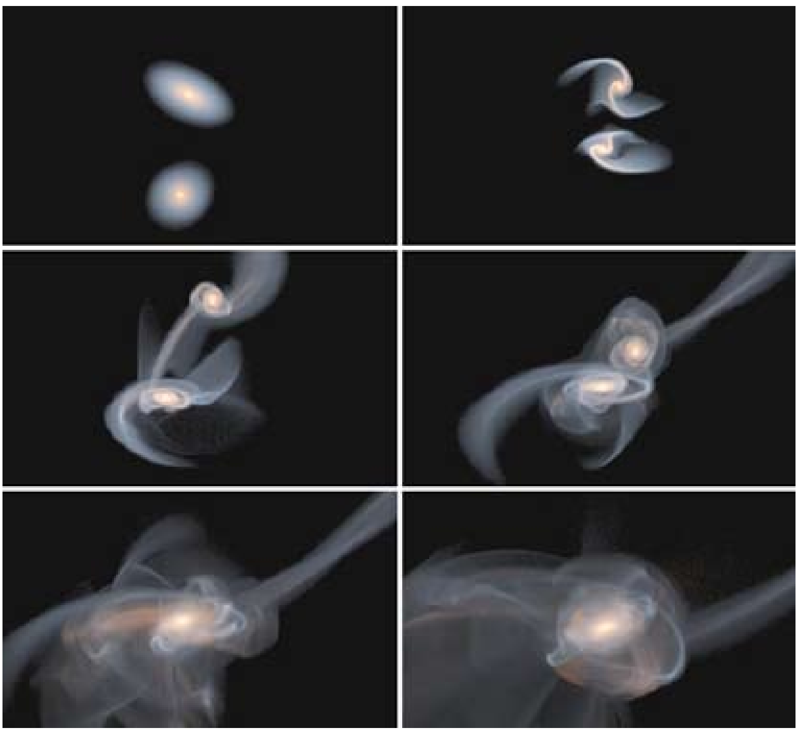

Figure 10: A computer simulation of the future collision between Andromeda and the Milky Way galaxies. At first, as the galaxies approach, little happens, but once the gravitational pulls increase sufficiently, the disks of these two galaxies are destroyed. The final remnant, which resembles a train wreck, will settle down to give a featureless elliptical galaxy.

Figure 11: A Hubble Space Telescope image of the Antenna Galaxy, actually a pair of colliding spirals. The hot blue stars were born in the collision and will burn brightly for a short time before exploding as supernovae. This is probably the future of our own Milky Way and the Andromeda galaxy.
NASA/STSci

disk structure. However, as the gravitational tidal pulls of one on another steadily increase, the spiral disks start to warp and distort. Eventually the pulls become too strong and the disks are ripped apart and flung from the galaxies, spreading out to form extensive tidal arms. The collision continues and some of the stars and gas are lost into extragalactic space. The remaining material begins to sink back together as the galactic bulges finally merge into a single body of stars.

Interestingly, during such galactic collisions, the probability of two individual stars colliding is tiny, as they are very small compared to their typical separation, and they sail harmlessly past one another. However, the disks of large spirals, like our own Milky Way, also contain a substantial quantity of cold gas, known as molecular clouds, which slam into each other during the collisions. This results in the clouds fragmenting and collapsing in a vigorous burst of star formation, with the collision lit up by strings of hot, blue stars; at this point, our colliding galaxies will resemble the well-studied 'Antenna galaxy' (Figure 11).

These hot, blue stars live fast and die young, and in a few tens of millions of years will be gone, but what will be left of Andromeda and the Milky Way? Some of the stars (including possibly the Sun which has roughly five billion years of life left) will have been ejected into intergalactic space, left to lonely wander the Cosmos. The rest will eventually settle down into a single galaxy, but unlike the two grand spirals that existed before the merger, this remnant (sometimes known as 'Milkomeda') is a giant featureless blob of stars, and the collision has created an elliptical galaxy. If our Sun remains within this new galaxy, any creature staring up at the future sky will see a very different view to ours today, with no Milky Way stretching around the sky, only a uniform sea of stars in all directions.

