RTT TECHNOLOGY TOPIC
August 2015

5G Astronomy

On the basis that you might be on holiday away from street lights with the time to look at a star lit night sky with a glass of wine in your hand we have a bumper sized technology topic for you this month on the subject of radio astronomy, drawing on a visit the Cambridge Wireless Heritage Group made to the Mullard Radio Astronomy Observatory in June.

The technologies and techniques used in radio astronomy span RF frequencies from VHF to 950 GHz. Channel bandwidths at shorter wavelengths can be greater than 500 MHz. The variable beam width variable bandwidth multiple frequency phase array antenna systems require exquisite control of phase and amplitude combined with backhaul timing accuracy far in excess of any present 4G or proposed 5G mobile broadband network.

The amount of raw data far exceeds present Internet traffic volumes and requires data mining and correlation techniques that are as yet untried and untested.

Radio astronomy, coincidentally now in its fifth generation provides a case study of technology innovation directly relevant to 4G and 5G mobile broadband physical layer and network design and optimisation.

Radio astronomy is the science of using radio to study the stars and other extra-terrestrial large and small (and compact) objects that emit radiation including the interstellar and inter galactic medium and the dust clouds of the Milky Way, the nursery for the formation of new stars and planets.

We also use radar to examine planets in our solar system and the odd moon or two (covered in next month's technology topic). It is a big subject getting bigger and getting bigger faster all the time.

Space - a big subject

The solar system and our galaxy – our local back yard

Within our solar system, the distance from the earth to the Sun is 149.6 million kilometres. The distance from the Sun to the centre of the galaxy is 26,000 light years. A light year is 9.5 trillion kilometres. Our Galaxy, the Milky Way has 100 billion stars. The closest spiral galaxy, Andromeda is 2.2 million light years away. It is approaching us at one million kilometres per hour and is on course to collide with us in five billion years. The Universe has 100 billion galaxies and continues to expand at an ever increasing rate.

The way we receive and process and analyses radio signals from man-made and natural objects in space including far distant space and the bits in between things in space has direct relevance to how we design terrestrial radio systems.

The ITU View of space

The ITU defines deep space as anything beyond two million kilometres. The moon is 405,696 kilometres from earth so is defined as near space. The deep space communication bands are at S band around 2GHz, X band at 7 and 8 GHZ, K band at 25 to 27 GHz and Ka band at 32 and 34 GHz. Frequencies down in the UHF and VHF bands are widely used for radio astronomy observation for objects observed with large red shifts.

Pre and Post War Radio Astronomy

Radio astronomy was invented by accident by Karl Jansky in the 1930's while investigating static on 30 MHz terrestrial radio links used by the Bell Telephone Company in the US.

After the Second World War, a generation of radar engineers including Bernard Lovell in Manchester (Jodrell Bank Observatory) and Martin Ryle in Cambridge (The Mullard Radio Astronomy Observatory) repurposed radar antenna and receiver systems including the 8 metre diameter German Wurzburg radar to look at signals from space.

This prompted a whole new generation of deep space radio observation techniques including Martin Ryle's use of multiple pairs of parabolic reflectors mounted on rails on an East to West axis, the One Mile and 5 Kilometre Arrays, large aperture antenna radio telescopes with resolution determined by the spacing distance.

The East/West axis allowed the antennas to sweep across a segment of sky hence the description of the device as an 'earth rotation interferometer'. The arrays were and are used to make high resolution maps of radio galaxies (large scale galaxies viewed at radio rather than optical wavelengths) and quasars (quasi-stellar small scale compact objects of high radio brightness including neutron stars).

After an upgrade in the 1980's the array was renamed the Ryle Telescope and is now used to help measure Cosmic Microwave Background radiation – the emission signature of the Big Bang 13.7 billion years ago and it's immediate (370,000 year) aftermath.

The Ryle Telescope – with thanks to Cavendish Astrophysics and the MRAO and the steady hand of Stirling Essex

The discovery of pulsars

One of Martin Ryle's colleagues, Antony Hewish helped by a research student Jocelyn Bell built a very different antenna consisting of 2048 dipoles 3.7 metres in length spread across 4.5 acres of Cambridge countryside. The MRAO site is a former mustard gas storage site so not a lot of people live there. The array worked at 81 MHz (3.7 metre wavelength). The garden shed that housed the receiving equipment is rotting away in the bramble undergrowth.

