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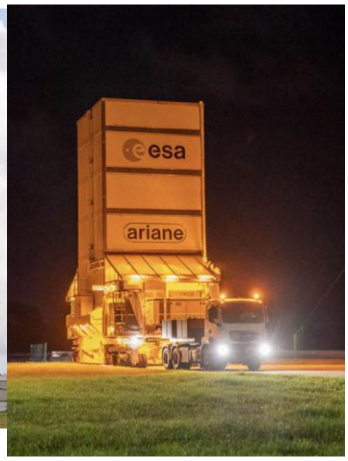
The James Webb Space Telescope, preparation for launch photography

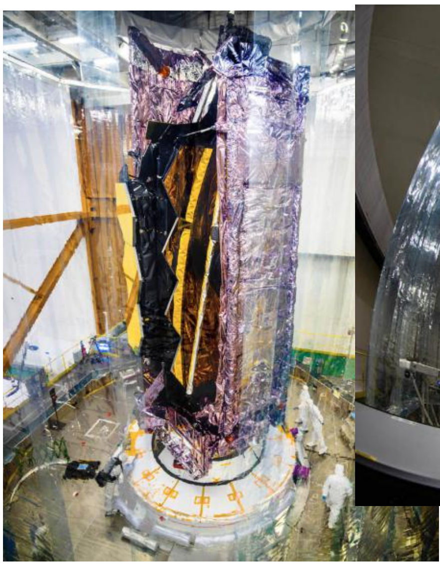
The James Webb Space Telescope is transported from Northrop Grumman to the ship. The arrival of the JWST in French Guiana in October 2021, after travelling through the Panama Canal, aboard the MN Colibri. After unloading it was transported to Guiana Space Centre. The JWST enters the Cleanroom Airlock and the container is opened. All photographs from the NASA JWST site.

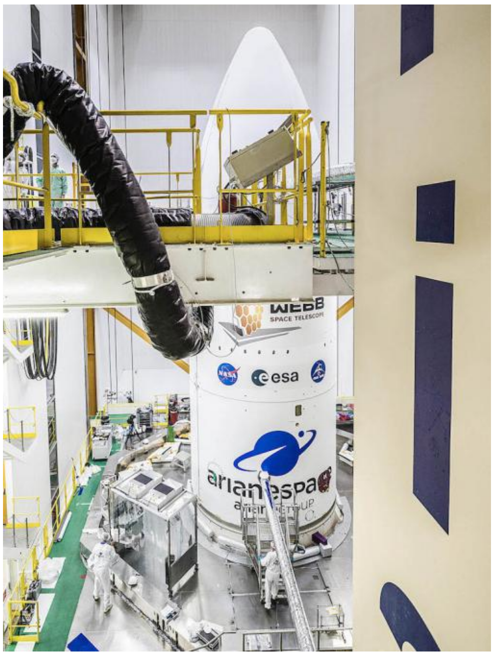



CONTENTS



The James Webb Space Telescope in the Cleanroom at the Launch Site is inspected and lifted upright. The Webb's Ariane 5 core stage made ready and the Ariane 5 gains an upper stage. The Ariane 5 is moved to meet JWSP. The James Webb is moved to meet its rocket.
Below, The Webb Placed on top of Ariane 5. James Webb Space Telescope on Launcher. The Webb is encapsulated in its rocket fairing.





The rocket fairing is slowly lowered down around the Webb as it's encapsulated and the James Webb Space Telescope hidden from view and air conditioning hoses are attached. Prelaunch of Ariane 5 with James Webb Space Telescope and Ariane 5 rollout with James Webb Space Telescope. At the launch site.

Below. Launch teams monitor the countdown to the launch of Arianespace's Ariane 5 rocket carrying NASA's James Webb Space Telescope. 25 December, Christmas day launch of the James Webb Space Telescope.

