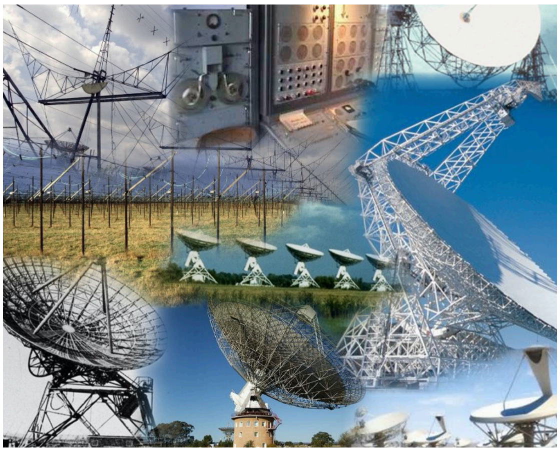
Slide 1: Titles



A long time ago, when I was a research student at Mullard Radio Astronomy Observatory in Cambridge, I frequently had to show visitors around the site. By far the most common questions we got asked was “Where is the eyepiece?”. This was usually at the end of the tour after I had just spent two hours explaining that radio telescopes didn’t produce images in at all the same way as optical telescopes.

Some radio telescopes do in fact eventually produce images of the sky, but in a rather roundabout and complicated way involving a lot of computing power – and some don’t do it at all because sky images are only one way of doing astronomy.

This talk is an explanation of how radio telescopes work, and how they changed the course of astronomy in the 20th century, and may well change it again in the next decade. I will also explain how this apparently purest of pure science has strong connections to devices you use every day.

The astrophysics revealed by radio astronomy is exciting, I am as fascinated by this as anyone else - but it is also important to understand the tools used to do science. Only then can you understand the strengths and weaknesses of the evidence.

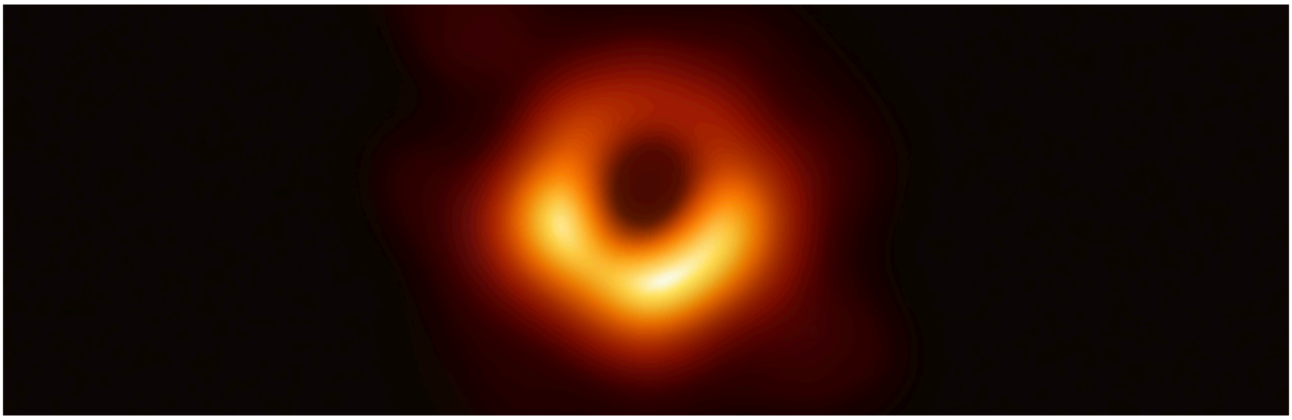
I can’t cover the whole of radio astronomy technology - anymore than you could give a comprehensive talk on “what you can do in a chemistry laboratory”. So, I am going to use as my focus an image which was published just about 3 years ago.

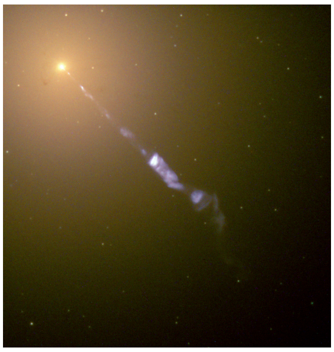
Slide 2:

The ring of bright light we are seeing here is produced by the super-hot gas spiralling into the black hole at the centre of a relatively close and bright massive galaxy first discovered by the 18th Century astronomer Messier - the 87th in his catalogue and therefore generally known to astronomers as M87. (The event horizon itself is within the dark zone in the middle.) It had long been known that something strange was going on in M87 because of a unique optical jet emerging from the core - and for want of any other plausible explanation we had long suspected that it harboured a massive black hole.

The angular size of this image is roughly comparable with that of a fifty pence piece imaged on the surface of the Moon. How do we do this! It is a remarkable technical achievement and the main purpose of this talk is to explain how it is done.
A lot of people went “Wow!” when they saw this image - I knew a lot more about the technology and I was even more impressed - but I also knew that the astronomers were treading a fine line between showing us reality and showing us what they expected to see.

It is a product one particular type of technology known as aperture synthesis. Its invention was though worthy of a Nobel Prize back in 1974 because of the impact it had already had on astrophysics ad cosmology. The Nobel Committee got it bang to rights - because the the technology has become ever more dominant and important in astronomy right up to the present day. Of course, things have also move on technically in the last 45 years - very substantially indeed.





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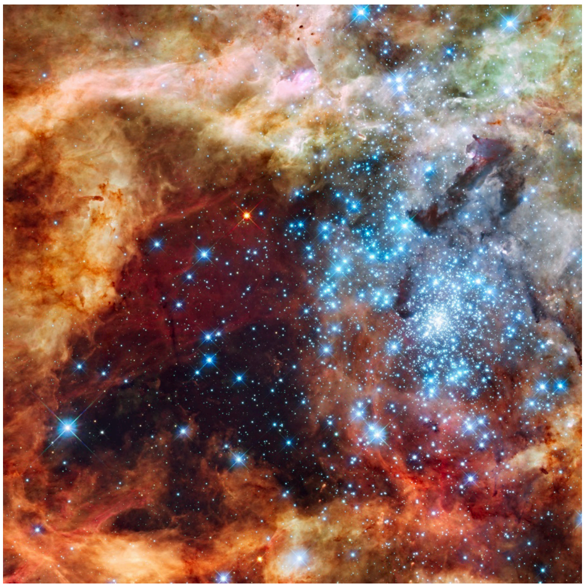


For thousands of years people have looked at the sky and what they mainly see is "hot stuff". Even in the case of our relatively near neighbours the planets and moons, we are actually just looking at reflected light from the Sun – the light from a hot surface modified by reflection.

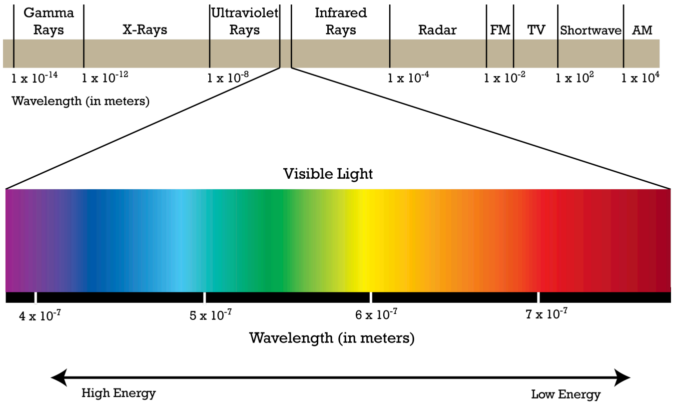
This glowing gas (on the screen) is emitting light because it has been heated up by these stars, ionised and we see the photons emitted when electrons start to fall back down the energy levels of emitting atoms towards the nucleus.

Physicists call this thermal radiation: any normal material (you may have heard it called "barionic matter") above absolute zero gives out thermal radiation. The hotter the material the more it radiates, and on average does it at higher frequency (shorter the wavelengths). Our eyes have evolved, in particular, to see the best in the light emitted by our own Sun – which has a surface temperature of about 6000 deg C.

Light (and heat) is a form of electromagnetic radiation, and most of what we know about the Universe comes from studying electromagnetic radiation. Even though we now have other windows, such as neutrino and very recently gravitational wave astronomy, these are still delicate and limited tools: the vast majority of astronomers still deal with electromagnetic waves. Until the middle of the last century, all of astronomy was concerned with using electromagnetic waves in the very narrow optical waveband – which necessarily meant that most of what we saw was "Hot Stuff".

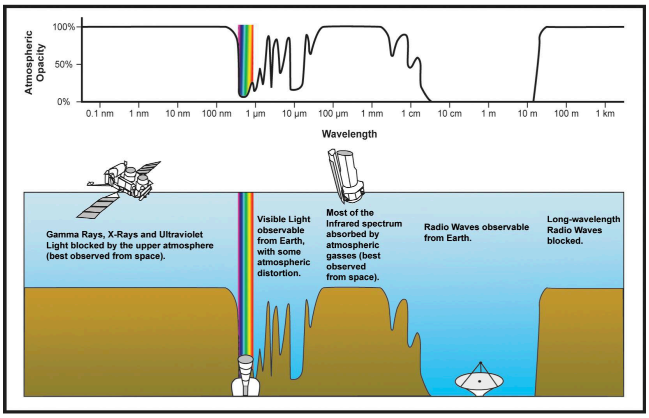
30 Doradus - R136 Hubble Space Telescope

Slide 4



Let’s just remind ourselves about the electromagnetic spectrum – and just how narrow is that optical band. The only difference between visible light and radio waves is the wavelength. As you go to the left the energy carried by individual photons gets larger, and its get smaller to the right. The left is the domain of “high energy astrophysics” – though as we will see radio astronomy was the first to reveal the high energy universe. Note that physicists talk pretty much interchangeably about *wavelength* – which is literally the distance between one wave peak and the next, and *frequency*, which is the number of times a wave goes up and down each second. They are related: wavelength is just the speed of light divided by frequency and vice-versa. So a wavelength of, say 6 cm, is equivalent to 5 GHz in frequency terms and 2 meters is equivalent to 150MHz. Radio astronomers are multilingual about this, and switch back and forth – sometimes in the same sentence – without thinking. Often, when we are talking about the shape of aerials we discuss them in term of the wavelength they are designed to receive – because the size of the active elements are directly related to wavelength. When we are talking about receiver electronics we are more likely to talk about frequency – because it is the time constants in the electronic components that relate to the receiver frequency. I shall try to be consistent and give you both ways of looking at it.

Slide 5:



Our ability to see through the atmosphere is fairly limited. Unless you fly above the atmosphere we are pretty much limited to the visible, slightly obscured views in parts of the Infra Red and then a wider and clearer band in radio waves.

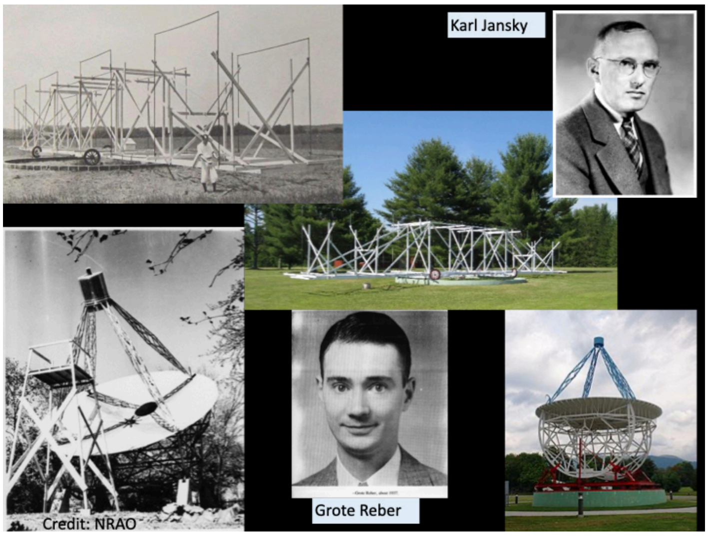
Hence, although a lot exciting astronomy needed satellites above the atmosphere, its modern era really started with radio astronomy, which opened the first new window in the middle of the 20th Century.

The wavelength range of radio astronomy is limited by several factors:

- At the long wavelength end, the Earth's ionosphere reflects radio waves, so we can't see through it. That tends to limit our observation to above about 70MHz – (though150MHz – 2 meters – was until recently a common lower limit for radio astronomy). There are a few places in the World where the ionosphere is more transparent at low frequencies, such as Antarctica. My own research supervisor Peter Scheuer spend some time there back in the 1960s – but it is a difficult environment to work in. As we shall see, there has been a recent revival of interest in low-frequency radio astronomy.
- At the short wavelength end, the atmosphere becomes opaque, mainly because water vapour absorbs the waves. We can overcome this to some extent by going to very high altitudes and dry areas such as the Atacama desert, or indeed the South Pole, where with modern electronics it is possible to do radio astronomy at mm wavelengths (terra Hz frequencies) where there are many spectral lines from complex molecules found in space.

One big advantage of radio astronomy is that you can do it 24 hours a day - and one of the reasons it took off in the UK is that in the middle of this clear band it is not affected by the weather. Our poor weather certainly meant that we did not have a powerful establishment of optical astronomers deciding how research funds should be spent , which is one of reasons why the Americans took a long time to really get going.

Slide 6



Astronomical radio emission was in fact discovered in 1931 by an American physicist and radio engineer called Karl Jansky who was investigating sources of radio interference for Bell Telephone Labs. (At that time transatlantic telephone communications relied on radio links.) He eventually worked out that there was a component of the interference that rotated with the fixed stars and pretty much aligned with the Milky Way. Unfortunately Karl died in 1950 of chronic kidney disease, at the age of 44 - otherwise I suspect that he would have shared in a Nobel Prize. (He was nominated shortly before his death - but it was too soon for the impact of radio astronomy to be fully apparent. 10 or even 5 years later I think that the case would have been unanswerable.)

Bell’s business was operating a communications network so once Jansky had identified the problem and written up the work the project was terminated. A bit later a young man called Grote Reber wanted to join Bell Labs to do further work on radio astronomy but work had already stopped, so in 1937 he built this dish in his back yard.

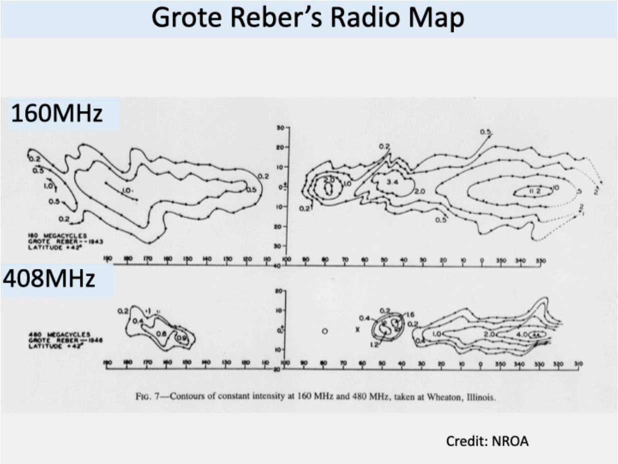
For about 10 years Reber was the world’s only practicing radio astronomer largely ignored by the astronomical establishment, who didn’t know what to make of this new field. His career was interrupted by the war, when like many talented electrical engineers he worked on radar. After the war he returned to radio astronomy, but never made much of an impact. Although he was alway well regarded his ideas were frequently too far ahead of his time and un-fundable in the Byzantine and highly political American science funding system (with which he had very little patience).

Everyone also agreed that he was essentially a loner and the last person anyone would want running a big project - or even a university research group.

His dish was later moved to NRAO were it is now classified as a National Monument.

