Island Universes: Discovering Galaxies Beyond the Milky Way

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Our Universe is built on a grander scale than we can easily imagine. Our Sun, it turns out, is just one of a few hundred billion stars in the Milky Way galaxy, which is itself only one of hundreds of billions - some would say trillions - of galaxies within the part of the presumably much vaster Universe than we happen to be able to see. There are, probably, more stars in the observable Universe than there are grains of sand on the Earth[1]. Far from occupying a privileged position in creation, we live on an ordinary planet, orbiting an ordinary star, far from the centre of a galaxy that's nothing special, adrift in this cosmic vastness.

This realisation has odd effects on people. I'm a big fan of 1930s Oxford philosopher and visionary science-fiction writer Olaf Stapledon, who described the effect of our species' looking into cosmic distances and attempting to understand how things work as 'very beautiful, though also terrible,' and I think anyone who has stood under a dark, clear sky and allowed their imagination to wander amongst the stars will recognise both feelings, born partly from the impossibility of wrapping ones' head around the billions and billions whirling above us.

I'm afraid anyone expecting help on this front from these, my Gresham lectures, is likely to be disappointed. When I tell people I'm an astronomer, the third most common response (behind 'Have you found any aliens?' and 'Do you know Brian Cox?') is some variation on 'You must be very clever.' I'm afraid to say that we astronomers have no innate ability to really comprehend large numbers, though I get more used, I suppose, to saying 'billions' than most. What I can try to do in these lectures, and in particular this first one (which deals with the discovery that we live in a vast Universe), is explain what we do and don't know about the cosmos and how new discoveries, some made in the last few weeks, are altering our view of our place in it. It is a grand story that runs for 13.8 billion years and ends up with us, sitting here, thinking about such things.

I'm especially excited to be giving this lecture now, in the golden age of observational astronomy. New telescopes and techniques are leading to new discoveries on an almost daily basis. Take, for example, a view of the Milky Way, where we see stars in their multitudes, along with some nebulosity - gas, from which we can form future stars - and, if you look more carefully, perhaps we might spot the presence of a dust lane, an area where grains of carbon and silicon, much smaller than sand grains, exist in such density as to block the light of more distant stars. From such dust, assembled around stars, planets can form, and one of the great triumphs of the last ten years has been the realisation that almost every star in the galaxy - every star you see when you go out and look at the night sky - likely has planets going around it. Of course, as I'll discuss next time, for a certain kind of theorist that's not surprising, as the physics and chemistry that formed our own Solar System must surely be that operating throughout the cosmos, but to me it still came as a revelation. It transforms that view of our galaxy into a map of worlds, each waiting to be explored.

It is also a reminder that looking at our neighbourhood might not always be the best guide to what to expect. We have found not just an abundance but a diversity of planets that few expected. As well as worlds more or less Earth-like, we have found Jupiter-sized gas giants that are so close to their stars that they complete an orbit in just a few days, and rocky counterparts whose scorched surfaces are molten, making them lava worlds. Planets exist around double stars, and pretty much every kind of world science fiction writers have

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[1] This oft-quoted fact turns out to be rather uncertain, not because we can't count the stars but because we are not sure about the amount of sand.

imagined has turned out to exist in reality. This burgeoning crop of unusual planets, of unusual solar systems, reminds us to be alert to the unexpected as well as the familiar, to be surprised by the Universe, as well as seeing our own position endlessly repeated on its vast stage. Richard Feynman – a complicated figure, though as good with a turn of phrase as he was with an equation – asked 'What men are poets, if when Jupiter be a man, sing, but if he be an immense spinning globe of ammonia and methane, stay silent?' A vast Universe should contain some surprises, and it won't all look like our home patch.