The James Webb Space Telescope in Operation

By Ivor Clarke

So by now everyone will have uncrossed their fingers as the JWST is safely in its L2 orbit about a million miles away and still cooling down before the final alinement of its mirrors so that the scientific work can begin. The launch on Christmas day was a text-book launch and was so precise that the amount of propellant still aboard should last up to ten years. It may have looked a bit strange when you think about it, that it took off going in the wrong direction! The Ariane 5 launched towards the sun, then when it had cleared the atmosphere, turned east and dived past the Earth gaining extra speed as well as the 1,000 mph it had from an equatorial launch position out towards the Moon and the L2 halo area.

There was a lot of discussion about whether there should have been cameras on board to show the unreeling of the sunshield and the other parts in the light. There was no point putting cameras on the mirror side as that was in total darkness with only starlight and planets illuminating it. As the Ariane 5 took off a couple of days before last quarter Moon that wouldn't have helped as the Webb shot past the Moon's orbit in just over a day and the unfolding happened later. But it would have been great to watch the sunshield unreeling and the tensing as this was the missions first critical deployment. NASA has in the past been reluctant to put cameras on missions, even the one on Juno currently going around Jupiter was an afterthought. The landing of Perseverance on Mars was a thrilling sight and showed what can be done with todays tiny lightweight cameras.

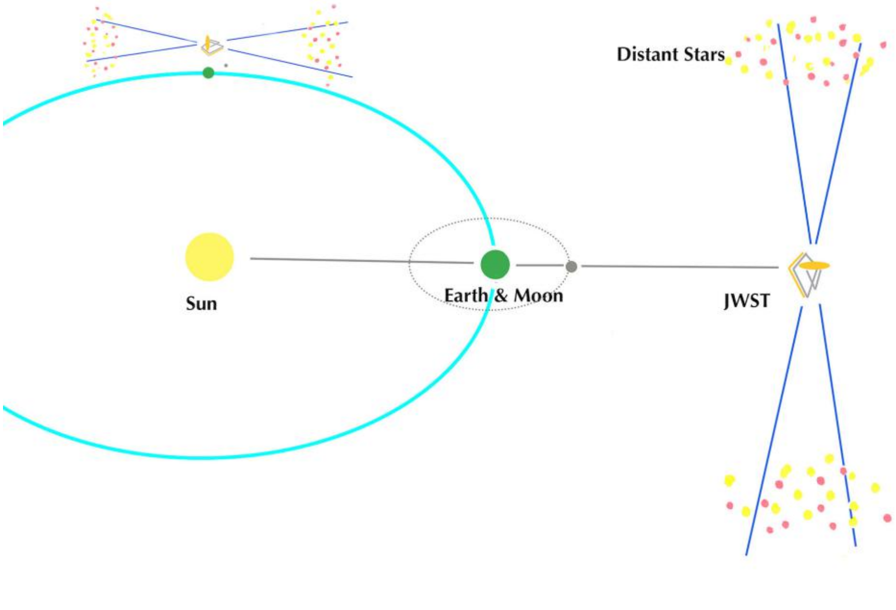
At all times from the deployment of the sunshield the telescope must keep the sunshield perpendicular to the sun so that no part of the telescope structure ever catches the rays of the sun and remains in shadow. All the mirror segments were moved from their launch positions 12.5mm into their alinement positions and as they cool down towards the target temperature of 37° - 39° kelvins they will be alined. This process of alignment will take several months before it's complete. Photographs of single stars will be made and the18 individual images will slowly be corrected and moved into one to make the final image.

Now that it's arrived in the L2 Lagrange area it will require very little fuel to maintain its elliptical orbit around this point, which is a little smaller than the Moon's orbit around Earth, but will take Webb 6 months to complete. If objects are placed or drift into these points, they will not be stable in the long term and objects will drift away into their own orbits. Only the L4 and L5 Lagrange Points are stable and have objects in them. This is why L1, L2 and L3 don't "collect" objects like L4 and L5 do. All the while it will be in full sunlight and not pass through the shadows of either Earth or the Moon.