NRAO also rebuilt a replica of Jansky’s original aerial.

Slide 7:



Grote Reber's Radio Map

160MHz

408MHz

FIG. 7—Contours of constant intensity at 160 MHz and 480 MHz, taken at Wheaton, Illinois.

Credit: NROA

Reber was able to make a map of the emission - the earliest map of radio emission from the sky. Note that it does not show very much detail but it does show, as Jansklу had deduced, that the emission is correlated with the plane of the Milky Way.

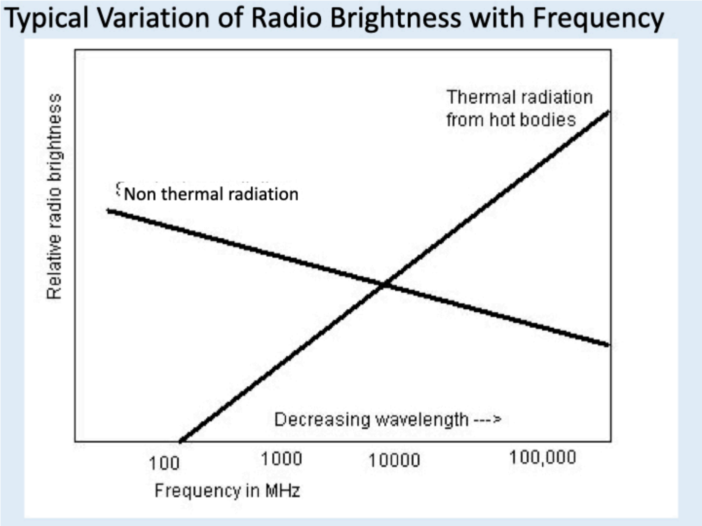
The big question was whether what we are seeing is the effect of emission from the aggregated mass of stars.

In fact, although our Sun is the brightest radio source in our sky that is just because it is very close. Reber also deduced that if most of the stars in the Milky Way were like the Sun, they could not account for the emission we see. That did not exclude the possibility that a proportion of stars unlike the sun might be “radio stars” - much more powerful emitters - and for many years this was a strongly favoured theory.

However, the radio telescopes of this time had very low resolution - they could not see fine detail - so this could not be confirmed. Working to get more resolution with radio telescopes is a major theme in the development of radio astronomy.

He observed at two frequencies 160 MHz and 408 MHz (about 2m and 75cm wavelengths) so he could also work out how it varied with frequency. He made the extremely important observation that there was less emission at higher frequencies, and Reber correctly deduced that he was not seeing any form of thermal emission.

Why is this observation so important?



Firstly, we do not expect to see a lot of radio emission from typical "hot" stuff at typical radio frequencies (and certainly not those easily accessible to electronics in the middle of the last century). This is the basic, fundamental physics of so-called "black body" radiation: it falls off very rapidly as we go to longer wavelengths.

(Even for temperatures as low as 2.7K – the universal microwave background – the peak frequency of emission is at a wavelength of only about 2mm – or 150GHz – pretty much off-scale at the right, a very high frequency for radio work.)

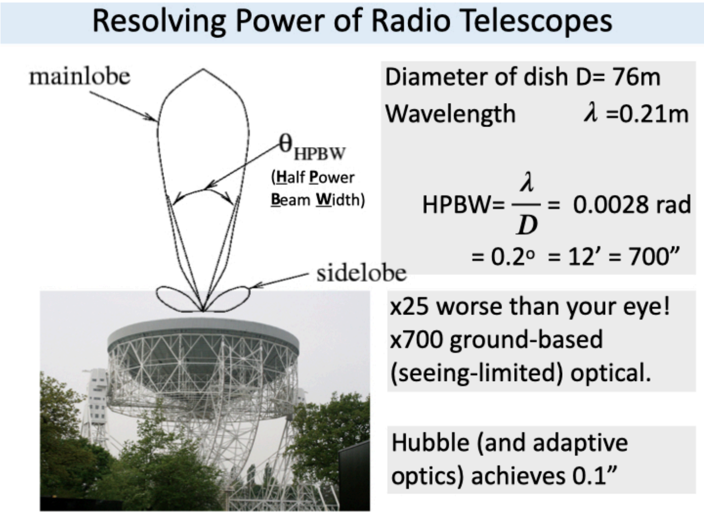
So the amount of radio emission from the sky was a surprise, and it was also a surprise that the spectrum was definitely non-thermal.

It was much stronger at low frequencies. It also turned out to be polarised – that is preferential direction of oscillation of the electric fields in the radio wave. Thermal emission always produces random field directions.

This is why we know that non-thermal physical processes must be involved. Something very interesting and unusual is going on and it took a couple of decade to work out what it was. More on this later.

Of course, then everything got put on hold by the Second World War. Anyone with experience of electronics went to work on radio communications and radar - and came out of the experience with many skills they didn't have at the start of the war.

Slide 9:



Resolving Power of Radio Telescopes

Diameter of dish D= 76m
Wavelength λ =0.21m

$$\text{HPBW}=\frac{\lambda}{D}= 0.0028 \text{ rad} = 0.2^{\circ} = 12' = 700''$$

x25 worse than your eye!
x700 ground-based (seeing-limited) optical.

Hubble (and adaptive optics) achieves 0.1″

A basic issue of radio telescopes is resolving power: because they operate at much longer wavelengths than optical telescope they see less detail. (And, of course, telescopes like this do not form images – they have a one pixel detector – so you have to scan the telescope around the source to understand the way intensity varies across the sky and that takes a lot of time.)

We can get more resolution by building bigger telescopes – but there are engineering limits. Slightly bigger dishes than Jodrell Bank have been built – but only slightly. The biggest fully steerable dish is only 100m in diameter near Bonn in Germany – just a bit larger than Jodrell Bank and that commissioned way back in the 1972 – over 40 years ago. This is pretty much the limit for fully steerable dishes. Although there are some larger non-steerable dishes, such as the recent 500m telescope in China they are restricted in the part of the sky they can see. This again is pretty much the limit for Earth-bound structures.

Or else we can go to shorter wavelengths. In fact, Jodrell Bank has been upgraded twice with new more accurate reflecting surfaces allowing it to work at very short wavelengths. That also increased costs so as we move to even shorter wavelengths we tend to make smaller dishes. Hence, the resolution you can get from single dishes is pretty much what you see on the slide.

However, the electronics also gets more difficult as we push to higher frequencies (it generates noise that competes with the radio sources), and for most radio sources the intensity dies away rapidly at shorter wavelengths. Furthermore, we have to deal with a lot more background noise – just because all the hot stuff is emitting more radio waves at these shorter wavelengths.

There is also the problem that we are still dealing with a single pixel detector: the higher the resolution, the more time we spend scanning across the radio source to make a map.

Slide 10:

You can get higher resolution by building bigger or going to shorter wavelengths. Incidentally, you might like to worry a bit about how you move and point a structure weighting many thousands of tons to fraction-of-degree accuracy. The mechanical engineering is impressive.

The largest dish is FAST, the Five-hundred-meter Aperture Spherical Telescope (FAST) in the remote Pingtang county in southwest China's Guizhou province. China. Although this is now the largest telescope in the World, the aerial feed does not fully illuminate the entire dish and Arecibo is still in practice competitive.

These represent the largest realistically achievable dishes. Unfortunately the shorter wavelength route is also difficult. In general the surface of your dish needs to be an accurate to about 1/10 of the wavelength that you are using to work effectively. The larger you make your dish the harder this become. So, big dishes working on their own will usually be limited to a few minutes of arc in resolution.

Arecibo – 1000 feet (305m). This has been running on a shoe-string budget for some years, because NSF wants to fund exciting fields such as gravitational wave astronomy. A lot of damage in a recent hurricane has made the problem worse.

Efflesberg (Bonn) 100m (328 feet).

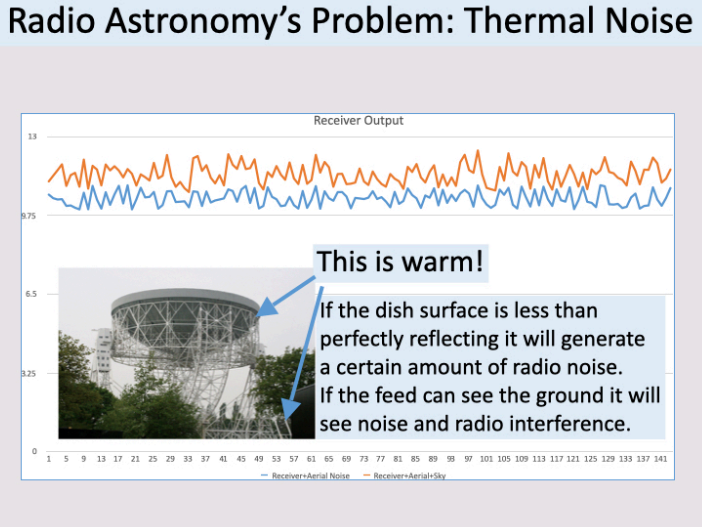
Parks 210 feet (64m)

Green Bank: 100m (328 feet).

Jodrell Bank 76.2m 250 feet.

There are also at least six 70m radio telescopes. (Three, Goldstone, Madrid and Canberra were primarily designed by NASA for deep space communication with spacecraft. Three similar dishes in the former Soviet Union probably had a similar purpose.)

Slide 11:



Radio Astronomy’s Problem: Thermal Noise

This is warm!

If the dish surface is less than perfectly reflecting it will generate a certain amount of radio noise.
If the feed can see the ground it will see noise and radio interference.

If you plug a loudspeaker into the output from the radio telescope receive it just sounds like random noise – pretty much like any domestic receiver not tuned to a radio station.

In fact, most of it noise generated in the receiver itself – and the receiver noise sounds just like the cosmic noise. In your average tranny, the broadcasting station produces much more power than the receiver noise. This is not the case with most of the radio sources we are looking at.

The red line shows the received output when you are pointing at a radio source. The blue line is the output when the telescope is pointing at blank sky.

You can see that in general the signal we are trying to identify is a small part added to noise generated inside the telescope itself – and the signal from the sky tends to look just like the noise from the telescope.

Even the dish – if not perfectly reflecting - generates noise because it is warm. Any imperfections in the wave guides, electronic junctions and the early stage amplifiers feed noise into the system.

How do we manage to distinguish between the two?

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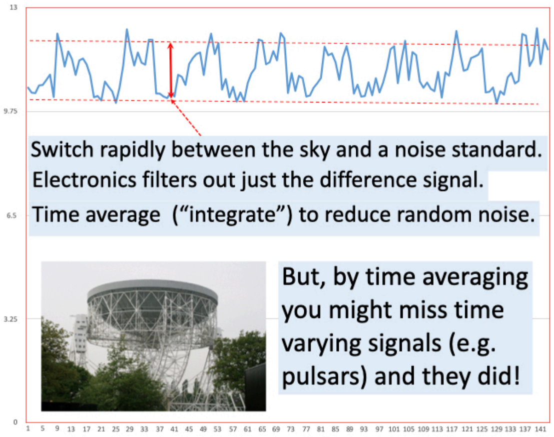

Switch rapidly between the sky and a noise standard.
Electronics filters out just the difference signal.
Time average ("integrate") to reduce random noise.

But, by time averaging you might miss time varying signals (e.g. pulsars) and they did!

There are several ways to deal with this problem. The main method used today is the "Dicke Switch" where we inject a precisely known amount artificial noise into the aerial feed as a comparison standard at regular intervals, and then arrange the electronics to switch rapidly between the sky and the noise source, picking out the difference.

The point is that we have to take great care with designing our amplifiers and receivers to reduce noise. Because this noise is thermal we often we cool the electronics with liquid nitrogen or even liquid helium. Our standard noise source today may well be a resistor cooled in liquid helium.

There is also a need to make the electronics very stable over time, otherwise this averaging procedure will not produce reliable results.

You can spoil all the care with poorly made cable junctions: anything that causes reflection of sky noise and adds resistance will feed in thermal noise that swamps the sky signal.

The pioneers of radio astronomy learned all these technical tricks when they worked on the development of radar during WWII.

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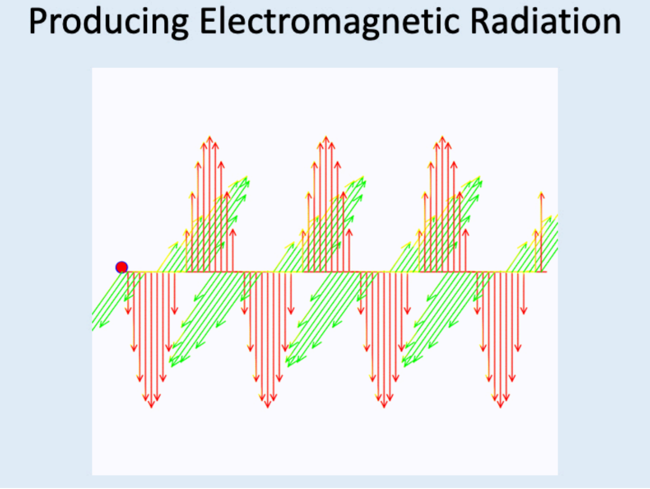

Producing Electromagnetic Radiation

Electromagnetic waves are produce only by jiggling around electric charges. This type of motion happens in dipole radio aerials, like those used to transmit the BBC.

In hot bodies like the Sun most of the stuff is hot ionised gas, both the electrons and protons from hydrogen and helium are separated and are moving randomly – that is what heat is. On the whole it is radiation from the electrons that we see, because being lighter they move much faster.

The hotter the body, the faster the electrons move so the higher the frequency of the waves.

The other way we can oscillate electrons is using magnetic fields because magnetic field exert forces on charged particles.

Slide 14:


NASA/SDO/AIA, NASA/STEREO, SOHO (ESA & NASA)

The visible Universe is mostly plasma – that is the atoms are broken apart into charged particles. Stars are all plasma of course, but most of the space between the stars (and between galaxies is filled with low density plasma. It has a very high electrical conductivity because the gas is so tenuous that electrons rarely hit anything to slow them down, so current just keep flowing.

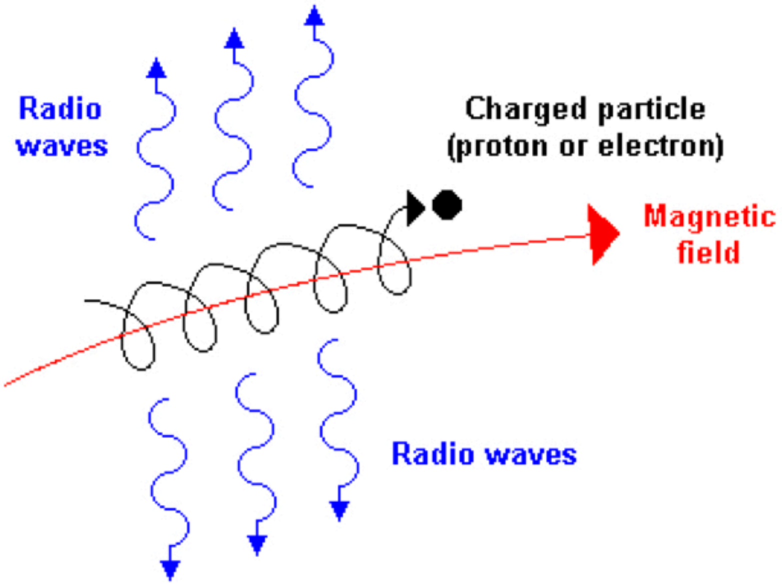
This means that plasmas can support magnetic fields and usually do. This is where things get complicated because the current cause the fields and the fields exert forces on the currents, so plasmas behave in complicated ways.