Output data from this extraordinary instrument which today looks like an over grown hop field was recorded on four 3-track pen recorders, producing 30 metres of chart paper each day. These charts were analysed visually by Jocelyn Bell. Two months into observations Bell became aware of 'scruff' on the records. These turned out to be the first observed signal from a pulsar, a compact neutron star producing bursts of radiation due to its rapid rotational spin.

The existence of pulsars had been theorized in the 1930's. It had taken over thirty years to see one in the sky. Over 2000 pulsars have now been identified including unimaginably exotic unimaginably dense millisecond pulsars, a sun sized mix of gas crushed into a 30 kilometre radius object with super liquid super conducting cores (cores with no viscosity or electrical resistance) surrounded by a crystalline crust made of iron and massive elements emitting free electrons and neutrons and rotating most of the time independently at 1000 times per second.

Earth has a magnetic field of one gauss. Our sun has a dipole field of about 50 gauss. New neutron stars have dipole fields measured in teragauss. Because the electrons are superconducting the magnetic field does not reduce over time

The magnetosphere around a neutron star is rotating at a radial distance hundreds or thousands of times the radius of the star which means it reaches the speed of light. These are extreme radio transmitters.

Occasionally neutron stars, usually young pulsars like the Crab Pulsar, generate a giant pulse. Giant pulses have been detected by the Arecibo radio telescope in Puerto Rica.[1] They have a pulse duration of 2 nanoseconds –requiring a receiver bandwidth of several GHz. 2 nanoseconds is the time it takes light to go 60 centimetres. The pulse has travelled 6000 light years from the Crab Pulsar without apparent distortion. Each individual pulse must be generated from a cubic volume of just a few metres. These Nano pulses are therefore generated by the smallest object detected so far outside the solar system.

Pulsars as the travel clocks of space

Apart from the occasional glitch when the core locks to the crust every few million years, pulsars are fabulously accurate radio bright clocks providing a unique way of measuring the dynamics of the universe including the inter stellar medium between stars within galaxies and the inter galactic medium between galaxies. Some of them are moving fast as well, at hundreds of kilometres per second.

They allow Einstein's two theories on relativity to be tested on a cosmological scale.

Just as a reminder, Einstein's Special Theory applies to stationary observers looking at things and events in a system which is moving at an appreciable fraction of the speed of light.

His general theory is about what happens when the system is not simply moving but accelerating, for example when a planet or star is moving in the gravitational field of another star.

General theory shows us how to describe these phenomena as the effect of gravity on time and space.

[1] https://www.naic.edu/

General theory is directly relevant to an expanding universe and the local effects of a massive star on time and space. Pulsars provide a stringent test of general relativity particularly pulsars with massive stellar companions, a black hole or another pulsar, in binary systems.

In a binary, if the pulsar is behind its companion, the line of sight passes through the companion's gravitational field. This should induce a distortion in time and space.

Why pulsars are important

Pulsars are important because apart from testing Einstein's theory, they enable us to observe the Universe in a number of ways.

This includes not just the obvious objects like stars but the spaces in between, the inter stellar and inter galactic medium and the gravitational and magnetic fields that exist at both a local and universal cosmological scale.

The density of the Universe

The density of the Universe at a cosmological scale is still a subject of debate, for example does the Universe get less dense at its outer expanding edges? There certainly seem to be some unusually empty parts of space.[2]

The **average** density of inter stellar space is however known. Every cubic metre contains a few hundred hydrogen atoms, mostly ionized by ultra violet radiation from energetic stars. This equates to 10,000 electrons per cubic metre. Inter stellar space is on average 1000 times more dense than inter galactic space.

The Molecular Clouds Magnetism and Gravity - the nursery of life in the Universe

However it is also possible to observe areas of molecular clouds where heavier elements have combined into molecules like ammonia and carbon monoxide.

We know this because we can measure the total electron content along the line of sight path to a pulsar by making inferences from the pulse delay and the Faraday rotation of the radio pulses. The pulse delay is typically a second per several thousand years and is frequency specific, typically measured at frequencies between 1400 and 1600 MHz and gives us a measure of electron density. The magnetic field effects the polarisation of the radio pulse. Over light years of distance this can result in several rotations which can be estimated by measurements at multiple wavelengths.