So, let's start with that view of the night sky. How do we know those points of light are suns like our own? The idea that they might be is old, in Western culture dating back to the ancient Greek philosophers, but real evidence only came in the 18th and 19th centuries (it would be fascinating to know what early Gresham professors taught on the subject). The key is establishing the distance to the stars, a measurement first successfully done through the successful detection of parallax - the apparent motion of a nearby star against the background pattern of more distant objects, caused by the movement of the Earth in its orbit. The effect is small - in the first successful measurements, made from Europe and South Africa in the 1830s, even the closest stars showed a parallax of less than half an arcsecond[2] - precisely because the stars are distant. 61 Cygni, the first to have a reliable parallax recorded in the literature, is ten light-years away. In setting out the scale of the galaxy, these measurements made it plausible that the stars were suns, owing their relative faintness to their remoteness. Spectra of the stars, the gathering of which became something of a cottage industry later in the 19th century, confirmed that their composition, though it varied between stars of different colours, was essentially similar to the Sun.

Even before then, the great English observers William and Caroline Herschel had attempted to map the galaxy. Having the most powerful telescope in the world, they scanned the sky counting stars. Assuming that their telescope (and eyes!) could see all the stars in the Milky Way and that they were roughly evenly distributed, William reasoned that the more stars he could see in a particular direction, the further that the galaxy extended in that direction. The result of observing more than 600-star fields was the first map of the Milky Way. It is not, it must be said, a thing of beauty, looking more like roadkill than something celestial, and the Herschels were wrong in positioning the Sun at its centre, but this early map captures the essential truth that we live in a galactic disk. This is the explanation for the presence of the Milky Way as a band in the sky; when, in summer or winter evenings, we see it crossing the sky we are looking through the galactic disk. At other times of the year, we look out of the disk and up at the broader Universe.

Mapping the Milky Way continues to be a concern of modern astronomers, most recently via the remarkable Gaia satellite, which continues the proud track record of the European Space Agency in celestial cartography. Gaia's latest catalogue release contains the precise positions of two billion stars. Taken together with radio data, which can reveal what is happening on the other side of the galactic centre, we see the Milky Way revealed as a system with four major spiral arms, wheeling around a central bulge and bar. There is more complexity here, with the disk split into thin and thick components, but Herschel's essential picture is right.

The next stage in understanding the vastness of the Universe was to place this one galaxy as one of many 'island universes.' This was a hugely controversial idea for much of the late nineteenth and twentieth century when observers argued over the nature of the nebulae. These objects, non-stellar in form and mostly observed as faint, misty patches in small telescopes, seemed to come in several forms. Most, like the Orion Nebula, had indistinct or amorphous forms, but as larger telescopes were developed, most notably the 'Leviathan of Parsonstown' in Birr, Ireland, a small number revealed a spiral structure.

Were these spiral nebulae a distinct class from things like Orion? It wasn't clear, and the fact that the argument was played out through sketches, often completed in difficult conditions at inconveniently placed eyepieces, did not help. As discussed in the brilliant Observing by Hand, by Omar Nasim, the same object could look very different in sketches prepared by different, dispassionate observers on either side of the debate. As late as 1920, the question of whether there were galaxies beyond our own could fuel a series of high-profile discussions at the Smithsonian in Washington DC, with Harlow Shapley and Heber Curtis, two prominent astronomers, arguing the toss in what became known as the 'Great Debate'.

Shapely argued that, if the brightest of the 'spiral nebula', in Andromeda, were a distinct system from our own then it must be hundreds of billions of light-years across. Such a size was too high for most contemporaries to accept. A recent supernova spotted in the system, which seemed to outshine the entire

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2 An arcsecond is 1/3600 of a degree, just as a second is 1/3600 of an hour.

rest of the nebula, would, he said, surely have needed a prodigious rate of energy production to put on such a display from such a distance.

It is notable from the distance of a century that all of these arguments are correct. What we would call the Andromeda galaxy is, indeed, that big, and the radioactive decay of elements produced in the initial explosion of a supernova can shine more brightly, briefly, than a few hundred billion stars. Curtis had a more subtle argument, noting the surprisingly large number of novae that appeared to be observed within the nebula; if it were simply part of our galaxy, then why would we see more of these stellar explosions in that region in particular? Better to accept it was a galaxy, with a galaxy's worth of novae, in its own right.