You get a good idea of how plasmas can behave when you look at Solar flares. The hot plasma is being channelled along the lines of magnetic force.

In fact, thinking of magnetic fields in plasmas as if they were elastic bands turns out to be a fairly good approximation for astrophysical plasmas. You can pull them out, twist them, compress them and wind them around and around.

Where does the magnetic field come from? Small fields can be enormously magnified by the turbulent motions in the Sun – like wrapping an elastic band around a pencil – you get more lines of force. The energy that goes into the fields is from the mechanical work done by this stretching and it is being taken from the kinetic energy of the turbulent plasma motions – which ultimate are produced by heat-generated convection in the Sun's surface layers. We also know that some of the energy in the magnetic field then gets used to accelerate high energy charged particles, by complex processes that are not all that well understood. We do, however, know that they are surprisingly efficient – say compared to the Large Hadron Collider.

Slide 15:

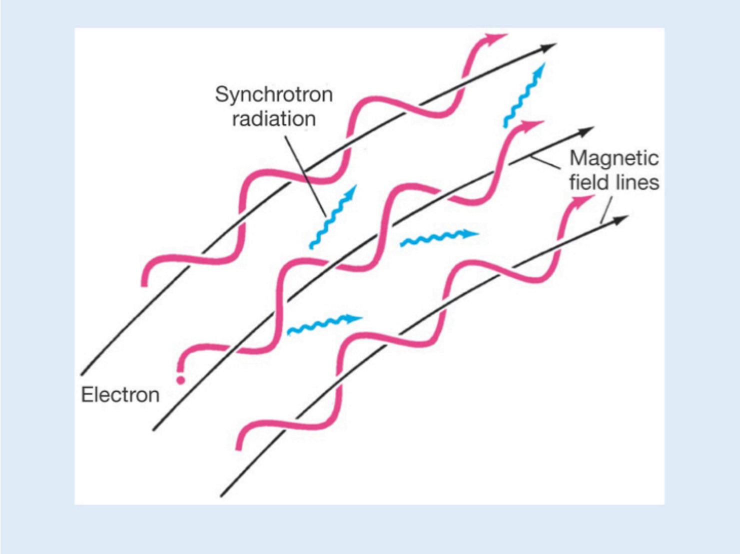


http://nrumiano.free.fr/

So, electrons spiral around magnetic field lines as shown in the slide, and normally they emit radiation of a frequency that corresponds to the cycle time of the electron – mostly fairly low.

Some of the whistlers and shrieks that one sometimes gets on old AM radios at long wavelengths are produced in this way by electrons spiralling in the Earths magnetic field.

Slide 16:

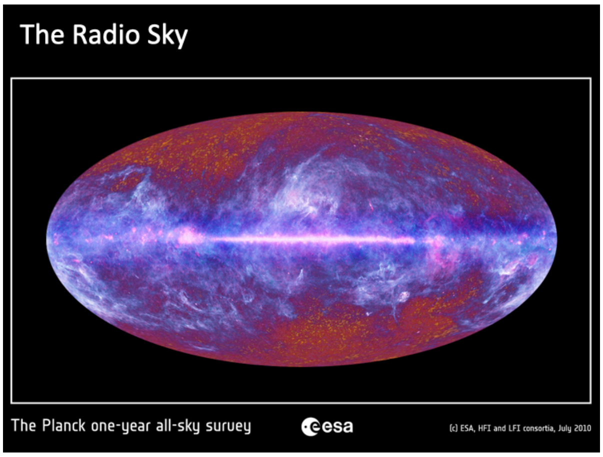


However, when the electron is travelling very fast, nearly at the speed of light you have to take account of Einstein’s theory of relativity and then the radiation does not come out uniformly – it is focused forwards and is also shifted to very much higher frequency. There is no easy way to explain this other than doing the university level theoretical physics.

This is called synchrotron radiation because it happens in big particle accelerators where the particle beams loose energy this way – it is why the LHC has to be so big and use so much electrical power. Astronomers love it because it can tell us a lot about the conditions inside radio sources. So, this is what is happening inside solar flares and in many other radio sources.

The radiation tends to be polarised and shows you the direction of the magnetic field. In addition each energy band of electrons produces radiation that peaks in a fairly narrow frequency band. So, by looking at the way the radiation varies with frequency we can find out the energy spectrum of the relativistic electrons.

Slide 17:


The Radio Sky

The Planck one-year all-sky survey

esa

(c) ESA, HFI and LFI consortia, July 2010

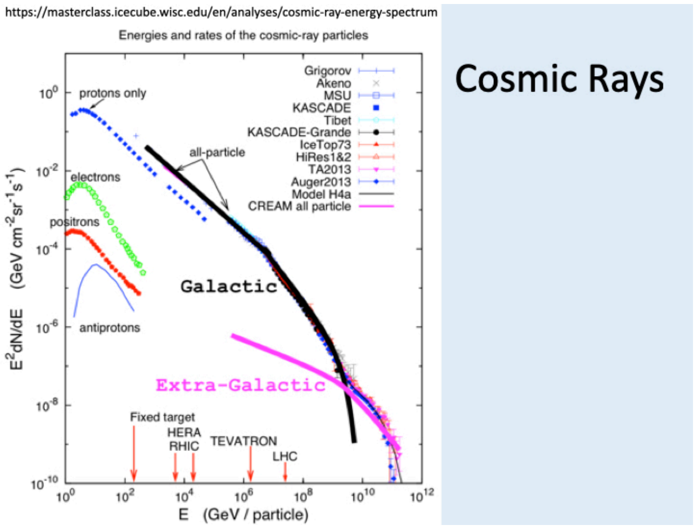
If we look at a modern map of the sky in radio waves, the stars do not figure at all. The first thing that strikes you when you look at this map is the we are obviously seeing stuff *between* the stars. On the largest scales, as with the Sun, we are obviously seeing the effect of magnetic fields carried by the interstellar medium. (In fact, we can also map the polarisation which confirms this interpretation.)

A few of the very bright splodges in right in the plane *are* probably just “hot stuff” – “HII” star forming regions where there is enough hot dense gas to make them radio bright. Most of the radio emission here is caused by electrons moving randomly and making close passes against protons, emitting a bit of EM as they change direction. (This is known as “bremsstrahlung” – but the technical name really just describes a form of “hot stuff” emission.)

There *are* also compact sources, however, these are still not stars. More on these later.

Our own Sun does produce radio waves, both because it is hot and also because solar flares emit powerful bursts of radio waves. However, these are loud on Earth only because the Sun is very close. We would have to work hard to detect them from other stars like the Sun. (In fact, there are some stars that produce much larger scale flares than the Sun, which are detectable with big radio telescopes, and Sir Bernard Lovell spend quite a lot of time at Jodrell Bank studying these “Flare Stars”. But this is not a big area in radio astronomy today.)

Slide 18:



https://masterclass.icecube.wisc.edu/en/analyses/cosmic-ray-energy-spectrum

Cosmic Rays

We are, of course sitting in the middle of the Milky Way with the interstellar medium all around us, and it turns out we can detect some of the high energy particles that are responsible for the diffuse emission – we know them as cosmic rays.

The slide show the energy spectrum which shows that the particles are much more common at low energy than high energy. This is also the explanation of why the spectrum of the galactic emission also looks like this.

Since we now know the density of cosmic rays in our locality we can work back and estimate the strength of the interstellar magnetic fields from the basic physics of synchrotron emission. Most of the emission comes from the electrons, remember, which are light and easily deflected by magnetic field, though only account for about 1% of the kinetic energy in cosmic rays – most of it is in high energy protons. It is a reasonable guess that for synchrotron radio source where we cannot directly measure the amount of energy in electrons versus that in protons there will also be in imbalance in favour of the species that do not happen to radiate much energy.

As always answering one question raises another. Where to the cosmic rays come from. Radio astronomy has helped to solve part of this puzzle. More on this later.

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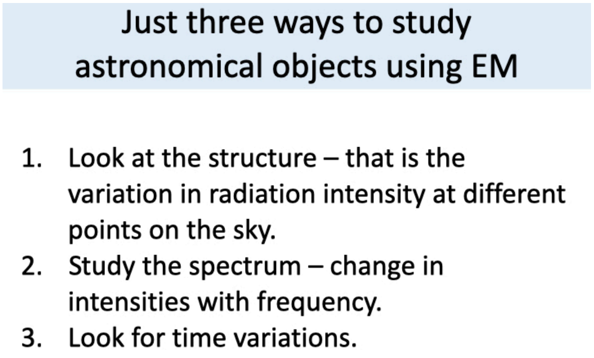


Just three ways to study astronomical objects using EM

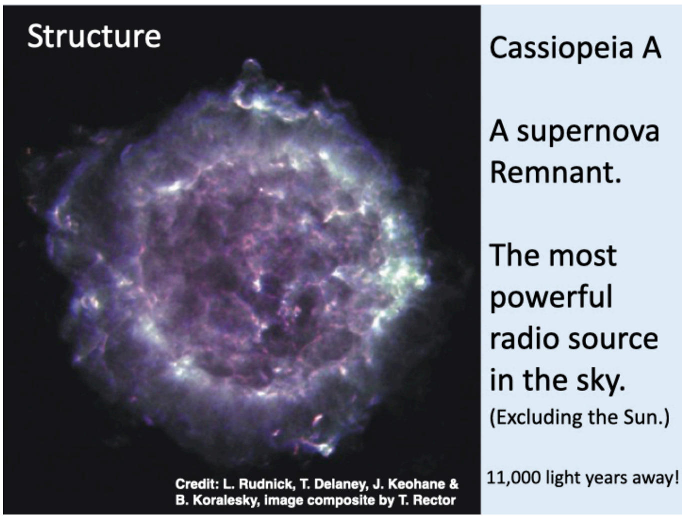
1. Look at the structure – that is the variation in radiation intensity at different points on the sky.
2. Study the spectrum – change in intensities with frequency.
3. Look for time variations.

All of astrophysics is based on these methods.

Telescopes like Jodrell Bank are very good at the second two methods, but much worse than optical telescopes at studying structure because their resolving power is poor.

It is worth remembering that although optical telescopes are very much better than radio telescopes at resolving structural detail, in practice stars are still unresolved points of light, and it was the introduction of spectroscopy (method 2) that really launched astrophysics as a science at the start of the 20th Century, and use of time variation (light curves) is still a major technique for finding extrasolar planets.

Slide 20:



Structure

Cassiopeia A

A supernova Remnant.

The most powerful radio source in the sky.

(Excluding the Sun.)

11,000 light years away!

Credit: L. Rudnick, T. Delaney, J. Keohane & B. Koralesky, image composite by T. Rector

I am just going to talk about looking at structure, because I would need another couple of lectures to properly cover radio spectroscopy and time varying radio sources

11,000 ly away, 1ly across.

(This is a shame, because I wrote a couple of papers with Martin Ryle and a whole section in my PhD thesis about a well known variable source.)

In reality if you want to know about the processes going on in astrophysical objects you will need to combine at least two out of the three fundamental approaches in any particular case.

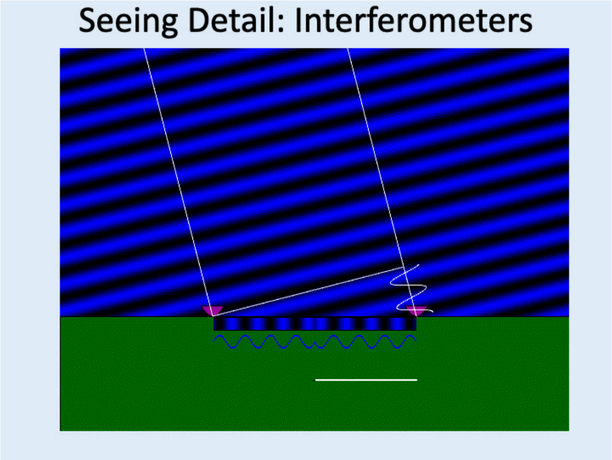
This is Cassiopeia A, the most powerful radio source in the sky (other than our Sun which doesn't count because it is so close). It is hardly visible at all in visible light, though what we are seeing here is a composite image of radio waves and X-Ray emission from very hot gas. It is so powerful that if you know what you are doing you could easily detect it using a couple of commercial TV aerials.

It is the remnant of a relatively nearby supernova explosion some 300 years ago and only 11,000 ly away – though nobody saw it, which puzzled astronomers for many years. We now have several plausible explanations, including obscuring dust or perhaps it was a rather unusual explosion of a very massive star that has previously ejected its outer layers which absorbed most of the light from the event.

We can learn a lot of astrophysics from these high-resolution images that just can't be obtained any other way. For a start some of the bright spots are so small that they can't hold much energy but are also radiating so much power we know that they must fade away very rapidly - but we still see them so some mechanism is regenerating the high-energy particles.

What we think is going on here is that the ejected material from the star is ploughing into the interstellar medium, creating lots of turbulence and this is winding up magnetic field, and creating shock waves that accelerate electrons to very high energies – especially in these bright knots. It is objects like this that may be the source of most cosmic rays we see on Earth.
It is one of the three or four astronomical objects that you always look at when commissioning a new radio telescope.

Slide 21:



Seeing Detail: Interferometers

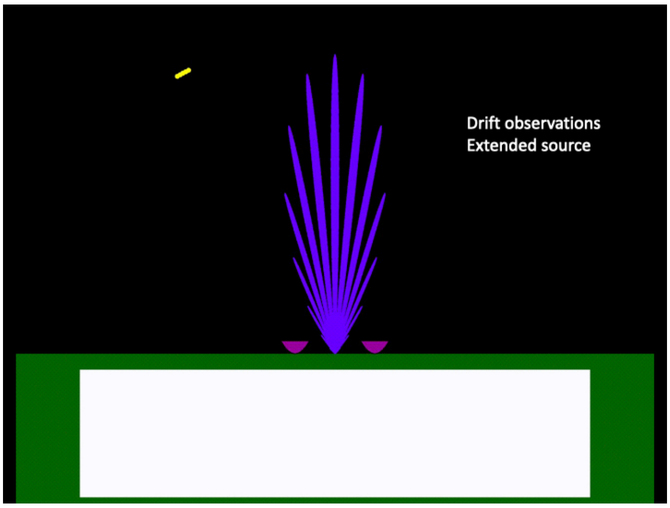
At radio wavelengths, if we want to study detail we need interferometers, and I am going to talk quite a bit about how these work, because that is the way I used to work and also because most large radio telescopes these days are build as interferometers.

Furthermore, similar techniques are now becoming important in optical astronomy, where for the first time we are starting to get resolved images of the surfaces of stars other than the Sun.

What we can see here are the plane wave fronts of radio waves approaching a radio interferometer. The signals from the two dishes are collected and transmitted along cables to a central point where they are added together in the same radio receiver. At some angles the radio waves arrive here “in phase” and produce a big signal – at other angles the peaks arriving at one dish cancel the troughs at the other dish and we pick up nothing.

Before I go any further I should note that for the next ten minutes or so I am going to describe radio interferometers as they were build up to, say 30 years ago. This is because they are relatively easy to understand this way. These days analogue receives have been replaced by digital receives and the coaxial cables by data links. The new technology makes the telescopes much more powerful – sometimes by factors of 1000 or more – but it is hard to explain the technology without using mathematics. Just bear in mind that todays telescopes essentially simulate this hardware in a computer effectively but instead of having the two aerials working at one wavelength they allow the same aerials to be used for observations over many different wavebands at the same time. But it is very complicated!