Magnetism is important in space because it produces synchrotron radiation, the radiation produced by any charged particle forced by a magnetic field to travel along a curved path. The CERN Large Hadron Collider studies (among other things) synchrotron radiation and its ability to produce bright visible light and ultra violet or X ray radiation (quarks and sparks) from particles accelerated to close to the speed of light.

Jupiter with a magnetic field far stronger than earth is a synchrotron generator millions of times larger than CERN but still tiny when compared to the Milky Way where the curvature radius is a

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[2] http://www.theguardian.com/science/2015/apr/20/astronomers-discover-largest-known-structure-in-the-universe-is-a-big-hole

function of the distance between stars. You do not necessarily need a Swiss Mountain to study quantum physics when you have the Universe doing the same thing on a rather grander scale.

The giant molecular dust clouds can be seen with a naked eye in the Milky Way obscuring the stars behind them. Within the clouds are trillions of micron sized dust grains which atoms hit and stick to.

The dust grains act as an atomic dating agency, an efficient way for atoms to meet other atoms to produce molecules of water, methyl and ethyl alcohol, ammonia, acetylene, hydrogen cyanide and formaldehyde. Each of these has a recognisable spectral line which gets red shifted down over light years of distance into the RF spectrum. These molecules are the building blocks of life.

Pulsars have their own dating agency and team up from time to time with other pulsars to become binary pulsars or occasionally decide to live dangerously and team up with a Black Hole.

Understanding how this happens requires a digression into how stars live and die.

How stars live and die - the Life Style Choices of a Star

A star is a large continuously exploding hydrogen bomb. Our own sun has a 11 year cycle in which the intensity of this process both overall and locally on the sun's surface, changes in intensity – the solar flares that coincide with high levels of radio interference from the Sun.

Measuring and characterising this interference has been and continues to be an important radio and optical astronomy task. Very occasionally there is a coronal mass ejection emitting a sudden blast of x rays, high energy particles and plasma (hot ionized gas).

The biggest geomagnetic storm on record is the Carrington event in 1859 observed by Richard Carrington[3] through an optical telescope.

In telegraph offices around the world, spark discharges shocked telegraph operators and set telegraph paper on fire. Even when batteries were disconnected aurora-induced electric currents in the wires allowed messages to be transmitted.

Today the impact on radio systems, electric utilities and aircraft, spacecraft, GNSS satellites and communication and observation satellites would be close to catastrophic. These super storms occur every 150 years or so and we are just about due for one **NOW.**

Putting these occasional hissing fits aside, the life style of a star is dependent on the size of the star.

In all stars the process of nuclear fusion produces radiant energy that opposes the gravitational force of the hydrogen. This stops the star collapsing on itself.

The nuclear fusion of hydrogen produces helium and the helium then starts its own fusion process producing carbon and oxygen in the process.

The Red Giant and White Dwarf Happy Ending

In a star the size of our sun, (1.4 million kilometres across, 119 time's earth's diameter and 330,000 times heavier than earth) the helium core then collapses allowing the remaining hydrogen to expand into a red giant, a relatively cool star with a huge radius.

[3] http://science.nasa.gov/science-news/science-at-nasa/2008/06may_carringtonflare/

A carbon core is left over in a planetary nebular of gas. The carbon core is a white dwarf. This is the final fate of stars with masses up to eight times the size of the Sun.

The darker birth of a neutron star

Stars with masses greater than eight times the mass of the sun end their life as neutron stars.

These stars have enough fuel to produce large quantities of carbon and oxygen.

If the carbon and oxygen core has a mass greater than 1.4 times the mass of the Sun the gravitational forces collapse the core beyond the White Dwarf stage and the carbon and oxygen fuse to produce neon, sodium and magnesium. The silicon and sulphur in the core produce iron, the most stable form of nuclear matter. The fusion of iron does not create energy but requires energy for fusion to take place. Fusion therefore stops at the centre of the star.

At this point the outer layers of the star collapse into the centre due to gravity. The iron core is compressed so that the nuclei of iron begin to touch, setting off a shockwave. As the shockwave spreads outwards it fuses elements into isotopes of every element including uranium.

As the shockwave moves inwards into the core it has enough energy to convert the protons and electrons in the iron into neutrons. This produces an explosion so powerful that it will typically outshine the host galaxy for a month or so.

If the original star is 8 -25 times the mass of the sun, the neutron core will remain as a neutron star with a mass up to three times the mass of our sun compressed into an object 30 kilometres across. A tea spoon of neutron dust weighs as much as a mountain.