Definitive proof waited for the development of telescopes capable of resolving individual stars in the spiral nebulae. With those observations, the Universe expanded enormously, making our galaxy just one of a cohort. Of particular importance were observations of Cepheids. This remarkable class of variable stars, which includes Polaris, the pole star, as a member, pulses in a regular fashion, with a period that depends on its luminosity.

Watching a Cepheid brighten and fade, one can compare the brightness computed from the period with that which is observed and hence derive a distance. These stars are the most famous examples of what are known as standard candles, categories of objects which can help us measure distances. Cosmologists have tried to turn almost anything into standards, from particular types of supernovae to gamma-ray bursts, and the colours of star clusters to the size of the gravitational waves produced by colliding black holes all having been pressed into service. (Technically, we should talk of standardisable candles, as many of these methods rely on the careful calibration of each observation; for supernovae, for example, the time taken to reach maximum brightness can be used to improve the estimate of luminosity on which the method depends).

Each step on the resulting cosmic distance ladder, which we'll revisit in the last lecture of this year's series, has been used to calibrate measurements of redshift, the effect on the spectra of distant galaxies caused by the expansion of the Universe, and which can then be used to map even the most distant structures. By the end of the twentieth century, large catalogues of galaxy distances and positions could be drawn up, and the results were somewhat surprising. Even the first large surveys, such as that carried out by astronomers at Harvard's Centre for Astrophysics in the 1980s, revealed a lumpier universe than most expected. There were vast agglomerations of galaxies which linked clusters together, including a 'Great Wall' that stretched halfway across the sky, and equally large regions of space that were devoid of any large galaxies at all. These were called voids.

This cosmic structure was seen most clearly in surveys in the early part of this century, which used new fibre optics to take spectra of many objects at once, greatly increasing the efficiency. The most well-known of them, the Sloan Digital Sky Survey, claimed the discovery of a wall of galaxies 1/60th of the size of the Universe, including hundreds of thousands of galaxies, more than a billion light-years end to end. It has inspired cosmologists to ask whether it should exist, and later observers to query whether or not it does (there seems to be some evidence that it is actually three, overlapping structures).

One of the joys of big surveys like Sloan is that the data can be put to uses that were not dreamed of when the survey was designed. (It provided, for example, the images which fuelled the first iteration of my Galaxy Zoo project, which recruited hundreds of thousands of volunteers to sort through images and sort galaxies by shape; the shape records the history of the system. You can still participate today at GalaxyZoo.org) The richness of the imagery almost demands close attention.

Or you can behave like a physicist and lump all the data together to make a single measurement. The best exemplars of this approach were a team led by Karl Glazebrook, then at Johns Hopkins, who decided to ask what the background light in the Universe, produced by contributions from all the stars in all the galaxies in 2dF, a contemporary survey of Sloan, would look like. The answer, announced in a footnote in a draft paper posted online, was that the fundamental colour of the Universe was a light blue turquoise.

Such a measurement tells us about the star formation history of the entire set of galaxies captured by the survey; blue stars are more massive than their yellow or red counterparts and run through their supplies of fuel much faster. A galaxy with recent star formation will thus be bluer than one which has ceased to be active when only long-lived red stars remain. Unfortunately, in translating the spectrum produced by the survey into a colour, Glazebrook and the team had made a mistake in calibration, and shortly after the initial announcement they had to correct themselves: the universal background light was an off-white, a shade they branded 'cosmic latte'. (The name hasn't caught on).

Debates about colour are mostly for fun, but the idea of looking at the background light we receive from the entirety of the Universe has proved useful over the years. Many people remember the New Horizons mission which flew past Pluto back in 2015, revealing that small world to be a place of surprising variety and interest. Following that encounter, the probe has continued its journey through the Kuiper belt, passing close to one of the many asteroid-sized bodies that accompany Pluto, heading ultimately for interstellar space. Out there, far from the Sun's glare and mostly free from interference from sunlight scattered off dust, a background that pervades the inner Solar System, New Horizons has been staring out into space to determine not the colour, but the brightness of the background.