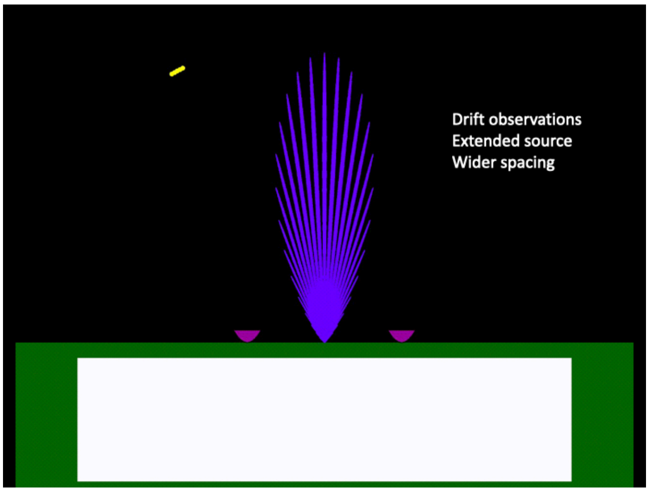
Slide 22:



So, we can put our aerials on an east-west baseline and let the sky drift past. The blue lobes represent directions in which we would see constructive interference - in the gaps we see no signal.

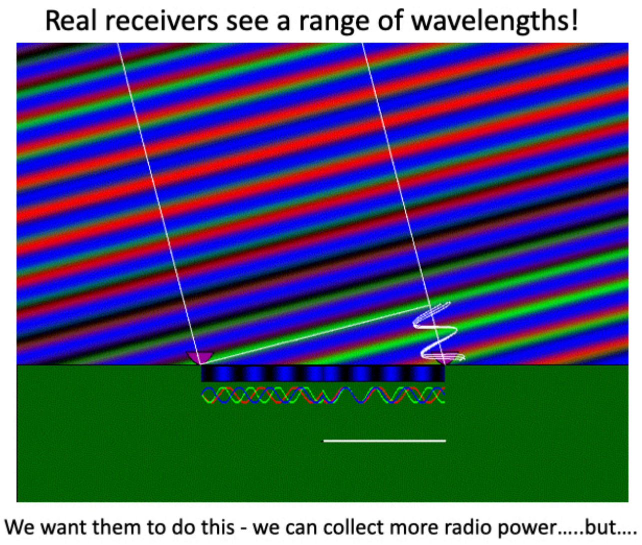
In reality the lobes of the response pattern are much more closely space (too close to even show separately on this diagram).

Slide 23:



As we increase the spacing (and reduce the separation of the fringes) we get a lower response because some of the source is always lined up with a lobe and some of it is not.

Slide 24:



Real receivers see a range of wavelengths!

We want them to do this - we can collect more radio power.....but....

Unfortunately, as I have described it does not work!

Real radio receivers accept a range of wavelengths and in general the more the better as far as radio astronomy is concerned because it means more power arriving at the receiver. However, while some wavelengths are giving constructive interference, others are being destructive.

For a real radio telescope we would only see a receiver response as a source passed through the N/S meridian line bisecting the baseline, when all waves from both aerials go down the same length of signal path and so always add constructively.

That is OK if we want to catalogue and measure the positions of radio sources accurately and are happy to use telescopes in drift mode.

It is a big problem if we want to observe radio sources away from the meridian line.

Slide 25

The “Path Compensator” - a vital trick

Only works if we know the EXACT position of aerials
in 3D space at all times on the rotating Earth. Easy? NOT!

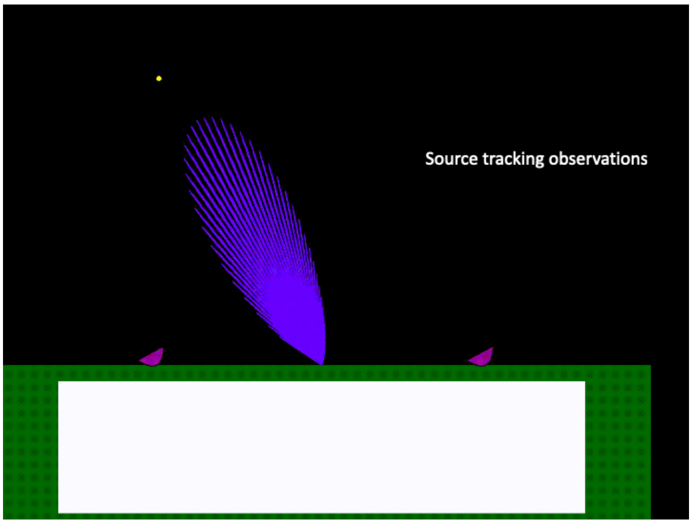
We deal with this problem using “path compensators” which add a variable amount of delay to one side of the interferometer and ensures that the two signal paths are always exactly the same.

In order to be able to do this we need to know the exact position of the radio telescope aerials relative to the part of the sky we want to observer, and that means we need to know its exact geographical coordinates and the exact time of the observations (which tells us the orientation of the Earth in space).

Furthermore, we need to use the real “Earth” rotation time taking account of the fact that the rotation rate can vary from day-to-day by a few milliseconds - and the milliseconds are important here. (Providing regularly updated “Earth-time” is one of the regular routine jobs of certain national observatories.)

Remember this - you will be tested later on because it is crucial to understanding that black hole image.

Slide 26

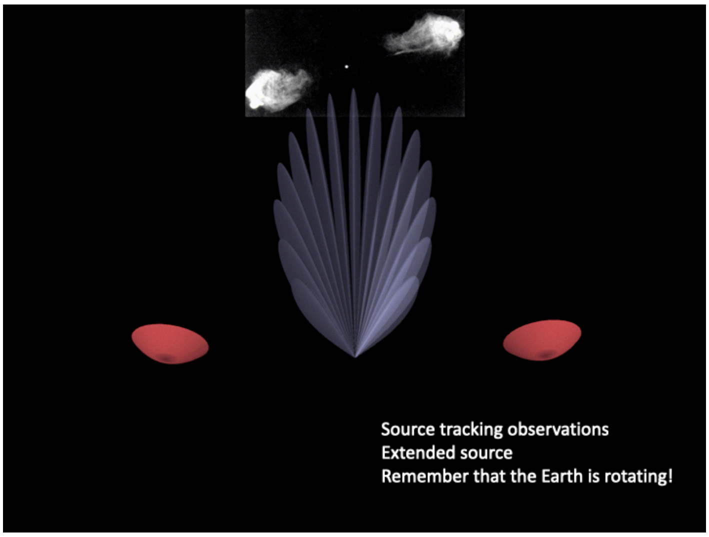


So here we are, getting our aerials to track a radio source across the sky.

We are also making the lobes rotate a bit slower than the main aerial reception pattern (adding variable delays) so we still get the fringes that allow us to distinguish between source noise and receiver noise.

But why would be want to track the source? Don’t we get enough information when it drifts through the aerial beam?

Slide 27



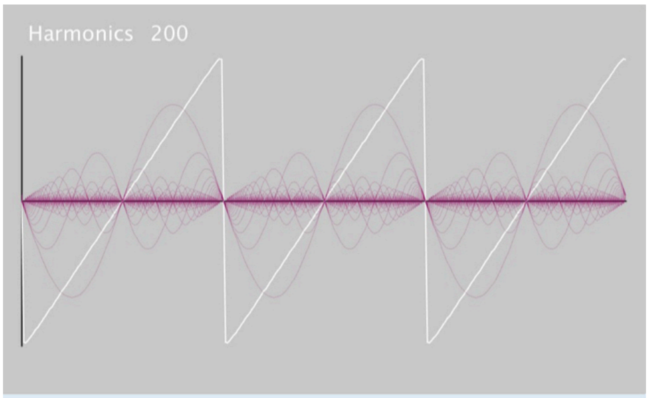
Source tracking observations
Extended source
Remember that the Earth is rotating!

But remember, as we are tracking the source across the sky, the Earth is rotating.

If we watch the source for12 hours our fringes rotate through 180 degrees and we record the observed amplitude in all the possible directions across the radio source.

It turns out that what we are actually observing here are a mathematical quantity called the Fourier amplitudes of the source brightness distribution - so I had better explain what those may be.

Slide 28:



Fourier Synthesis: we can build arbitrary curves using only sine and cosine waves.

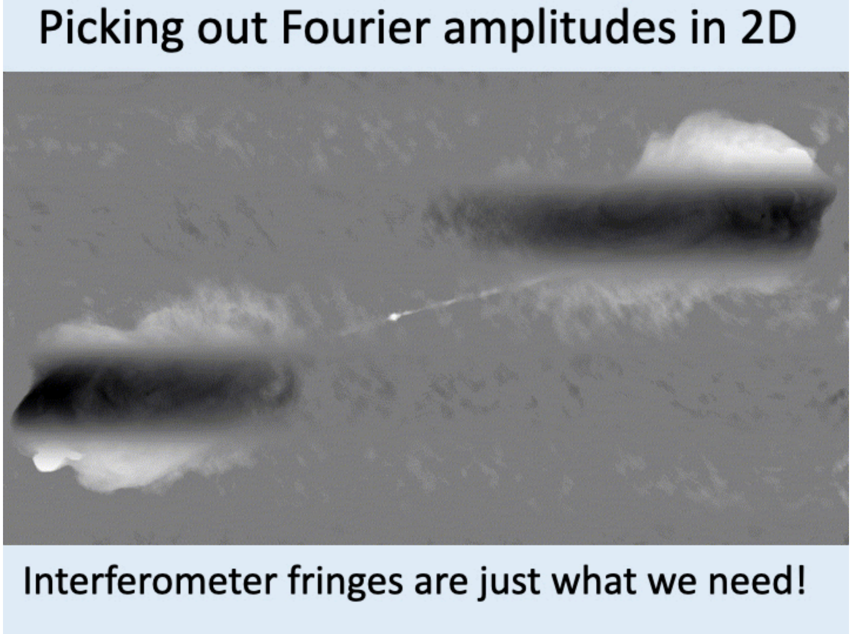
So now let me explain Fourier synthesis – but for simplicity I am only going to demonstrate it in one dimension.

It turns out (you need university-level maths to follow the argument) that any one dimensional curve can be represented as the sum of a set of smooth waves – even shapes with sharp edges. (This non-intuitive and surprising claim initially led to many fierce arguments between18th and 19th Century mathematicians but eventually to a great deal of extremely important maths.)

Anyone who uses an electronic keyboard will be using this maths when they synthesize the sounds of different musical instruments. Here we show how one can produce a triangular wave form (a bit like a trumpet sound).

It also works in two dimensions – for images. We can represent any image as a superposition of waves of different wavelengths running in all the directions across the image. It turns out that radio interferometers are exactly what you need to directly measure the various wave amplitudes. If we manage to do this accurately we can then add all the waves together in a computer and get a proper high-resolution image of a radio source.

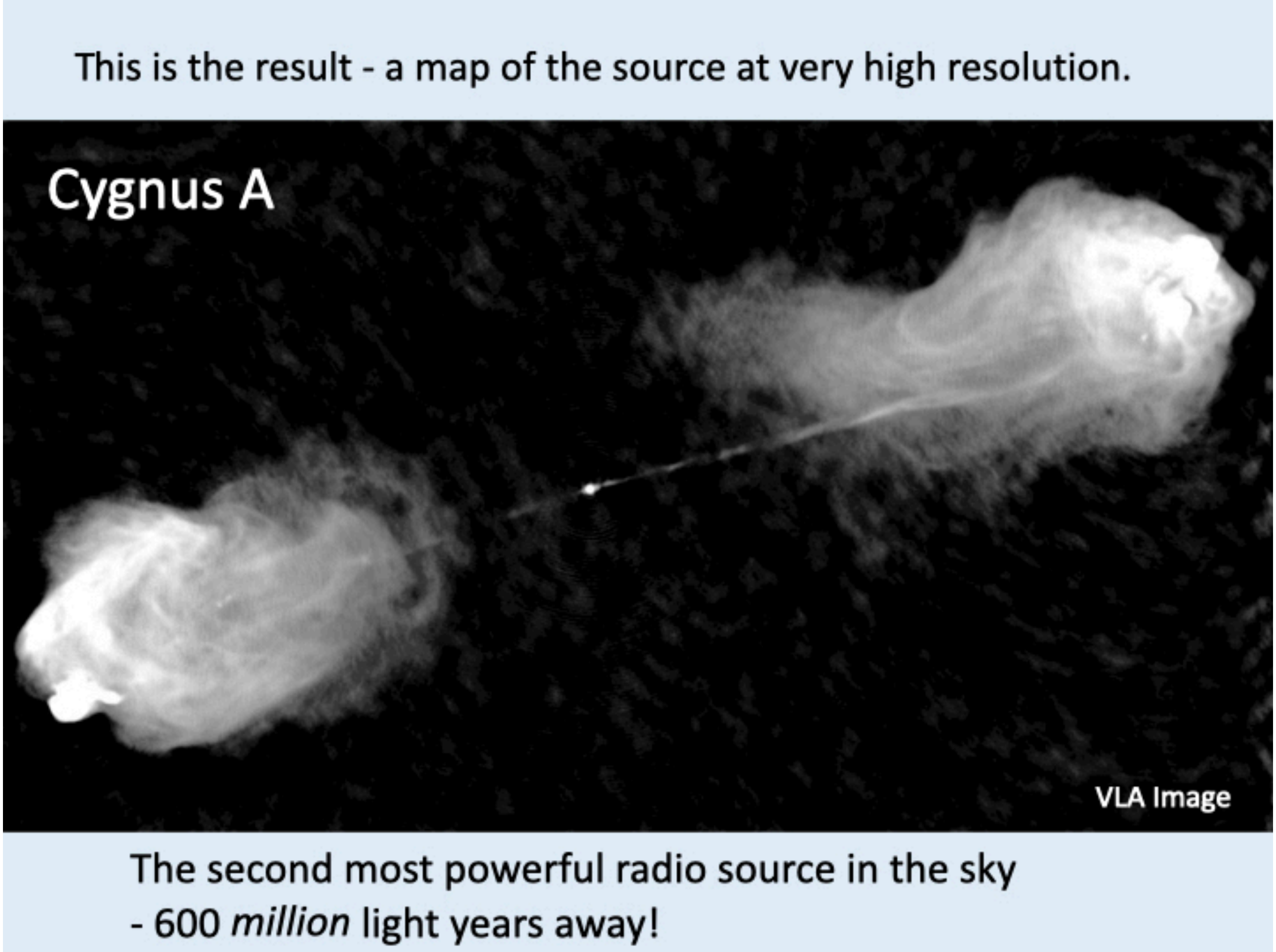
Slide 29



Picking out Fourier amplitudes in 2D

Interferometer fringes are just what we need!

Slide 30



This is the result - a map of the source at very high resolution.

Cygnus A

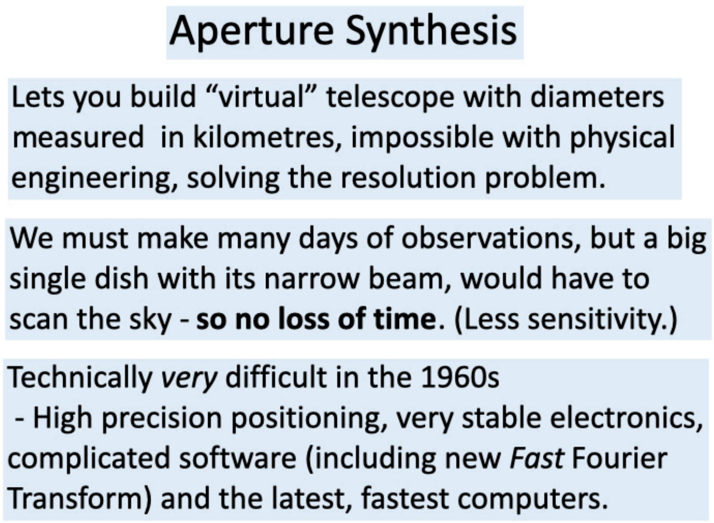
VLA Image

The second most powerful radio source in the sky
- 600 *million* light years away!