The JWST cannot point to anywhere it likes in the sky like Hubble can. The Hubble telescope can point anywhere in the sky which is away from the sun, so if anything suddenly appears, like nova, comet outbursts or planet clouds it is nearly always possible to get Hubble to observe it. Not so with the Webb. The telescope assemble mounted above the sunshield is fixed in one position and needs to stay cold, no more than 50°K, this means the Webb must ALWAYS keep the mirror assembly in complete darkness, not a ray of sunlight must touch any part of it or it will require time to cool down again. What this means is that the JWST can see about 39% of the sky at any one time. It will take 6 months before the whole sky is accessed as the Earth moves along its orbit.

In more technical terms, the observatory has to remain in the range of 85 degrees to 135 degrees with respect to the plane of the ecliptic, to keep the telescope behind the 70 foot sunshield. The region Webb can observe is a large torus on the sky that moves about 1 degree per day in ecliptic longitude, following the telescope in its path around the sun. The telescope can rock about 5°degrees side to side and between 5° - 45° length ways. It can also spin 360° degrees giving full access to a large area of sky all round 90° from the sun. All objects outside of this area must wait until they become visible to the telescope and maybe having to wait for months until the Earths orbit drags the JWST into a viewing position.

The next few months will be fine tuning and calibrating the optics and instruments, with everyone waiting for the first views of the universe in inferred.



In three months time the JWST will be at 90 degrees around the orbit of Earth seeing a new area of the sky. It will take nearly 6 months to observe the entire sky

Trying to understand the Early Stages of the Universe

By Paritosh Maulik

The Universe formed about 13.8 billion years ago but it is not easy to get images from such early days of the universe. Galaxies in the Hubble Ultra Deep Field image are about 1 billion years old and the James Webb Space Telescope is expected to image from about 100 million years. In the meantime we can get some information about the early Universe from special radio telescopes. These telescopes are not like conventional radio telescopes such as the parabolic dish at Jodrell Bank radio telescope. Instead these are more a radio antenna, rather than a telescope. Here we shall discuss some results from an experiment to study the early stages of the Universe as seen by one of these "new" telescopes.

Introduction

Only fundamental particles like electrons, protons formed in the Big Bang, the beginning of everything. When the temperature has cooled sufficiently, protons, positively charged particles, combined with electrons, negatively charged particles, to form electrically neutral hydrogen atoms. A small amount of helium atoms also formed. On further cooling, the clouds of hydrogen atoms collapsed gravitationally to form stars. These stars formed very early; with the current technology it is not possible to see these very early stars. Instead of optical detection, astronomers use the 21cm,1420MHz radio emission from hydrogen in the early Universe to map its state.

Both protons and electrons have a special property, called spin. Spin is not as straightforward as rotation. It is a kind of a state of the nuclear constituents of hydrogen. Whenever a hydrogen atom changes its spin state, it releases or absorbs low energy radiation, 21cm in wavelength corresponding to 1420MHz in the radio range. The term Spin Temperature is a measure of the state of the hydrogen atoms. The higher the spin temperature, the higher is the fraction of hydrogen in the high energy state. This has turned out to be a very useful tool for the astronomers, to deduce the stages of the formation of the Universe by monitoring the state of hydrogen.

Before the formation of the stars, the temperature was high and the Universe was small, also the density was high. Hydrogen atoms collided with each other and with electrons of opposite spin. This chaotic process sets the spin temperature of hydrogen.

As the Universe continued to expand, hydrogen gas was cooling down. Star formation began. But there was a certain amount of hydrogen gas in between the stars which had not taken part in the star formation. This gas absorbed the Cosmic Microwave Background radiation, CMB, and moved to the excited state. This process of absorption continued for a while.