The results of this careful study show that, at the optical and ultraviolet wavelengths that New Horizon's camera is sensitive to, there is twice as much light as can be explained from the galaxies we can see. This tells us that there are at least a few hundred billion such systems out there. Analyses which take into account galaxies whose light reaches us in the infrared, primarily smaller systems in the early Universe, add more to the cosmic census, with some astronomers claiming a count of two trillion galaxies.

You may have noticed I've managed to come this far without defining a galaxy. The old idea of an 'island universe', an isolated system majestically wheeling through the cosmic wastes has not survived modern observations. The Milky Way is surrounded by a retinue of small dwarf galaxies, most notably the Magellanic clouds, and is in fact in the process of consuming most of them. For the large part, though fatal to the smaller galaxies - a stream of stars ripped from the Magellanic Clouds by the main disk's gravity on previous close approaches already stretches across the sky - these violent encounters leave the more massive disk untouched.

This has not always been the case. The Gaia satellite's patient recording of not only the position but the movement of stars in the sky has enabled a form of galactic archaeology, unpicking the history of the galaxy by looking at features that have survived to the present[3].

It turns out that the Milky Way has survived at least two major mergers in its time. The remnants of these collisions remain in the galaxy today, moving together through the disk and are thus identifiable in Gaia data. The most spectacular of them, a collision with a dwarf galaxy that seems to have happened roughly ten billion years ago, transformed the Milky Way, producing the present-day form of the disk and triggering the greatest burst of star formation our galaxy has ever seen. (In such a merger, though no stars will hit each other, gas clouds do collide, with the resulting turbulence creating spectacular firework displays of new stars). In recognition of the momentous nature of this event, astronomers have named the remnant the 'Gaia-Enceladus Sausage.'[4]

There are signs of a second disruptive encounter in the Gaia data, this time with a smaller system that survived the encounter. The Sagittarius dwarf can still be seen, though its stars are scattered across such a large portion of the sky that only by looking at how they are moving will you see it as a distinct system. Five billion years ago, it plunged through the galactic disk, causing disruption that will have triggered a burst of star formation, an event which may have led - indirectly or directly - to the formation of our own Sun. We may owe our existence around this particular star in this particular part of the Milky Way to the passage of this obscure system through our neighbourhood, an event repeated throughout the universe countless times but, perhaps, here, of great significance to us and providing another dose of cosmic perspective.

Quite how common mergers and encounters between galaxies are, and how wrong the old idea of even large galaxies as isolated systems is, is revealed by studying modern cosmological simulations. Carried out using some of the most powerful supercomputers in the world, and incorporating approximations which allow us to include much of the relevant physics, the product of such efforts are spectacular movies which show the dance of the galaxies to produce the cosmic web revealed by Sloan and other large surveys.

As such simulations become more complex, and the recipes they use for prescribing star formation and galaxy assembly become more sophisticated, so the closer they get to producing a simulacrum of our universe. To test them, we can look around us, but we are also learning how to look at the early Universe directly.

Being an observational astronomer is not easy. Deprived of the ability to handle the objects of our study in the lab, to conduct experiments on galaxy scales, or even watch most of the cosmic processes we study play

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[3] I am obliged, out of loyalty to my friend Alice Gorman, to point out that this is not actually archaeology; Alice and her colleagues have developed space archaeology as the study of how humans interact with, and even live in space).

[4] Astronomers lacking poetry while naming things will be a theme of these lectures, though this will be hard to beat. When the Milky Way collides with the Andromeda galaxy in 4 or so billion years' time, we have decided to call the result 'Milkdromeda.'

out in real time, we are confined to looking at what the Universe and chance conspire to present to us. I would love to see the Andromeda galaxy face-on, for example, but will be stuck forever with an awkward edge-of-view of our nearest large neighbour.