And this is what we eventually get.

Of course, this image is the back end of a great deal of sophisticated computing that takes account of imperfections in the observations.

Slide 31



Aperture Synthesis

Lets you build “virtual” telescope with diameters measured in kilometres, impossible with physical engineering, solving the resolution problem.

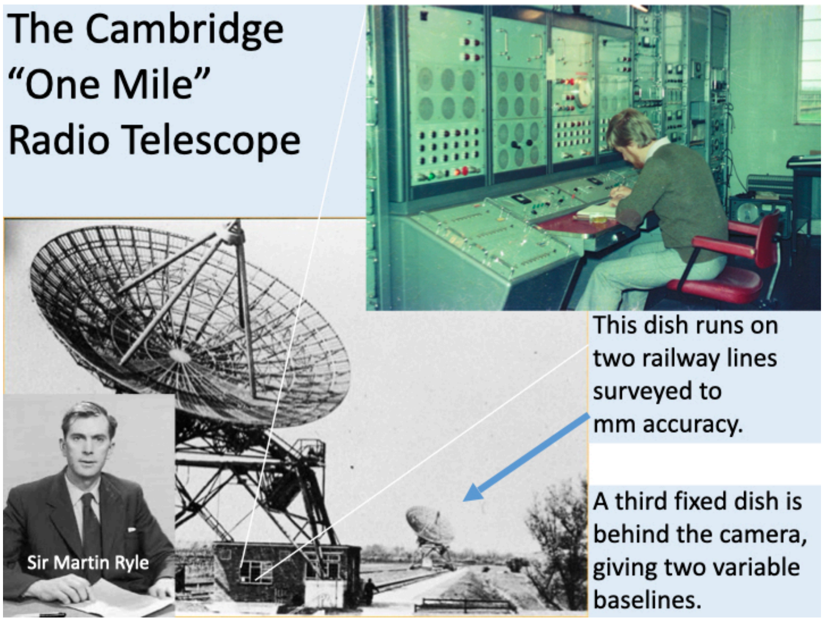
We must make many days of observations, but a big single dish with its narrow beam, would have to scan the sky - **so no loss of time**. (Less sensitivity.)

Technically *very* difficult in the 1960s
- High precision positioning, very stable electronics, complicated software (including new *Fast* Fourier Transform) and the latest, fastest computers.

The idea had been in the air for at least a decade - and in principle appreciated by astronomers at a number of observatories.

In fact, it is technically very difficult. You need to know the exact positions of all the receiving aerials (within 1/20 wavelength i.e. millimetres), you must have very well calibrated radio receivers and you also need to timestamp the radio signals to within a few milliseconds.

One American astronomer recalls explaining how it could all work to Sir Martin Ryle - only finding out later that one of Ryle’s own research students, and my own research supervisor, Peter Scheuer, had worked out the detailed maths in his PhD thesis and there was already a full engineering design which he wanted to get built before the Americans piled in with their massive funding.



The Cambridge "One Mile" Radio Telescope

This dish runs on two railway lines surveyed to mm accuracy.

A third fixed dish is behind the camera, giving two variable baselines.

All the practical and seriously challenging technical problems of "aperture synthesis" interferometry were solved by Martin Ryle, who later received the Nobel Prize for developing this technique – which had an enormous impact on astronomy - it completely changed our picture of the universe.

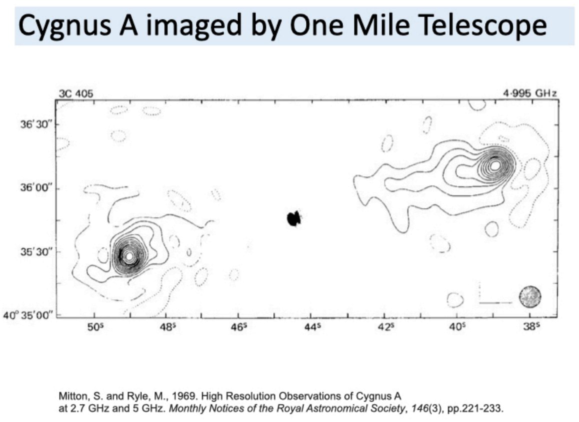
This was the first imaging radio telescope with a resolution better than the human eye.
The unique thing about this telescope was that it was the first that really produced images on a reliable regular basis.
It was also the telescope that I used to operate as a research student.

This physical telescope is one thing - but it was a new computer algorithm that actually made it possible to handle 24 hours of data in less than 24 hours: the *Fast Fourier Transform*, first published in 1965. Martin Ryle always used to emphasise that the main limitation on the power of radio telescopes was the available computing capacity - and it was the vast increase in capacity produced by the FFT which allowed the OMT to work successfully.

The OMT operated from1964-1990 and was important in many major astronomical discoveries because it showed optical astronomers exactly where they had to look to relate radio sources to optical objects, and the most important discoveries (such as the nature of quasars) needed input from many different wavebands.

It was the first radio telescope specifically targeted at understanding the physic processes of radio sources by revealing their structure.

Slide 33:



Cygnus A imaged by One Mile Telescope

Mitton, S. and Ryle, M., 1969. High Resolution Observations of Cygnus A at 2.7 GHz and 5 GHz. *Monthly Notices of the Royal Astronomical Society*, *146*(3), pp.221-233.

So now we can make images of radio sources showing structure.

When you are commissioning a new radio telescope there are three objects that you nearly always look at first: Cassiopeia A (which I have shown you – the brightest source in the sky) and this Cygnus A, the second brightest source.

By the time this image was made we knew that from previous (non-imaging) observations:

- That it consisted of two extended sources of emission;
- That there was a peculiar galaxy half way between them;
- That it was a very long way away (500 million light years) so had to be very, very luminous.

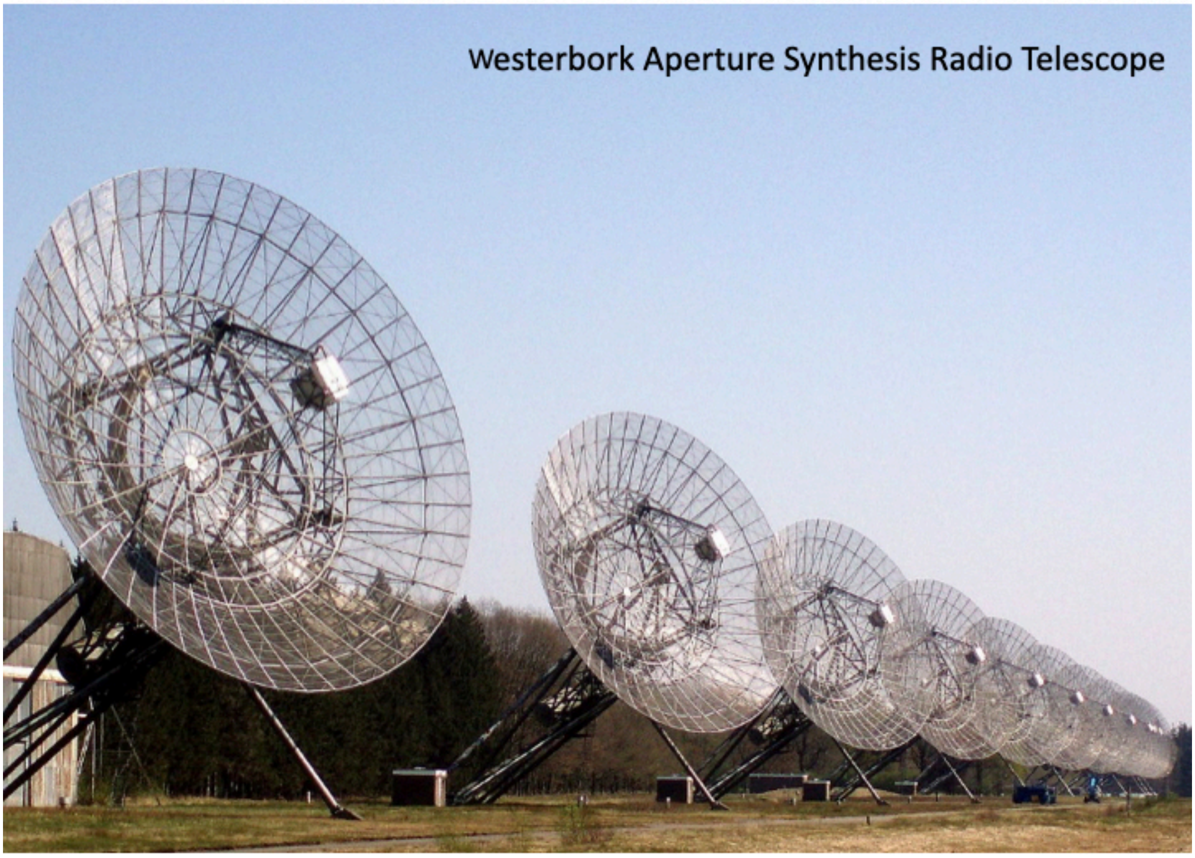
In fact, more radio power is being emitted than the sum total of light from all the stars in a typical galaxy.

Three important results came from this image:

- There was a central source coincident with an active galaxy;
- The double radio source structure was clear – with a concentration towards the outer edge;
- There was extended emission between the outer lobes.

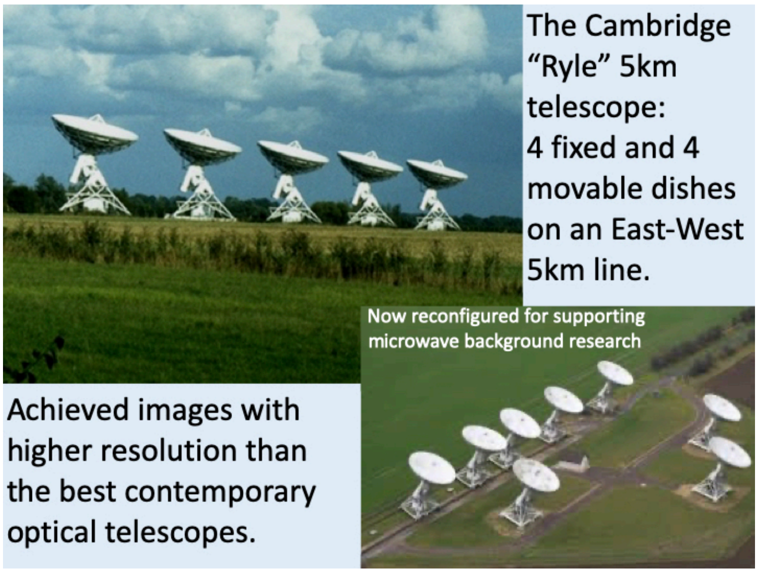
This tells us a lot about the physics.

Slide 34



Our main rivals at this time were the Dutch astronomers at Westerbork, who followed the OMT with this 3km synthesis array. (In fact my PhD examiner was one of the leading astronomers from this observatory.)

Slide 35



The Cambridge “Ryle” 5km telescope:
4 fixed and 4 movable dishes on an East-West 5km line.

Now reconfigured for supporting microwave background research

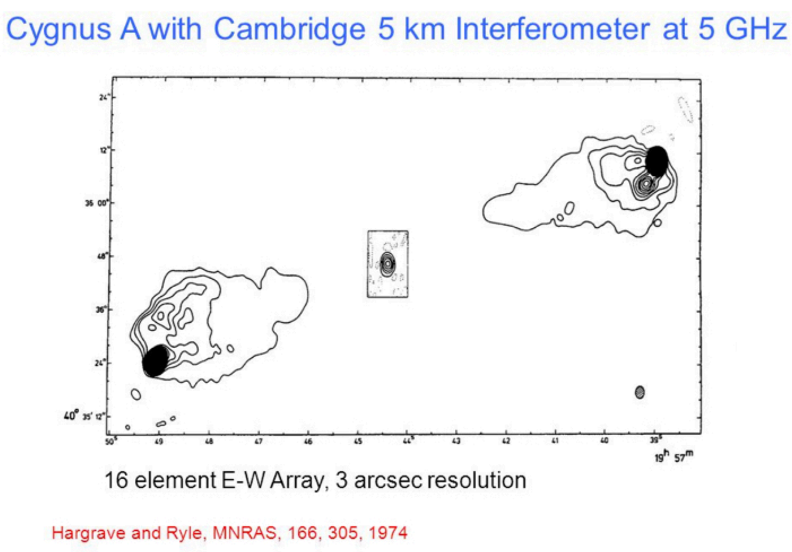
Achieved images with higher resolution than the best contemporary optical telescopes.

The One Mile Telescope was followed by the 5km Telescope (later known as the Ryle Telescope) which operated from 1971-2004.

With four fixed dishes and four movable dishes we could record 4x4 = 16 interferometer baselines at once, which meant that we could build up images eight times as quickly as with the OMT.

It was observations from this instrument that I used for my own PhD - though research students were not allowed on the controls! In fact this was the start of a trend separating the operation of telescopes from the people who used them for research. Most big telescopes are now complex facilities operated by specialist technicians. The research astronomers just draw up tables of observations to be performed.

Slide 36



Cygnus A with Cambridge 5 km Interferometer at 5 GHz

16 element E-W Array, 3 arcsec resolution

Hargrave and Ryle, MNRAS, 166, 305, 1974

Cygnus A was again one of the first object to be observed with the 5K telescope.

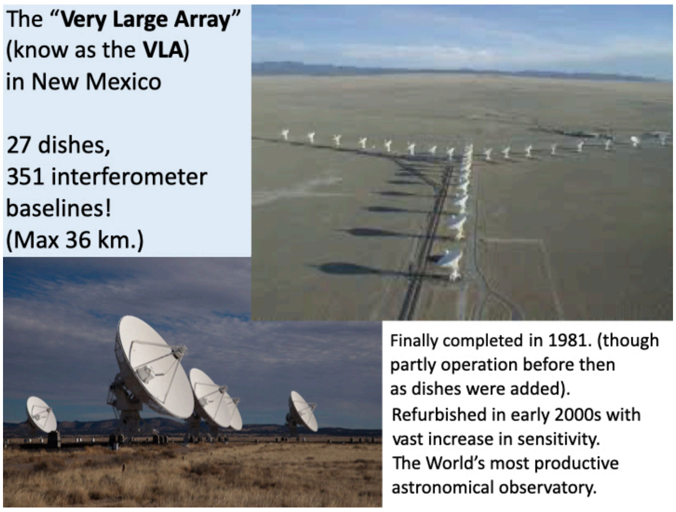
My research supervisor, Malcolm Longair and Martin Ryle has proposed about this time that something in the heart of the central galaxy was throwing jets of relativistic plasma out in to the intergalactic medium: my PhD project was developing the this theory and providing supporting evidence using the 5k telescope.

What can we deduce from this data?

The intense emission from the two “hot spots” can only be produced by electrons that loose their energy in about 10,000 years. The light travel time from the galaxy in the centre is about 250,000 years, so something must be accelerating electrons in these outer lobes.

We can now say a lot about the energetics: the least amount of energy in electrons and magnetic fields is equivalent to the mass-energy of about 1,000,000 Suns. We know of no process that efficiently converts mass into a radio emitting plasma, and have lots of reasons to think that we are seeing the effect of only part of the energy used in creating this object, so already we know that something is going on that involves a fair fraction of the total mass of a typical galaxy.

Slide 37



The “**Very Large Array**”
(know as the **VLA**)
in New Mexico

27 dishes,
351 interferometer
baselines!
(Max 36 km.)