As the stars formed, they gave off ultraviolet radiation. Hydrogen gas picked up the UV radiation and its temperature increased. This increase in temperature sent the hydrogen atoms to a higher energy state. Hydrogen released the excess energy by the emission of radiation. The state of hydrogen was not linked to the CMB any more. The UV radiation also ionised hydrogen atoms into protons and electrons. The characteristic hydrogen signal ceased to exist. This is the beginning of reionisation of the Universe. (FIG 1)

This process of absorption causes a drop in the CMB temperature and can be monitored by observing the 21cm radio signal. But due to the expansion of the Universe, the signal from hydrogen does not occur at 21cm, 1420MHz frequency but at a longer wavelength due to the redshift. For example, a photon emitted after about 180 milllion years would arrive to us at 4.5m, 68MHz. A photon released after a later date, say, 180+100 milllion years would arrive at a shorter wavelength, 3.3m, 92MHz. So the astronomers monitor the intensity/flux of radio signals across a range of frequencies; the frequency gives us a measure of the time, via redshift and the intensity tells us the state of the Universe as seen by hydrogen. It is to be pointed out that the observers are not measuring the magnitude of the temperature of hydrogen, but monitoring the change of the state of hydrogen from the radio signal, either in absorption or in emission compared to that of the CMB. The CMB is the only heat source.

The Set Up

Haystack Laboratory, at MIT, and Arizona State University jointly set up an experiment called the Experiment to Detect the Global EoR (Epoch of Reionisation) Signature; EDGES. They built a VHF radio antenna set up. It looks like two metal horizontal plates separated by short distance. The structure sits over a groundplane. The groundplane is to minimise interference. (FIG2). The location of the antenna was Murchison county, Mid–West Australia; 49,500 Sq. km; population 114 (2011). It is a very quiet radio spot. A lot of other astronomical radio antennas are also in this area. The observing team built three antennas, low-band, mid-band, and high-band, covering 50–200 MHz in range. Set ups like these are relatively inexpensive. They can use a lot of off the shelf electronics.

Results

Their results (FIG3) showed a trough in the hydrogen temperature profile. Initially the hydrogen temperature was

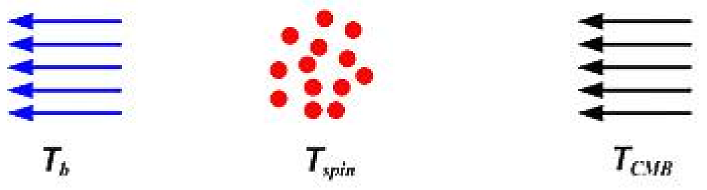


Fig 1. T_b is the hydrogen radiation temperature. T_{spin} is the hydrogen spin temperature. T_{CMB} is the cosmic background temperature. $T_{spin} = T_{CMB}$; no radiation from hydrogen. T_{spin} greater than T_{CMB}; radiation from hydrogen. T_{spin} lower than T_{CMB}, absorption.

Fig 2. EDGES experiment, antenna set up in Australia.

the same as that of the CMB; it was neither absorbing nor emitting any radiation. Then around 180 milllion years after the Big bang, hydrogen was absorbing from the CMB; the dip in the plot. The Universe was expanding, stars were forming, hydrogen which had not formed into stars had a lower temperature due to the expansion of the Universe. It was absorbing heat from the CMB. This is the birth of the first generation of stars. Then around 250 milllion years the amount of absorption decreased and around 300 milllion years or so from the Big Bang, the absorption stopped all together. Around this time, the newly formed stars were radiating UV radiation; the UV radiation ionised hydrogen and we stopped getting any signal from the hydrogen. This was the reionisation epoch of the Universe.

But there was a problem. Although the observed drop in temperature is very small, about 0.5°K, this low figure is much higher than the expected theoretical predicted drop. The EDGES team repeated the experiment over two years. They changed the location of the antennas, they looked at different regions of the sky, they changed the electronics, but the results were repeatable. A possible explanation of the observed drop was suggested as dark matter interacting with hydrogen lowering the temperature and/or some other as yet unknown phenomenon. So far these results have not been confirmed by any other group. This American group is continuing with further experiments. They would like to collect data at a still lower frequency of 20MHz. They have modified their set ups; tried various locations across the globe. Radio signals from the astronomical objects are often very feeble and are drowned by signals from other astronomical objects. Radio signal interference from Micro-meteorites is a constant problem. Then there are instrumental and man made noises. True signals have to be teased out from the raw data.