The Black Hole Option

If the original star has a mass of more than 25 times the mass of the sun, the neutron core will collapse to a density where gravity prevents the emission of any radiation, a Black Hole typically 20 kilometres across.

Matter falling into the black hole emits radiation before it disappears from view

The rate of rotation of the black hole determines the efficiency of this matter to energy conversion process.

A high rate of rotation produces an efficiency of greater than 40%. This is the most efficient conversion of mass into energy anywhere in the universe. The Sun by comparison is 1% efficient.

It would be useful to know how this works.

Spinning neutron stars (and spinning black holes)

The original star would have been spinning relatively slowly. Our Sun for example revolves every 27 days. However when a rotating mass is moved closer to its centre its rate of rotation speeds up due to the increase in angular momentum. A star rotating once a month will end up as a neutron star rotating once a second with a magnetic field of a thousand million Tesla.

Black holes are not completely black and the occasional photon makes the occasional escape a process described as a glowing event horizon. This has been better understood due to the work of Stephen Hawking studying the quantum physics of Black Holes and their immediate cosmic companions. Over cosmological time a Black Hole will disappear although the concept of something invisible disappearing is hard to grasp.

The Millisecond Pulsars

Neutron stars slow down at rates of about one millionth of a second per year. The ratio of a pulsar's present speed to this slow-down rate is a good way of telling how old it is.

Some neutron stars get a rotational rewind. When a star collapses into a White Dwarf the atmosphere of the dying star expands massively and the outer parts sometimes reach the nearest neutron star. The gravity of the neutron star pulls in the atmosphere increasing the mass of the neutron star by a small amount and the rotation by a large amount. This is what produces those millisecond pulsars sometimes described as ‘recycled pulsars’.

Pulsars - magnetism and gravity

Radio waves can be generated by an oscillating electric current or an oscillating magnetic source. The rotating neutron star provides us with the perfect magnetic source producing radio signals in two opposite directions, hence the lighthouse effect.

As stated earlier, pulsars allow us to map the magnetic field in the interstellar medium. The inter stellar magnetic field is sustained by bulk movements of electrons making currents in the thin ionized gas and is a million times less strong than the earth’s magnetic field and therefore difficult to measure directly but can be measured indirectly by the effect of the magnetic field on the signal from the pulsar, specifically the change of polarisation. The Faraday rotation gives an average strength of the magnetic field. The electron population along the line of sight is found from the dispersion delay,

Some pulsars have now been observed from earth for over thirty years including the Crab Pulsar which has now been recorded through over a billion rotations. The measurements have been used to study gravitational lensing, the impact of gravity on radio waves including instances when a pulsar can be seen on two separate ray paths - seeing double at radio wavelengths.

Pulsars have helped astrophysicists to produce localised magnetic and gravitational maps of the galaxy which remain separate but interconnected with the gravitational waves that are theorized to exist on the cosmological scale.

Pulsars allow astro chemists to explore the role of the molecular clouds in the formation of life. If at any stage we discover extra-terrestrial life we will need to have astro biologists and astro psychologists and astro psychiatrists as well although as Stephen Hawking points out our new terrestrial friends will probably have destroyed us by then.

Gravity has the ability to condense matter at any scale. The role of gravitational waves in this process is presently uncertain but pulsars are an important part of the observation process. Gravity and magnetism would appear to be the two primary change agents of the large scale Universe.

Pulsars are by far the best way to study how those change agents work. They are small but radio bright but require good angular resolution.

The need for better radio telescopes

That means more radio telescopes are needed with better resolution and better sensitivity. The most recent telescope to be commissioned on the Cambridge site is the Arcminute Micro kelvin Imager (AMI).

This is two separately correlated arrays of receivers operating at 12 to 18 GHz band with a small array of ten 3.7 metre parabolic dishes in a compact configuration able to resolve angular scales of 2 to 16 arc minutes linked to a large array formed by a compact configuration of eight of the 12.7 metre Ryle Telescope dishes in the Ryle array including two off set dishes to create a north south baseline to cover angular scales of 0.5-5 arc minutes.

The combination of the two systems works on the basis of the small array detecting shadows that galaxy clusters have imprinted on the cosmic radio background with the large array providing correction for contaminating radio sources. The overall bandwidth is six GHz divided into eight broadband 750 MHz channels. Independently of red shift this combined array should be able to see clusters that are impossible or hard to detect optically, for example galaxy clusters hidden behind dust clouds.