We can, however, engage in time travel[5]. The Universe is large enough that the light we detect in our most sensitive telescopes from some of the most distant galaxies has been travelling towards us for billions of years. Looking at such systems, we see them not as they are today but as they were when light set off on its cosmic journey. Though we must always be cautious about over-identification (can we be sure that the types of the galaxy we observed in the universe ten billion years ago are the same as those that we see around us today, or are we seeing outliers, the most extreme examples of a population?), this simple fact allows us to watch the Universe evolve.

The Hubble Deep Field may have a good claim to be the most important and influential astronomical image ever obtained, but it was nearly never taken. When it was first proposed that the then newly repaired Hubble Space Telescope should be pointed at an apparently empty patch of sky for more than a week, there were plenty who thought it was a waste of time. Important, eminent astronomers explained carefully that, assuming the local population of galaxies was representative of the whole cosmos, Hubble couldn't possibly discover anything new. The expected result of staring at nothing was disappointment.

As a result, when the proposal to take a Deep Field, as such an image would become known, came before the all-powerful Telescope Allocation Committee, which controls access to Hubble, in 1995, it was not selected. Fortunately, by long tradition, a small proportion of the time on a telescope is left in the personal gift of its director. This discretionary time is used for urgent requests, like following up on a supernova whose sudden appearance in the sky doesn't allow for the usual proposals, but there are no rules - a director can follow their whims.

Robert Williams, the then director of the Space Telescope Science Institute, who runs Hubble and other astronomical missions for NASA, was interested in the Hubble Deep Field. He had a team find the right patch of sky - just above the bowl of the Plough, as it turned out - and decided that the observations would be carried out over Christmas. This would provide the 100 hours or so of observations required, but also, given the repetitive nature of the work with the telescope returning time and time again to the same place, allow a skeleton staff to operate the facility at a time most would wish to be off. The resulting image was revealed to the world (and the data released to scientists everywhere) just a few weeks later, at a meeting of the American Astronomical Society.

The image is astounding. It shows a patch of sky that is hardly dark at all but is speckled with countless galaxies. Only four stars are visible; everything else in the image is a distant galaxy. The early Universe, it turns out, is alive with star formation on a scale that is unmatched today, and galaxies smaller yet more brilliant than those which surround us today sparkle unexpectedly in this image. Hubble went on to take deeper images - an ultra-deep field, followed by an eXtreme Deep Field - and this sort of observing, staring deeply at a tiny part of the early Universe has become a standard part of the astronomical repertoire.

It was one of the reasons for the construction of the recent JWST, launched on Christmas Day 2021. Its golden mirrors and sensitive detectors are optimised for the infrared and are perfect for catching images of distant galaxies whose light will have been shifted into this region of the spectrum by the expansion of the Universe during the aeons that it has been travelling towards us. As a result, even the first images taken of relatively nearby targets, such as the gravitationally lensing cluster SMACS 0723, have, speckled in the background, tiny red dots which represent distant systems.

Many of these have proved to be surprising. A team led by Karl Glazebrook - now ensconced in Australia, and not, as far as I know, thinking about the colour of the Universe - have been looking closely at a system which delights in the moniker ZF-UDS-7329, one of the reddest seen in JWST images to date. We see it as it was two billion years after the Big Bang, a period close to the 'cosmic dawn,' the epoch in which star formation was most active (things have been declining ever since).

What's surprising about ZF-UDS-7329 is that, even this early in its history, it is already a massive system. Glazebrook et al, in a paper that came out just a month or so ago, say that it's about the same mass at this distant era as the present-day Milky Way, and, furthermore, that it appears to be populated by old stars. This means it must have formed its stars extremely early on, perhaps in the first half billion years of the Universe's history. Yet simulations of the cosmos show no such massive, star-forming systems. The presence of this

[5] Though only to the past.

little red dot may be a sign that something we don't understand is happening early on.