Apart from the EDGES, there are also other experiments running to get a better understanding of the early stages of the formation the Universe; Low Frequency Array (multi-site Europe), Murchison Widefield Array (Australia), Giant Metrewave Radio Telescope (India), Square Kilometre Array (Australia and South Africa) to name a few.

Conclusions

At the beginning of the beginning there were only fundamental particles. The Universe expanded; it started to cool down. Star formation started around 180 milllion years after the Big Bang from the collapsing of hydrogen gas. These are the primordial stars. It continues for about another 180 million years. By now there are sufficient stars. Newly formed stars radiated ultraviolet radiation. UV radiation ionised the remaining hydrogen gas. A new chapter in the history of the Universe, Reionisation began. Ionised hydrogen gas cannot collapse to form stars; no more primordial stars. From now on star formation would continue by recycling material from the previous generation of stars. Now we have a tentative timeline of the history of the Universe.

Sincere thanks to Mark Edwards for suggestions.

Further reading

First Light; Chapman, Emma, Bloomsbury Sigma, 2021
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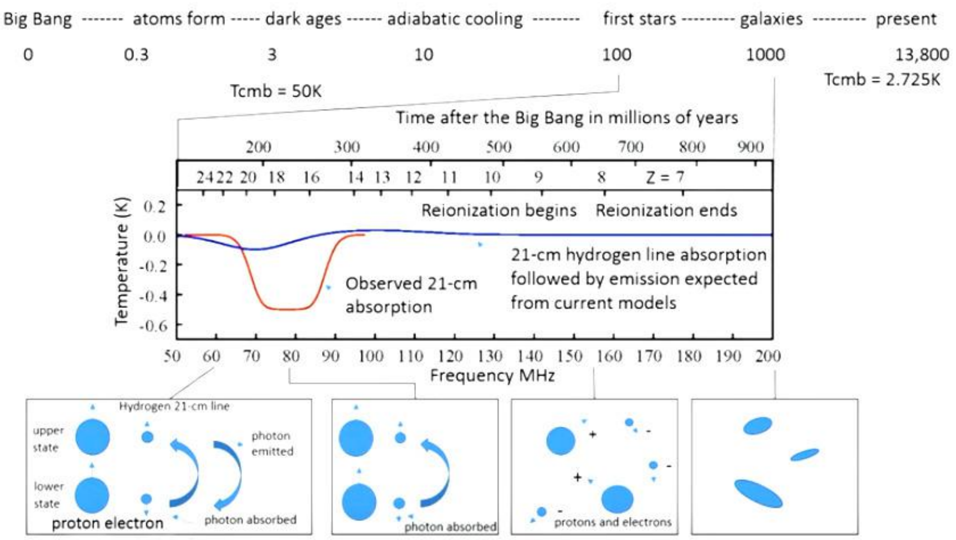


Fig 3. Result from the EDGES experiment. About 100 milllion years from the Big Bang, hydrogen temperature is lower than the CMB temperature. It absorbs CMB. The process is over by about 280 milllion years from the Big Bang. Newly formed stars ionises hydrogen gas and star formation stops. A few interesting points. When the CMB is about 3000°K, protons and electrons combine to form Hydrogen atoms. When the star formation begins, the CBM has dropped to 50°K and now it is 2.7°K. 50°K is about -223°C; solidification temperature of hydrogen is -259°C.

Rhumb Lines, Loxodromes, Great Circles and The Mercator Projection

By Mike Frost

One of my dead astronomers, Henry Beighton (1687-1743), edited a journal called *"The Ladies Diary"*, one of a number of annually published journals which competed for popular attention during the eighteenth century. *The Ladies Diary* used to feature mathematical puzzles, sometimes of complexity – Ada Lovelace published in it in later years, for example. But one puzzle might be familiar to you:

Suppose a ship set sail from the Latitude 51 deg North, and thence shape a north-west Course, and sail without interruption. Where will it at last arrive, and how many Leagues run? [Q201 from the 1738 edition]

This being the eighteenth century, there was a simple answer to the problem – sail north-west from anywhere 51 degrees north and you'll eventually hit something, probably Greenland or Siberia. It's a puzzle that had to wait for the twentieth century, and the invention of the airplane, to reach the form with which you may be more familiar with:

Suppose an airplane takes off from Coventry airport (55 degrees north) at mid-day, and flies north-west at 200 mph. Latitude lines one degree apart are separated by a distance of 69 miles. Where does the plane end up? When does it get there? How far does it fly?