Finally completed in 1981. (though
partly operation before then
as dishes were added).
Refurbished in early 2000s with
vast increase in sensitivity.
The World’s most productive
astronomical observatory.

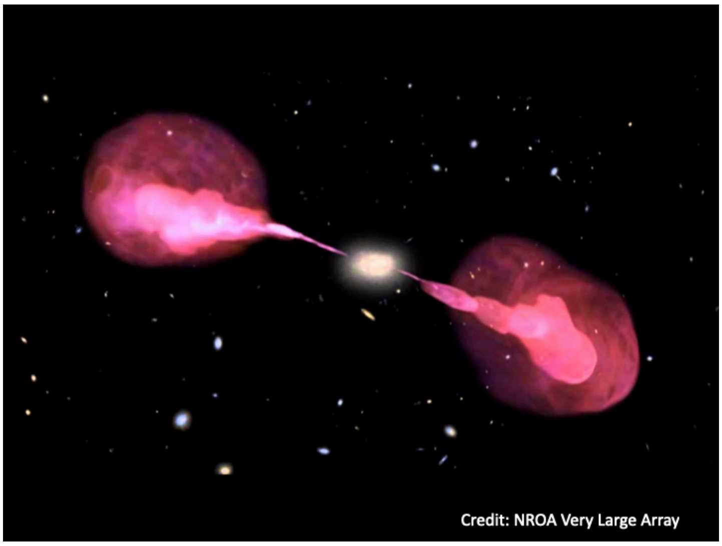
After this, things moved quickly and the Americans, who were late in this game, came up with big money – and lots of space – for the “Very Large Array”, using essentially the same technology as the Cambridge telescopes, just on a much larger scale.

36km Baseline – with 27 dishes you can potentially get many more simultaneous baselines (351) so it is possible to build up a detailed image of the source in only four hours of observations.

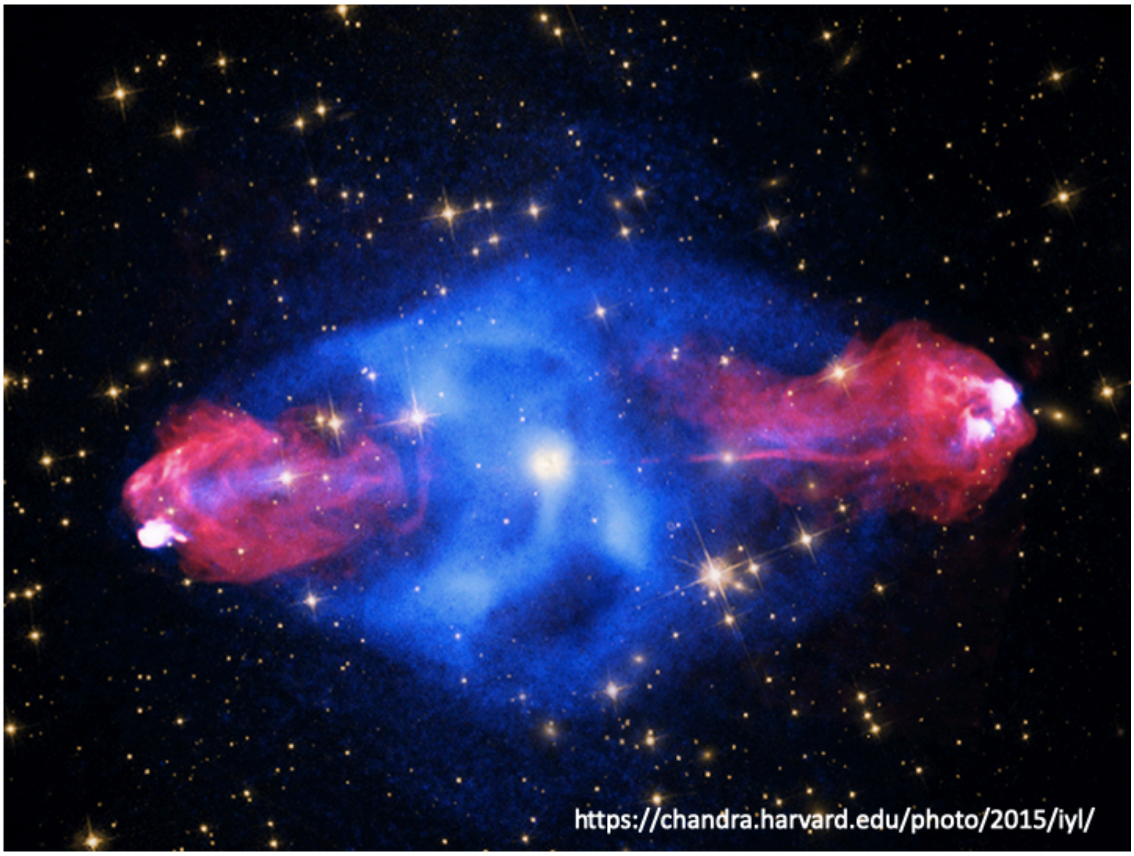
However, in the early days they underestimated the amount of computing power they required and for the first few years it could only observe at reduced capacity.

This instrument, now reconfigured with much more sensitive digital receivers and very much more sophisticated software is still the state of the art. (Modern digital received are about 100 million times as sensitive as the ones I once used!)

Slide 38


Credit: NROA Very Large Array

"Hercules A"



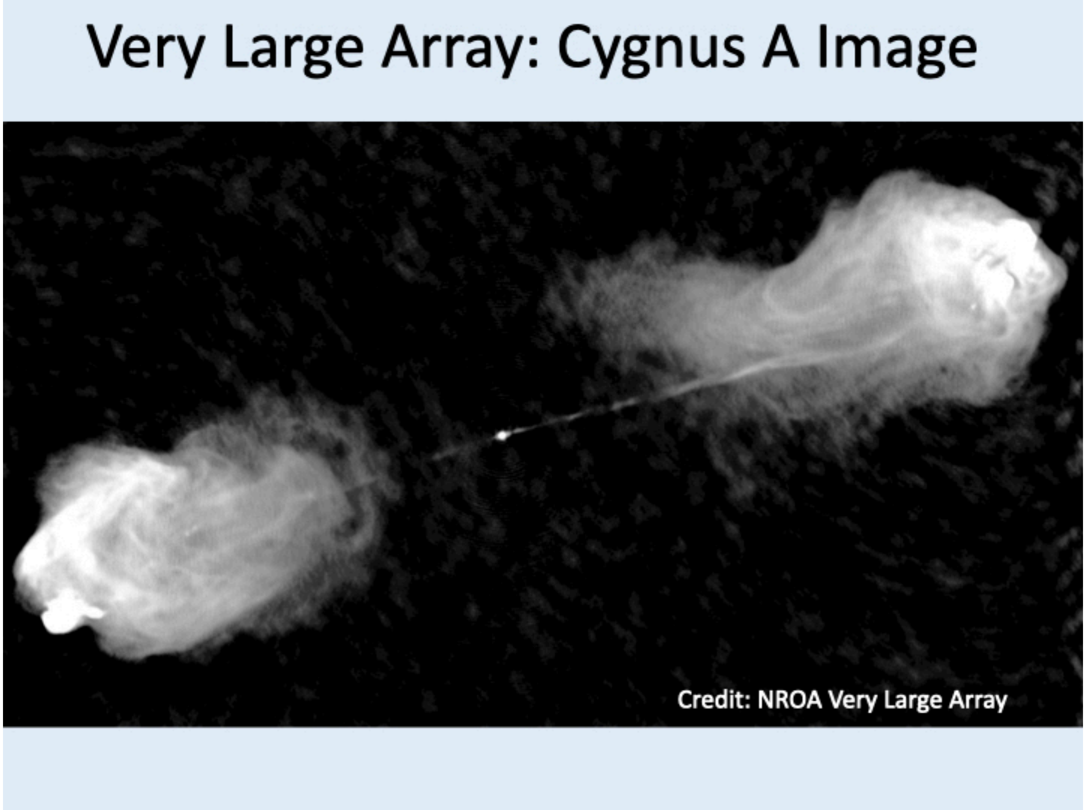
https://chandra.harvard.edu/photo/2015/iyl/

Multi-wave length image of Cygnus A – “Chandra” X-ray superimposed on radio.

This shows the ultra-hot gas filling the cavity in the inter-galactic medium which has been excavated by the jets.

It is also telling us something important about the evolution of galaxies. Most of the hydrogen in the universe is still between the galaxies, though it has a tendency to fall into them. In the galaxies that have super-massive black holes, as soon as you start to get significant in fall, the AGN switches on and this type of phenomenon heats up the surrounding gas and cuts off the fuel supply. This is probably the mechanism that limits the maximum size of galaxies.

SLide 40



Very Large Array: Cygnus A Image

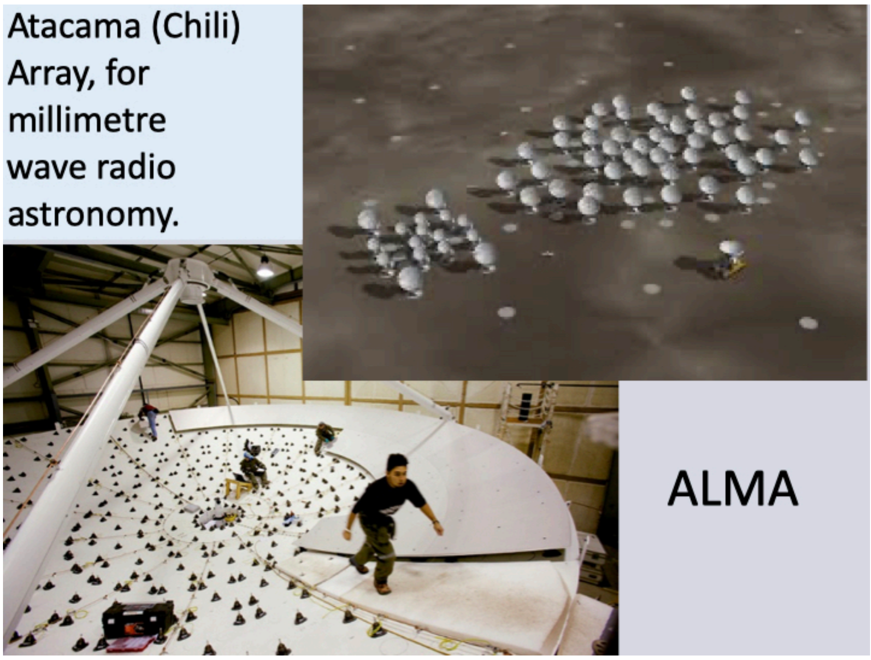
Credit: NROA Very Large Array

Now it is clear: there is a “jet” travelling from the nucleus to the outer lobes.

This had been deduced by Martin Ryle, Malcolm Longair and my own research supervisor Peter Scheuer back in the early 1970s from the analysis of the Cambridge data. (My own PhD was mainly concerned with developing the evidence for this explanation.)

Here, the evidence was irrefutable.

Slide 41


Atacama (Chili) Array, for millimetre wave radio astronomy.

ALMA

The most recent synthesis radio telescope to come into operation is the Atacama array. (And also the most expensive ground-based telescope ever built - so funded as an international project.)

Notice that there are many more dishes and they seem to be placed in random locations rather than regularly spaced arrays. You can use large numbers of dishes and get lots and lots of baselines because of digital electronics and vast increases in computing power.
None of this business of dividing up analogue signals and having to bury miles of coax in the ground – it is all done with digital delays – and we can get virtually instantaneous images – almost like having a telescope eyepiece.

One of the major targets of this telescope is understanding the process of star and planet formation. It is particularly well adapted to this because it can observe at mm wavelengths, where there are many spectral line.

Slide 41

The big frustration of optical astronomers is that all the really interesting aspect of star formation occur behind a cloud of dust.

Although we can penetrate the dust using far infrared observations, these do not always tell us as much as we want to know about the movements of gas. Nor do they have the prospect of extremely fine resolution that would, for example, allow us to study an proto-star accretion disk as it starts to make planets.

That is a primary target of Atacama.

Slide 42

Orion Nebula imaged With Alma

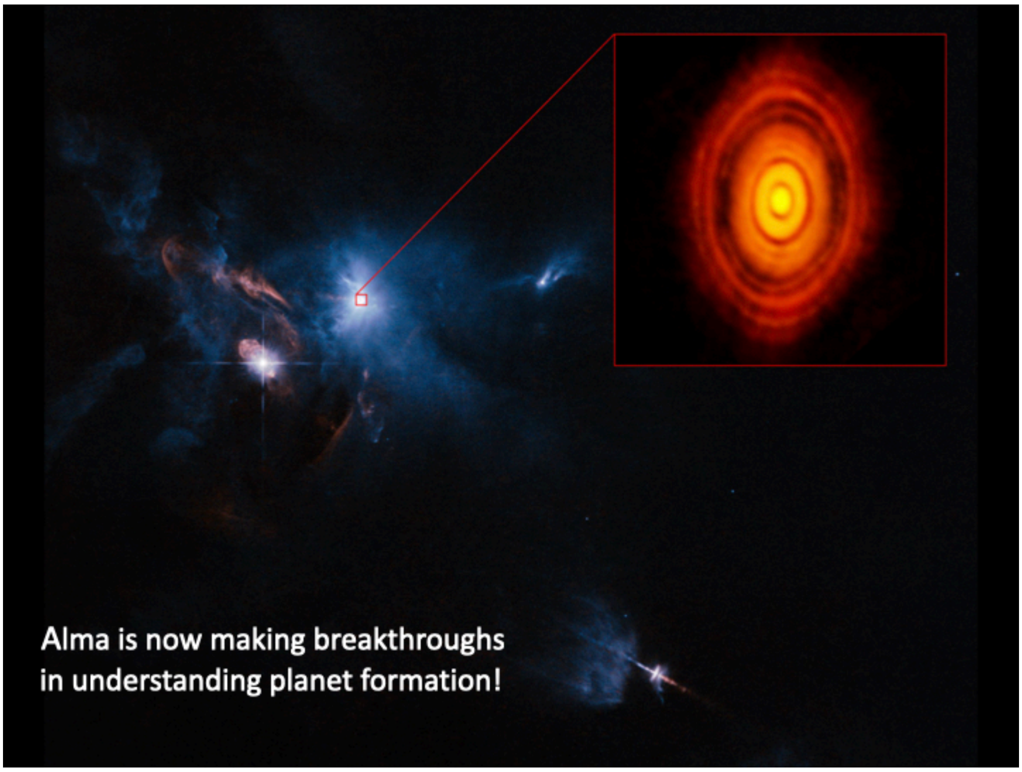
Possibly the result of a very close encounter between two protostars.

Credit: ALMA (ESO/NAOJ/NRAO), J. Bally/H. Drass et al.

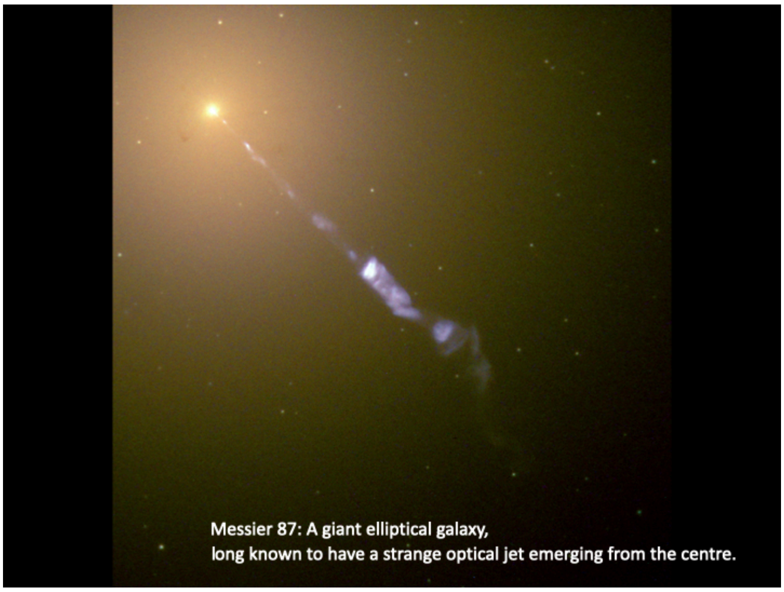
Alma is able to identify the emission lines of carbon monoxide and so tell from Doppler shifting which streams of gas are approaching and which are receding.