This should take us back to the period between 370,000 years and one billion years including pre galaxy structures as they coalesce under the influence of gravitational wave energy.

The AMI array – with thanks to Cavendish Astrophysics and the MRAO and Stirling Essex

The AMI array demonstrates the complexity of present day telescopes both in terms of their RF bandwidth, the RF phasing and linearity required to preserve phase and amplitude information and the digital processing needed to perform multiple channel correlation. It also demonstrates the performance capability of present radio telescope systems when used with other systems.

Looking further afield there are more ambitious projects under way.

The recently commissioned Atacama Large Millimetre Array (ALMA) in the Atacama Desert in Chile at an altitude of 5000 metres cost one billion dollars (the Hewish antenna cost £15000) and has 66 steerable 12 and 17 metre parabolic reflectors. The fibre connections for this array have tolerances of less than ten microns. The array is considered to be ideal for studying the shifted spectral lines of water, carbon dioxide, oxygen and nitrogen, the intellectual feedstock for a whole new generation of astro chemistry and to study the radio emissions from Black Holes at wavelengths between 30 centimetres and 13 millimetres (1 GHz to 230 GHz).

The concept was developed from earlier schemes such as the **M**ulti **E**lement **R**adio **L**inked **I**nterferometer (MERLIN) which linked the Lovell telescope at Jodrell Bank with the Ryle array in Cambridge 220 kilometres away. These are known as long base line interferometers.

As the name implies, Merlin originally used radio links between the antennas sites. These were replaced with fibre in 2011 which increased the bandwidth to 500 MHz centred at 1500 MHz. The additional bandwidth allowed frequency diversity gain to be realized from each antenna pair and delivered an increase in sensitivity. The radio telescope operates between 151 MHz and 24 GHz.

At a wavelength of 6centimetres (5 GHz), Merlin has a resolution of 50 milliarcseconds, comparable to the Hubble Telescope at optical wavelengths. Very Long Base Interferometers by comparison give a resolution of around 0.001 arcseconds.

Radio telescopes in space.

Longer baselines required a radio antenna in space coupled to a ground based telescope. This was achieved by Japan with their HALCA satellite 1997 to 2005 with an 8 metre diameter telescope coupled to an earth based telescope – a 21,000 kilometre baseline, three times the possible distance between any pair of earth based telescopes.

The Russian Radioastron Programme launched in July 2011 has a 10 metre diameter telescope in a highly elliptical orbit giving space/earth baselines of 200,000 kilometres using wavelengths of 1.3, 6 and 92 centimetres.

The Planck[4] satellite launched in 2012 spent 30 months observing cosmic background radiation from the First Lagrangian Point. The First Lagrangian point is 1.5 million kilometres inside the Earth's orbit and is the point at which the gravitational forces of the earth and Sun are in balance, allowing the spacecraft based telescope to hover in the sky.

The High Frequency Planck Receiver measured radiation in six frequency bands: 100, 140, 220, 350, 550 and 850 GHz (wavelengths of 3, 2, 1.5, 0.9, 0.5 and 0.3 mm). The peak for observable cosmic background radiation is 160 GHz.

The low frequency receiver measured radiation in three frequency bands: 30, 45 and 70 GHz (wavelengths of 10, 7 and 4 mm).

Measurements in space of the CMB have provided accurate estimates of the age of the Universe (13.7 billion years), the curvature of space (the flat universe) and a possible confirmation of inflation theory and the nucleosynthesis of helium. This is described by astro scientists as precision cosmology.

Planck produced enough data to estimate the relative contents of the universe as 4.9% baryonic matter (observable matter such as hydrogen and helium), 27% dark matter, and 68% dark energy.

How to look at invisible objects

It is humbling to realise that most of the universe is invisible to us anywhere in the electromagnetic spectrum.

However just because something is invisible does not mean we cannot study it. We just have to do the observation indirectly by proxy.

[4] http://www.esa.int/Our_Activities/Space_Science/Planck/Planck_s_HFI_completes_its_survey_of_early_Universe

Examining pulsar behaviour close to black holes is one example. Studying the shadow that galaxy clusters cast on cosmic background radiation is another or studying objects which have been eclipsed by another object (occultation). Indirect observations can in most cases provide enough data to support a reasoned inference.