The mathematics to solve this problem appears to be almost ridiculously simple. If a plane flies north-west at 200 mph then, by trigonometry, in an hour it will travel 141.2 miles west and 141.2 miles north. 141.2 miles is 141.2/69.0 or 2.05 degrees of latitude, so each hour the plane will cross two-and-a bit-lines of latitude. Coventry is 35 degrees of latitude from the North Pole, and 35.0/2.05 = 17.1.

So, after 17.1 hours, shortly after 5 AM the next day, the plane will arrive at the North Pole. During that time, it will have covered 17.1*200.0 = 3421 miles.

Simple.

And yet, and yet … the simple arithmetic conspires to hide a mind-bending paradox. How the heck does the plane manage to arrive at the North Pole? Because: however complicated the route to the pole is, surely the last step, by definition, has to be due north. *And the plane never flies due north!* It's this paradox which makes the problem so infuriating.

Think about the problem a little longer - I invite you to do so before reading on - and you might realise the resolution to the paradox. The plane does end up at the north pole, but its path there is (arguably) not physically realistic, consisting of a logarithmic spiral which winds round the pole an infinite number of times. In reality, for most of its journey, the path is straightforward. Only in the last few seconds of its journey does the flight become physically unrealistic, degenerating into a wild pirouette around the pole.

The curve described by the airplane's flight is called a Rhumb Line, or Loxodrome (Rhumb probably comes from the Spanish or Portuguese for "direction"; Loxodrome is Greek for "oblique-running"). There is a Rhumb Line corresponding to each angle of flight to a line of latitude. An angle of zero corresponds to a line of latitude (for example, the equator is a zero-angle Rhumb Line) and an angle of ninety degrees corresponds to a line of longitude. For all angles except zero, the complete Rhumb Line starts at one pole and makes its way to the other pole, in most cases spiralling infinitely around both poles.

Rhumb Lines are of course important in navigation. If the magnetic pole corresponded to the geographic pole, Rhumb Lines would be the same as compass bearings, so let's call them "true bearings" for clarity. Away from the poles, the Rhumb Line connecting two nearby points is almost the shortest path over the globe between the two points. The actual shortest route is the Great Circle, the circular arc, centred on the centre of the Earth, which connects the two points, but locally this is very close to the Rhumb Line. So, to fly from, say, Coventry to Liverpool, a true bearing of NW (45 degrees from true N) will be close to the shortest route.

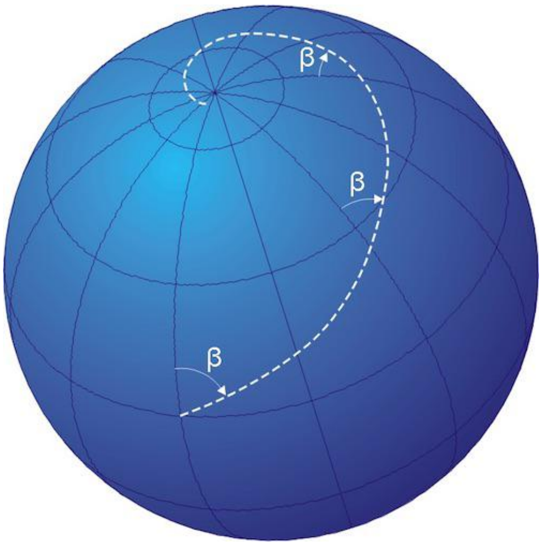
Why not *exactly* the shortest route? On a road atlas or an Ordnance Survey map, a true bearing sure looks like the shortest route between two points. But maps are flat, and the Earth is not. Locally, it appears flat, and so a flat map is a good approximation. But clearly the approximation is not good when trying to produce a map of the whole Earth.