This is a whole area of radio astronomy where amazing work is currently being published – a whole talk could be given just about this area.

SLide 44



Alma is now making breakthroughs in understanding planet formation!

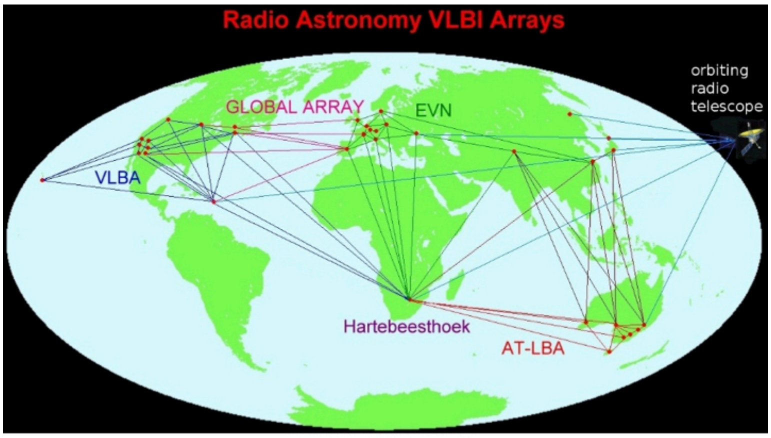


Messier 87: A giant elliptical galaxy,
long known to have a strange optical jet emerging from the centre.

Let’s go back to our extragalactic sources.

We still cannot see what is going on down in the centre of the galaxy in sufficient detail.

Slide 46



We get higher resolution by going the shorter wavelength or using bigger separations. With VLBI with use the diameter of the Earth to maximise the resolution, and improvements in technology mean we can also go the shorter wavelengths at the same time.

This allows us to peer down in the details of accretion disk around black holes, for example, with resolution of 1/1000" arc.

It is an exceptionally difficult technology, involving careful time-stamping of observations with atomic clock time signatures. We still need to know the absolute positions of telescopes to within a few mm, even though they are separated by the diameter of the Earth, so we can do the path compensation properly. Conventional surveying techniques are way too inaccurate - for a start, Continental Drift keeps changing the separations.

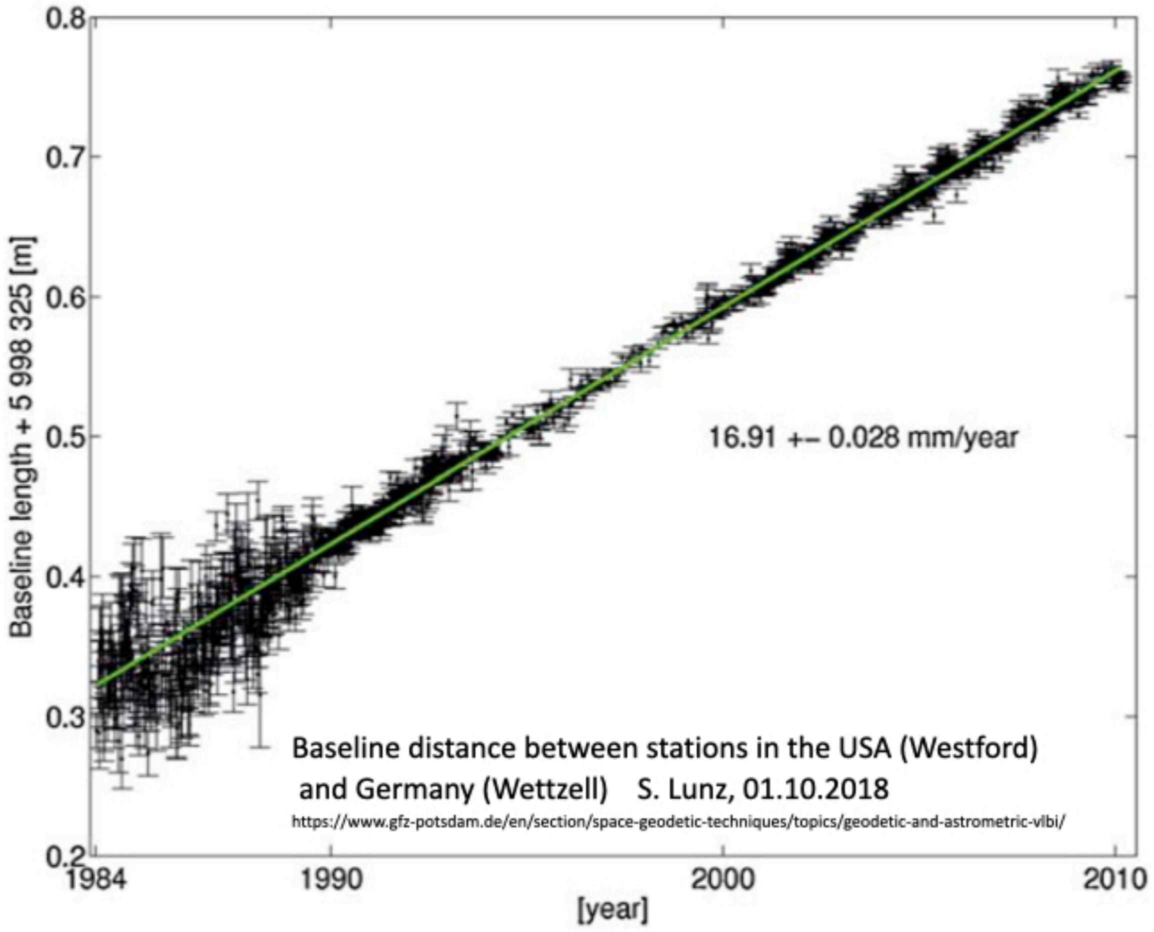
We pull ourselves up by our bootstraps.

If we know that we are looking at a very distant **point** source, we can work backwards to get the exact positions of aerials. This is currently the most accurate way to work out the shape of the Earth and the movement of the continents – in fact it is now the ultimate basis of all Earth-surface coordinate systems.

Once we have fixed the aerial positions we can go forwards looking at the source we think we should be able to resolve.

Actually, we still have a problem: we still need amplitudes and phases to reconstruct images and we don't have good phases because different atmospheric paths delay the signals by unknown amounts over each telescope.

However, if we pour a huge amount of computing power into the analysis we can use some of our prior knowledge about the sky to make good guesses at the missing data. For example, the emission from the sky is always positive and in general it is fairly smoothly distributed, using with the radio power concentrated in the minimum area. In practice, we now know that the "maximum likelihood" solutions that satisfy these constrains are overwhelmingly likely to be very close to the real brightness distribution. However, the astronomers who interpret the data need to have a deep understanding of the type of errors that may occur in this process so that they do not over interpret the evidence, because there is a risk that you are over-fitting the data to match your expectations.



16.91 +– 0.028 mm/year

Baseline distance between stations in the USA (Westford) and Germany (Wettzell) S. Lunz, 01.10.2018

https://www.gfz-potsdam.de/en/section/space-geodetic-techniques/topics/geodetic-and-astrometric-vlbi/

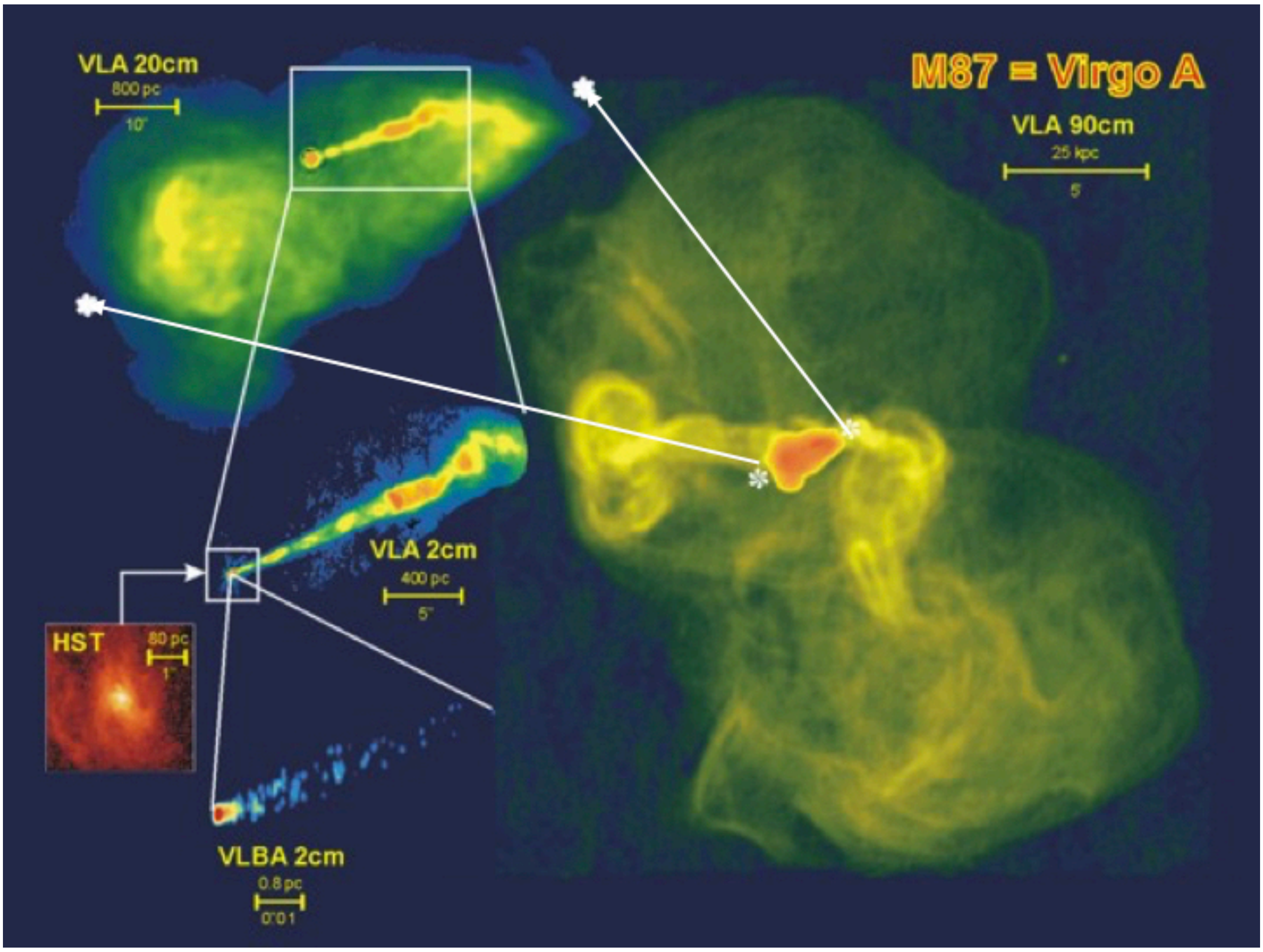
Here, for example is an example of a graph showing the separate of two VLBI dishes measured over three decades, showing the effect of continental drift.

You may think that we could do this with GPS, so what. However, it is this type of VLBI measurement that helps to define the frame of reference which is fed back to the GPS satellites. So, next time you use GPS in your car, bear in mind that ultimately its accuracy depends on radio astronomy observations of a group of very distance quasars.

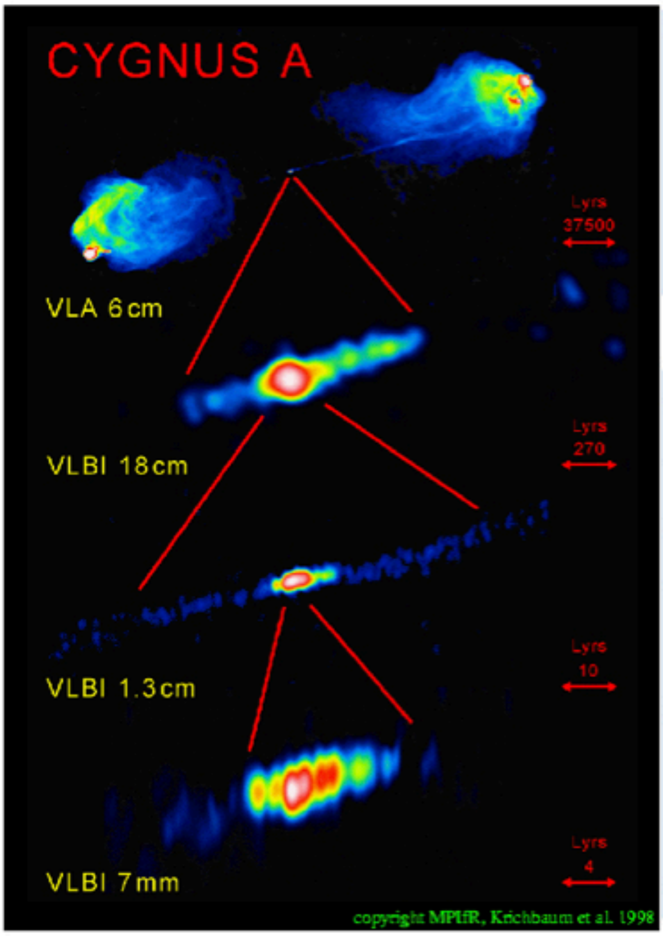
Some of this work is funded by the US Naval research office, and because accurate navigation has always been a concern of navies - back to the appointment of the UK Astronomer Royal.

It is not so widely advertised that this type of accuracy is now essential to the US Navy so they can guide ICBMs to their targets. Once above the atmosphere they navigate by the stars so you need to tie together astronomical and geographical coordinate systems very well indeed.

Slide 48:



Here is an example of how we can now zoom in on the centre of the M87 with VLBI.