Return to the Dark Ages

As we have seen, in a few billon years from now, the Milky Way and Andromeda will be destroyed, merged into a single large elliptical galaxy. However, the evolution of this galaxy is not completely over, as dwarf galaxies remaining within the Local Group will still be future food if they stray too close and get dismembered by the gravitational field of the large galaxy. It is now time to think of what the distant future hold for the Milkomeda?

We know that the Local Group is streaming through intergalactic space, caught in the gravitational field of the nearest cluster of galaxies, in the constellation of Virgo, and it appears that our destiny is to eventually fall into and merge with this cluster, like so many dwarf galaxies have with the Milky Way. However, things are not so simple, as we need to think not only about our motion through the Cosmos, but also that the Universe is expanding. One of the most significant cosmological results of the last decade has been the realisation that the rate of expansion is not slowing down, the prevailing thought through the twentieth century, but is actually accelerating due to the presence of mysterious 'dark energy' that pervades the Cosmos. This acceleration will have a significant influence on our remaining evolution, driving all galaxies and clusters to greater and greater distances, until Virgo is too far away to influence us. In the very distant future, a hundred billion years from now, all galaxies will be receding from the Milkomeda so fast that they will become unobservable, and the night sky beyond the local stars will be pitch black.

The accelerated expansion leave the Milkomeda apparently alone in the Universe, and when all of the local dwarfs have been consumed there is little to do except for the stars to age gracefully, slowly burning their hydrogen into heavier elements. Every so often, any remaining massive stars may explode in a supernova, throwing their gas back between the stars and providing raw material for the building more stars, but more and more matter gets locked up in small, red dwarfs that, rather than exploding when they exhaust their nuclear fuel, simply switch off and cool down, slowly radiating away their energy.

Unfortunately, the very, very distant future of our Universe appears to be quite grim, and after a hundred trillion years, all star-formation has ceased and the Milkomeda is filled with the remnants of star formation; black holes and white dwarfs from more massive stars, and the dead and dying red dwarfs. Eventually, it is thought that the basic constituents of matter, the particles that make up the nuclei of atoms, will begin to decay, turning the stellar remnants into nothing but radiation and elementary particles. At the same time, black holes also decay through a process known as Hawking radiation, and the Milkomedea slowly evaporates until, after a trillion, trillion, trillion, trillion years, it will have dissolved into effectively nothingness; the Universe will have arrived at a new, never ending Dark Age.

The End?

The distant future of the Universe appears to be a dark and lonely space, with essentially nothing but the emptiness of space to keep you company. Is this truly the fate of all the stars and galaxies we see today? Some think not! There is a chink in our scientific armour and that is the fact that science is not a single, all encompassing theory that can be applied to all reaches of the Universe. In physics, we rely on two very powerful, but incompatible, theories; Einstein's theory of General Relativity which describes the action of gravity and the large scale Universe, and Quantum Mechanics, which explains the seemingly wacky properties of subatomic particles. We have known for a long time that in regimes where both of these are important, including the birth of the Universe, they step on each other's toes, and confusion reigns. This is why we cannot understand the very beginning of the Big Bang.

Scientists are, however, making inroads, with ideas such as string theory and loop quantum gravity beginning to meld gravity and quantum mechanics. This has led to some interesting ideas, with some, such as Neil Turok and Paul Steinhardt, suggesting that the Universe is a 'brane', one of many floating in a higher dimensional sea. They suggest that once our Universe is large enough and old enough, it may collide with another, leading to a new Big Bang and a rebirth of our entire Universe and the cycle of star birth, life and death will start again; surely the Universe is the ultimate in recycling!

Until we have that final theory, the unification of gravity and quantum mechanics, such ideas are more fancy that rigorous science, and the true ultimate fate of the Universe remains a mystery. Hopefully, one day in the not too distant future, a smart, young scientist will see the trail that leads to the solution of this mystery, unveiling the darkest secrets of the Universe and answering our most sought after questions. While I am certain this person will not be the author of this article, I do hope that it will be someone who has read it.