We can reach further back using JWST. Consider GN-z11, which is a small smudge of a thing observed at exactly the period that ZF-UDS-7329 must have been forming most of our stars. Detected first in another field in Ursa Major, next to the original Deep Field, we see it as it was 400 million years after the Big Bang; its light has travelled for more than thirteen billion years before encountering JWST's golden mirror.

In some ways, GN-z11 is more like what we'd expect at such a time. It's small - about 1/25th of the Milky Way and weighs in at only about one per cent of our galaxy's mass. The fact that we can see it at all is due to the fact that it's rapidly star-forming, host to a firework display; 25 solar masses worth of stars are produced each year, compared to the Milky Way figure of roughly one solar mass.

GN-z11 was known before JWST launched, though the new telescope confirmed its extreme distance from us. What JWST has contributed is the discovery - still to be confirmed - that such systems, such pale red dots, are more common than we would have predicted. If the result stands up, and there's still a chance that we're confusing some population of relatively nearby red blobs for their more distant counterparts, then it adds to a picture where stars form, galaxies form and, perhaps, black holes form earlier than we have expected. Whether this means rewriting the rules of star formation, or a more fundamental change to cosmology, remains to be seen.

Looking at the spread of galaxies in images like the Hubble Deep Field, it's easy to get back to the feeling I alluded to at the beginning, of being lost in the Universe. However, realising we can try to understand these systems, and that they can, via a Sausage, tell us about the formation of our own Milky Way and hence our position in space, makes me glad that they are there. By telling a single cosmic story, we can learn to live in a large Universe.

References and Further Reading

Finkbeiner, A. (2012). ***A Grand and Bold Thing.*** **Free Press**

The Sloan Survey - and the astronomers who built and operate it - is well described by Anne Finkbeiner in 'A grand and bold thing.'

Huchra, J. P., Geller, M. J., De Lapparent, V., & Corwin Jr, H. G. (1990). The CfA redshift survey-Data for the NGP+ 30 zone. Astrophysical Journal Supplement Series, vol. 72, pp. 433-470. Research supported by the Smithsonian Institution.

The CfA survey of our environs is described in this paper. Access: https://ui.adsabs.harvard.edu/abs/1990ApJS...72..433H/abstract

Nasim, O. (2013). ***Observing by Hand: Sketching the Nebulae in the 19th Century*****. University of Chicago Press.**

An excellent discussion of the techniques used to sketch galaxies and nebulae.

Ponzen, A. (2023). ***The Universe in a Box*****. Penguin**

The role of simulations in science is discussed by cosmologist Andrew Ponzen in his recent 'The Universe in a Box.'

Stapledon, O. (1930). Last and First Men: A Story of the Near and Far Future. Reissued as part of the SciFi Masterworks series (1999). Orion Publishing Company. ISBN 978-1857988062

I would recommend skipping most of the first hundred pages or so.

Media Resources

There's more on Feynman on poets here: **https://www.themarginalian.org/2018/01/09/richard-feynman-poetry-science/**

A full description of Herschel's 'star gauges' is given by Todd Timberlake: https://arxiv.org/abs/1112.3635

A recent map of the Milky Way is available here: https://www.scientificamerican.com/article/a-new-map-of-the-milky-way/

Glazebrook et al on the Colour of the Universe:

Glazebrook et al (2023): https://ui.adsabs.harvard.edu/abs/2003ApJ...587...55G/abstract

Glazebrook et al (2002): https://www.astro.ljmu.ac.uk/~ikb/press/color.html

New Horizon's view of the cosmos is described in Lauer et al. (2020): https://arxiv.org/abs/2308.05606

See also the blog post from Chris Conselice: https://astronomersnotebook.wordpress.com/2021/01/19/the-number-of-galaxies-in-the-universe-and-new-horizons/

The JWST results reported are described in Scholtz et al (2023) (Access: https://arxiv.org/abs/2306.09142) and Glazebrook et al (2023) (Access: https://arxiv.org/abs/2308.05606).