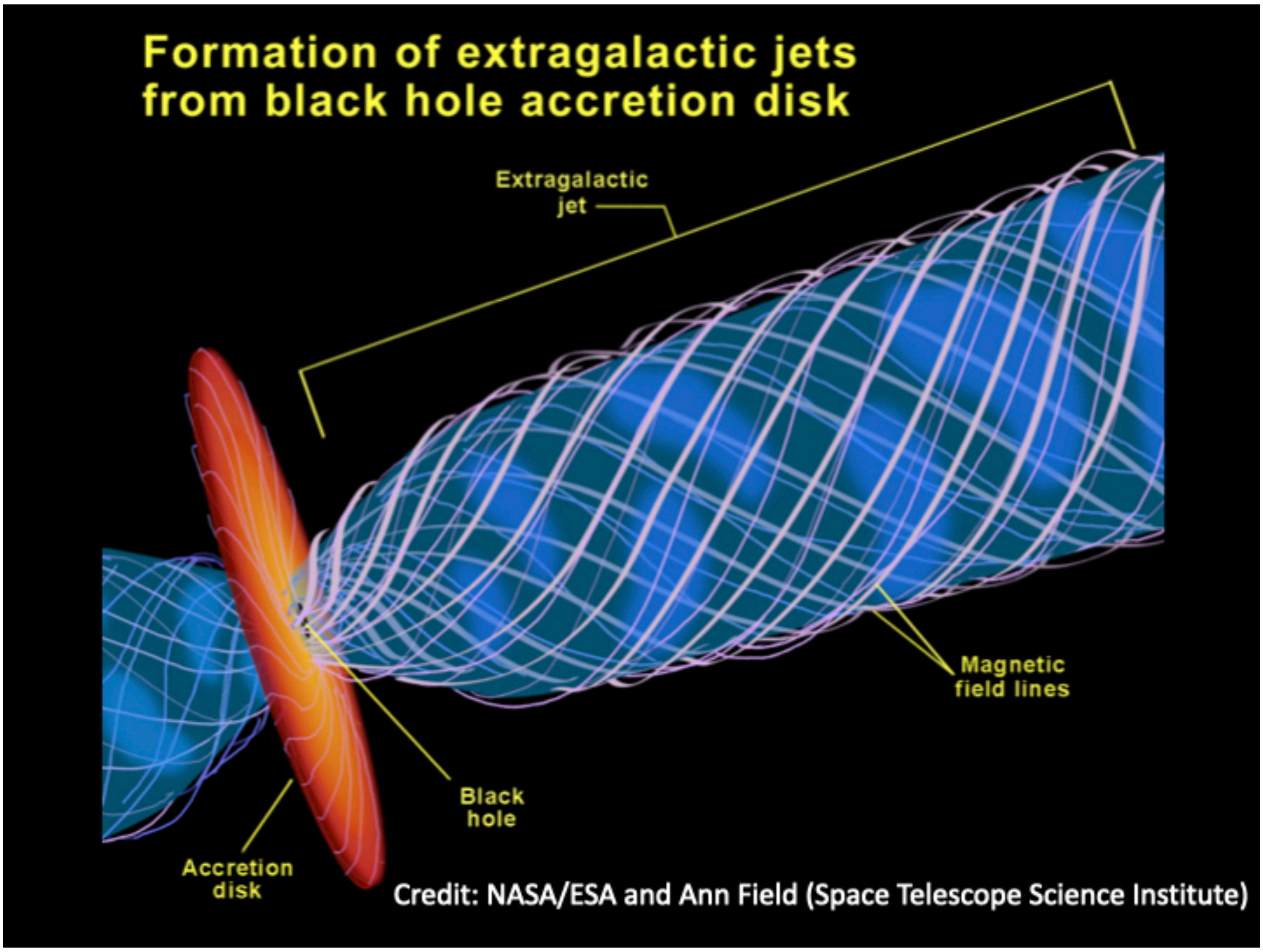


copyright MPIfR, Krichbaum et al. 1998

VLBI resolution Is measured in 1/1000 arc-secs!

Still not enough to see the details of physical processes around the event horizon of supermassive black-holes. Light variations on ~days in some cases means energy release is concentrated in volumes comparable to the scale of our Solar System

Slide 50



Formation of extragalactic jets from black hole accretion disk

Credit: NASA/ESA and Ann Field (Space Telescope Science Institute)

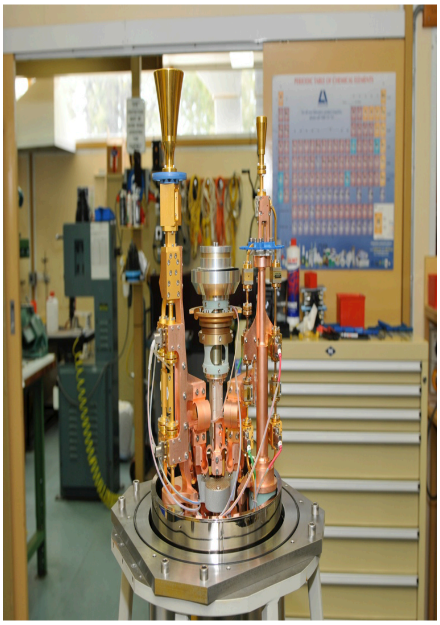
So here we are back at M87. For this thousandth of a second of arc is not good enough we need to be 100 times better. Since the size of the Earth is fixed we need to get better resolution by working with VLBI at mm wavelengths.

The technical problems are formidable.

We now need to work out positions of all our radio telescope - each capable of observing at wavelengths of 1mm to 1/20 of a mm over the width of the Earth.

The Event Horizon Telescope

2017: The the shadow of a black hole



Modern receivers are exercises in Olympic standard plumbing - all cooled to liquid helium temperatures with an integrated refrigerator.

The active electronic elements are microscopic bits of exotic superconductor working with high quantum efficiencies.

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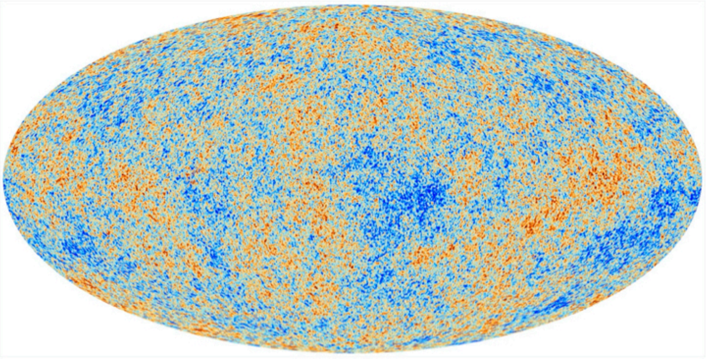

The Microwave Background
(Plank Satellite measurements)

Image Credit: European Space Agency, Plank Collaboration

What of the future?

This is the furthest we can look with astronomy, back to the last scattering surface at which radiation and matter become decoupled in the early universe. We are seeing it as it was about 300,000 years after the big bang.

At this stage the Universe is very, very uniform. (The intensity variations shown on the map are tiny!)

After this, electrons and protons and alpha particles combine into hydrogen and helium, and everything goes dark, for several hundred million years, until the galaxies start to form and the first stars light up.

There are many important questions in cosmology that cannot be answered unless we get a handle on galaxy formation - issues related to dark matter and dark energy. We would really like to see how the neutral hydrogen is moving as it condenses into galaxies, and we would like to know when those supermassive black holes form.

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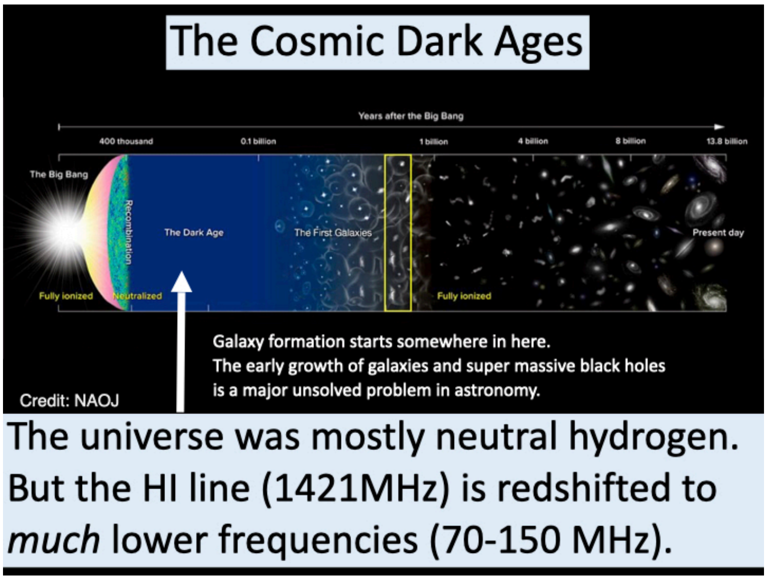

The Cosmic Dark Ages

Galaxy formation starts somewhere in here.
The early growth of galaxies and super massive black holes is a major unsolved problem in astronomy.

Credit: NAOJ

The universe was mostly neutral hydrogen. But the HI line (1421MHz) is redshifted to *much* lower frequencies (70-150 MHz).

One of the biggest unresolved questions in astronomy is how do the first stars and galaxies form.

At the start of the dark ages the universe is very uniform, at the end it is very lumpy. How does this come about? ~300,000 year to about 1 Gy.

The only way we have of addressing this issues is observing the neutral hydrogen line, which emits at 1421Mhz – but in this time zone would be red-shifted from anything between 142 MHz to 14 Mhz.

We need very high sensitivity and very high resolution, and that implies we need to largest and most complex radio telescope ever conceived.

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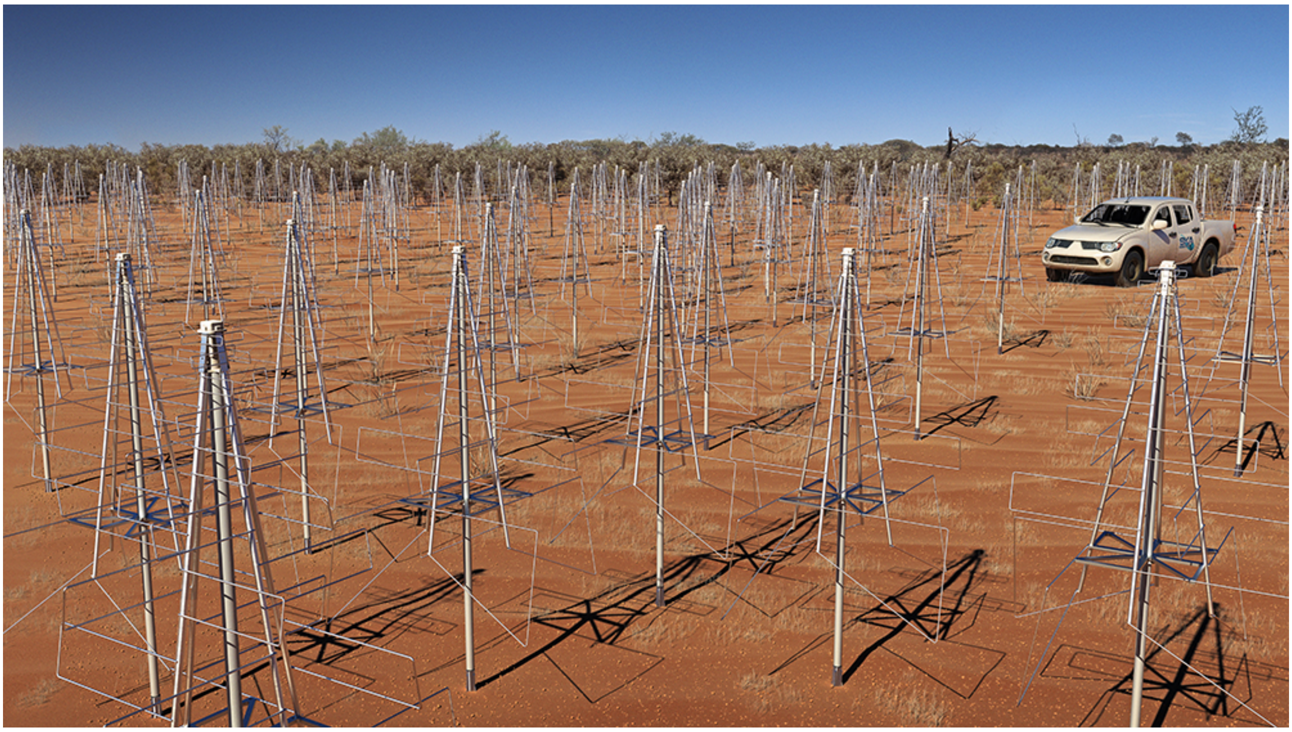
This is an artists impression of part of the proposed Square Kilometre Array, which will be the most complex telescope ever built.

It will work on frequencies from 70MHz up to many GigaHz, using a variety of aerials, on two continents, Africa and Australia. Note that the aerials will be individually relatively simple and cheap.



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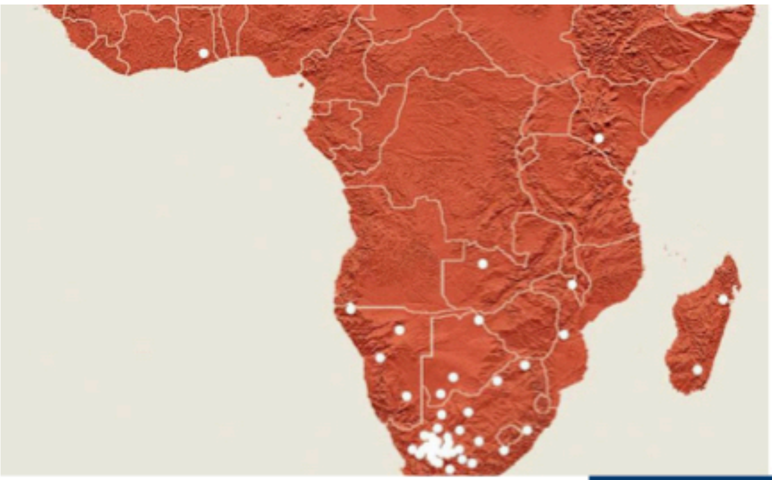
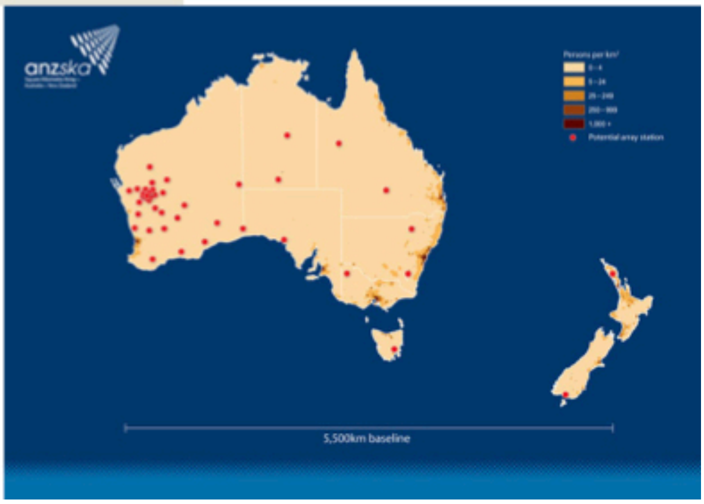
SKA Sites





skatelescope.org

Data will be collected over the whole range of frequencies simultaneously and over a very broad angle. That means that the rate at which data is acquired is beyond any other scientific instrument ever built. (The designers measure it in Internets – the total data transfer rate of the entire Internet.)

This continues a trend in Big Data Astronomy, where the real complexity of the design is in the software as much as the hardware.

My advice to younger members of the audience wishing to be astronomers is become very, very good at computing, because discoveries will be made by mining data as much as by looking directly at the latest observational data.

I am certain that it will revolutionise astronomy yet again, because it will also be able to image the finest detail of star formation, the physics of pulsars, as well as some of the largest and faintest structures in the Universe. Good Hunting!

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A taste of what is to come: The Galactic Centre

Imaged by the MeerKAT Array in South Africa

Field width is 2° (1000 by 500 light years)

MeerKat is a precursor of the SKA, but is now doing science operations in its own right.

The 64 dishes provide 2,000 unique antenna pairs, far more than any comparable telescope, resulting in high-fidelity images of the radio sky.

“This image is remarkable”, says Farhad Yusef-Zadeh of Northwestern University in Evanston, Illinois, one of the world’s leading experts on the mysterious filamentary structures present near the central black hole but nowhere else in the Milky Way. These long and narrow magnetised filaments were discovered in the 1980s using the Very Large Array (VLA) radio telescope in New Mexico, but their origin has remained a mystery. “The MeerKAT image has such clarity”, continues Yusef-Zadeh, “it shows so many features never before seen, including compact sources associated with some of the filaments, that it could provide the key to cracking the code and solve this three-decade riddle”.