But is does highlight the need for better optical and radio telescopes.

Radio telescopes can see some things that optical telescopes miss. Large red shifted spectral lines that end up at RF frequencies for example which includes the white hot fireball of the big bang red shifted down to millimetre RF wavelengths.

The longer wavelengths (compared to optical) are a potential disadvantage in terms of achievable resolution but this can be offset by building very large terrestrial arrays.

Terrestrial systems can be bigger and they can adapt for atmospheric distortion by measuring the water vapour and oxygen resonance peaks, using those measurements as a correction factor for measurements either side.

The largest ground based interferometer array is the Very Large Base Line Array in the USA with an 8000 kilometre baseline resolution giving a resolution of a thousandth of an arc second. This array is able to measure pulsars at distances of over 7700 light years with 10% accuracy. It has a primary beam, an area of sky covered by the individual elements and a smaller synthesized beam width created by a combination of the elements in the array.

A new frequency array (LOFAR) is being constructed by the Astron Astronomical Institute. There are 36 antenna clusters each containing a few hundred omnidirectional dipoles with the clusters distributed across the Netherlands, the rest of Europe and Chilbolton Down in the UK.

LOFAR can survey the whole sky above the horizon or discrete parts of the sky or both simultaneously. It is a software telescope with no mechanical pointing. There are two antenna lengths, one covering low band 10 to 80 MHz and one covering high band 110 to 210 MHz missing out the noisy FM band .

Amongst other tasks LOFAR will be detecting hydrogen line radiation at 1420 MHz which has shifted by a large red factor into the VHF band and will help to tell us what happened between 370,000 years after the Big Bang and one billion years – the period when stars and planets started to coalesce.

The capabilities of ALMA and LOFAR will be combined in the next even more ambitious terrestrial project, the Square Kilometre Array to be built in South Africa and Australia

SKA will cover the radio spectrum from the low frequencies of LOFAR though to the millimetre wavelengths of ALMA but primarily centred between one centimetre and one metre with three antennas spanning from 70 MHz to 10 GHz. There will be 3000 high frequency 15 metre radius parabolic reflectors supplemented by lower frequency dipoles like LOFAR all beam steerable based at dense centralized antennas farms with outliers along radial arms reaching out 3000 kilometres.

All sites will be interconnected by fibre with each channel carrying multiple frequency channels to allow fine resolution of spectral lines and rejection of narrow band man-made signals.

Observations are planned to start in 2019 with performance improving in a second phase to be completed in 2025. SKA is therefore a project that is contemporary to terrestrial 5G deployment.

The SKA should provide exquisite resolution for resolving small compact radio objects including pulsars immediately adjacent to black holes. This will support research into gravitational waves which to date have been impossible to measure but theoretically must exist. It will also be able to do big sky searches efficiently and fast.

The data handling requirements will be significantly higher than present day to day global internet traffic and exceeds present super computer performance capabilities but then that's the point of new technology on a cosmological scale.

5G Astronomy

This is the point at which the relevance of next generation radio astronomy to 4G and 5G radio systems should become apparent.

The radio astronomy industry is producing radio systems which rely on electronically steerable antenna arrays capable of working from VHF to 950 GHz with channel bandwidths of 500 MHz or more at the shorter wavelengths. These arrays produce multiple beam widths including adaptive electronically steerable narrow beams within wide beams with receive signals combined through ultra linear ultra-low noise multiple receiver front ends.

The wide area timing accuracy required to maintain phase and amplitude information from thousands of antennas thousands of kilometres apart over fibre back haul requires timing accuracy at least an order of magnitude better than present terrestrial radio systems.

Astronomy started more or less from the time when people looked up at the sky and started to be curious about what they were looking at. The Ancient Greeks coined the term Kosmos - the well-ordered universe and gave our Galaxy a name -the Greek name for the Milky Way (Galaxias) is derived from the word for milk (gala).

You could regard astronomy is being now in its fifth generation. This can be either be defined by people or by technology or by wavelength and whether or not optical and shorter wavelength observation is included.

In terms of people, Galileo marks the start of **the first generation of astronomy** with his first observations with an optical telescope in 1610 just before Edmond Halley and Newton (the 1687 Principia) set out the basic mechanics of motion of the more visibly obvious celestial objects (the sun and the moon and the stars).

Hubble marks **the second generation of astronomy** with his discovery in 1929 that the universe is expanding and that the expansion rate is increasing, giving us the insight to use red shift to determine the age of the universe and red shift and blue shift to determine the speed at which stars and galaxies are moving towards or away from us within that expanding space (the Doppler effect at optical and RF wavelengths).

The space telescope that now bears his name continues to produce exquisite pictures of distant parts of our galaxy including images of exoplanets in adjacent solar systems that may be fostering life forms that are presently scarcely imaginable. The Hubble Telescope is the first of a new generation of spaced based optical observatories measuring wavelengths from 0.1 to 2 micrometres.[5]

20th and 21st century astronomers now have Einstein's Law of Special Relativity (1905) and General Relativity (1916) as a theoretical background to the influence of gravity on time and space. Hubble's thesis that the expansion rate of the Universe was increasing led to the theory that expansion is governed by gravitational waves emanating from the Big Bang with possible wavelengths that span thousands or millions of year – an extreme version of long wave radio which to date has proved impossible to measure or observe.

[5] http://www.spitzer.caltech.edu/mission

Karl Jansky and Grote Reber mark **the third generation of astronomy** or rather the recognition that radio astronomy could be used to supplement optical observation. Karl Jansky, a US radio engineer investigating interference on Bell Telephone 30 MHz radio links was the first to observe radio waves from space. His findings were published in the 1932 Proceedings of the Institute of Radio Engineers and (the more widely read) Nature Journal. The *jansky* (Jy) is a unit of spectral flux density, or spectral irradiance, equivalent to 10^{-26} watts per square metre per hertz.

Inspired by Jansky, Grote Reber, a radio engineer in Chicago became an amateur radio astronomer and in 1937 built a 9.5 metre radio dish telescope with a receiver working at 1.87 metres (160 MHz) and 0.63 metres (480 MHz) which he used to draw radio emission maps of the Milky Way. His first paper was in the proceedings of the Institute of Radio Engineers in 1940.

The fourth generation could be characterised as the period after the Second World War when radar technologies were repurposed for radio astronomy with Lovell and Ryle as two of the most active UK based pioneers. The following forty years marked a developing ability to measure the Universe across the whole of the electromagnetic spectrum from metre band to millimetre wavelength radio through infra-red, optical and ultra violet and X ray imaging (from space**).**

The fifth generation adds massive multiple antenna arrays, digital imaging and digital processing and massive computing power to the technology mix and includes a much improved coupling of radio, infra- red, optical, ultra violet and X ray and Gamma ray and Y ray observation techniques**.**

Intellectually the back end of this era has been informed by what could be described as the Hawking/Dawkins effect- the combined impact of Stephen Hawking's theoretical analysis of the cosmos and Richard Dawkin's questioning of creationism, though we still do not know what happened before the Big Bang, who lit the fuse or why ….. Or what exists outside the flat universe.

The search for extra-terrestrial life

Stephen Hawking recently lent his support to a search for extra-terrestrial intelligence despite reservations as to what would happen if we found anything.[6] This involves studying exoplanets which can be hard to see optically due to surrounding star light and usually have low RF brightness.

The recent discovery of an aurora around a brown dwarf, a cross between a super large planet and a star then never quite made it to the fusion stage was achieved by correlating radio observations from the Very Large Array Telescope and the Hale and Keck optical telescopes. The exoplanet, LSR J1835 is 18 light years away in the Lyra constellation.

On a cosmological scale this is local science but in practice studying the solar system (our sun and its nine planets), our galaxy and other galaxies is an integrated science combining measurements across the whole of the electromagnetic spectrum with magnetism and gravity as localised and cosmological scale enablers of change. This is why measuring gravitational waves and mapping the magnetic universe is important.

The behaviour of pulsars next to Black Holes, those mysterious stores of dark energy and dark matter that we know are there but cannot see will test Einstein's General and Special theories of relativity at an altogether higher level.

And the discipline of astro chemistry remains in its infancy but has almost infinite potential.

Summary

[6] http://www.space.com/29999-stephen-hawking-intelligent-alien-life-danger.html

5G radio has a lot to learn from 5G astronomy. In terms of radio innovation this includes receiver optimisation from VHF to 950 GHz, interference cancellation and dynamic correction for atmospheric distortion and the effective integration of RF observation with observations across the whole of the EMC spectrum.

In terms of network innovation this includes super accurate long distance multipoint to multipoint timing accuracy over wide band optical fibre.

In terms of data processing this includes an unprecedented volume, velocity and variety of data that will require a new generation of Big Data management and data mining and correlation capability.

In the meantime, 5G Astronomy is about to reveal a lot more about the Universe than we ever knew before or at the very least prove or disprove the theoretical models that exist for those parts of the Universe that can only be observed indirectly - the visible invisible universe.

Ends

Post Script - The Harmony of the Spheres

On a whimsical note, the Ancient Greeks talked about the Music of the Spheres and Harmony of the Spheres in the context of a well-ordered Universe, the Kosmos. As usual they might turn out to have been spookily prescient.

Gravitational wave theorists talk about the Universe as a huge resonant bell with the Big Bang as a point source, a moment of infinite mass. Inflation growth theory proposed by Alan Guth in 1981 suggested that the Universe underwent exponential growth for one second then switched to 13.7 billion years of linear expansion with the ripples explaining why the expansion appears to be getting faster with time (as the ripples move away from the point source).

This is the thesis that supports the theory that the Universe is flat when viewed from the outside, a theory which will be difficult to prove for obvious reasons but would appear to be the only option that satisfies the increasing expansion rate observation.

At least up to the pre Socratic era there was a general feeling that the world was flat. Aristotle (384-322 BC) reasoned that the Earth must be spherical because of the circular shadow it cast on the Moon during a lunar eclipse. Luckily for Columbus he was right but it is curious that we have gone from thinking the world was flat to realizing the world is round but the universe is flat and galaxies come in various shapes and sizes.

But back to the Harmony of the Spheres and forward in time to 1884, the composer, Giuseppe Verdi wrote to the Music Commission of the Italian Government arguing the case for lowering the standard pitch for Concert A from the 435 Hz used in France to 432 Hz on the basis that music sounded better when tuned to that resonance. You can listen and decide for yourself by listening to A432 shifted music on various comparison web sites.
http://omega432.com/

In the grand spirit of European and US integration the US decided to use 440 Hz. A440 was officially designated by the American Federation of Musicians in 1917 and adopted as an ISO standard in 1953.

There are advocates arguing for a return to A432 on the basis of it being a multiple of the 8 Hz Fibonacci number series used by nature to duplicate itself, for example petal growth and seed germination. 432 times 432 equals the speed of light in millions of miles per second and crops up in various terrestrial geometric relationships including the Pyramids and the Golden Mean and extra-terrestrial distances and ratios. This could of course be new age nonsense but it might fill the occasional awkward pause at a party. The A432 is the road that goes north east from Bristol but that is probably not particularly relevant unless you live in Bristol.[7]

Our thanks to the Mullard Radio Astronomical Observatory for hosting the Cambridge Wireless Heritage Group on a recent tour and for permission to use photographs of the Ryle and AMI arrays.
https://www.mrao.cam.ac.uk/outreach/
https://www.astro.phy.cam.ac.uk

Geoff Varrall is a Special Interest Group Champion for the Cambridge Wireless Heritage Group. The group studies examples of radio technology history that can be shown to have direct relevance to present and future decision making in the radio communications industry.

The next Wireless Heritage event is 75 Years of Radar at the RAF Air Defence Museum in Horning, Norfolk on 16 October.

http://www.cambridgewireless.co.uk/sigs/heritage/

Further reading

If you would like to read more about the role of radio astronomy then there is an excellent book, The Unseen Cosmos written by Francis Graham Smith. Francis Graham Smith and his wife both worked with Martin Ryle so this is a first-hand living memory description of the last seventy years of radio astronomy innovation and discovery.

Unseen Cosmos
Oxford University Press
ISBN 9780 19 966058 2

About RTT Technology Topics

RTT Technology Topics reflect areas of research that we are presently working on. We aim to introduce new terminology and new ideas to help inform present and future technology, engineering, market and business decisions. The first technology topic (on GPRS design) was produced in August 1998.
http://www.rttonline.com/tt/TT1998_008.pdf

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RTT, the **Jane Zweig Group** and **The Mobile World** are presently working on a number of research and forecasting projects in the mobile broadband, two way radio, satellite and broadcasting industry.

If you would like more information on this work then please contact **geoff@rttonline.com**
00 44 208 744 3163

[7] http://www.sabre-roads.org.uk/wiki/index.php?title=A432