It is worthwhile to think about how we attempt to produce flat maps of the whole spherical globe. The most common way of trying to do this is the Mercator Projection, which produces the map of the world which probably hung on your classroom wall at school. This is the projection where Greenland and Antarctica appear huge, but Africa is relatively small.

Have you ever wondered why Mercator maps never show the North or South Pole?

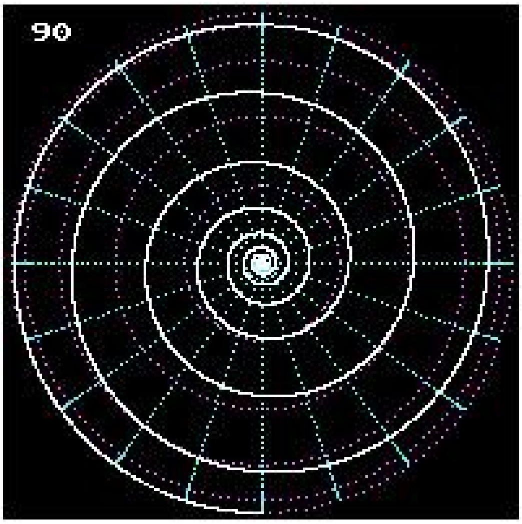
Conceptually, the Mercator Projection is obtained by folding an infinite cylinder, aligned with the Earth's axis, around the Earth. For any point on the Earth's surface, take a line from the centre of the Earth through that point and extend it onwards to the cylinder to find its projection onto the map. Then unwrap the cylinder: this is your map (you are allowed to shrink it to classroom-wall size). The equator maps to a straight line around the middle of the map. The North Pole? The projection line from the Earth's centre goes straight up through the pole and never meets the cylinder. So, the North and South Poles do not appear on the Mercator Projection of the Earth. Your Mercator map always terminates somewhere in the higher latitudes, around 80 degrees.

One benefit of the Mercator Projection is that it preserves angles – if the angle between two lines is x degrees on the



Left, flight path or loxdrome, (rhumb-line) spiraling towards the north pole.

Right, looking down on North Pole showing flight path getting tighter.



Earth's surface, it will be x degrees on the Mercator Projection too. This means that it is ideal for displaying local maps which allow the user to select a bearing, true or compass.

How do Rhumb Lines appear on the Mercator Projection? Well, as I said earlier, the projection preserves angles – so Rhumb Lines on the Earth are Straight Lines on the Mercator Projection. In its cylindrical form, the 45-degree Rhumb Line is simply a straight diagonal line which spirals around the cylinder for ever – an infinite number of rotations around the Pole, as we discussed earlier.

So, maps using the Mercator Projection are an essential aid to navigation. Except around the poles. To put it another way, bearings are not a good way to find the shortest route across polar areas. This doesn't matter in day-to-day navigation, of course, but there are airline routes which cross the polar areas.

For example, consider a trip from Coventry to Anchorage, Alaska (actually to a point a little to the west of Anchorage, but let's not worry about the detail). Coventry and Anchorage are on similar(ish) latitudes, so you might think that a flight due west would the quickest way to make the trip. But that is a Rhumb Line rather than a Great Circle. Actually, the shortest route is to travel through the Arctic between the North Pole and the Magnetic North Pole (in Northern Canada). This involves heading slightly west of due north as you leave Coventry, then gradually modifying the bearing to due west as you pass over the Arctic, veering round to slightly west of due south as you approach Anchorage. These are the true bearings. If you use a compass bearing, it's almost the mirror image, setting off just to the east of due north, gradually changing to due east, and finishing up on a compass bearing just to the east of due south. I have passed through Anchorage airport and can confirm that there are direct flights there from Europe which pass over the pole - I, however, took a route closer to the Rhumb Line as most flights to Anchorage are from the lower 48 states of the USA.

So, navigating in the Artic and Antarctic is tricky. Fortunately, airplanes today have GPS, so know exactly where they are. But what about Arctic explorers from Beighton's time? Well, you might remember me telling you in the November meeting about Revd George Fisher, the chaplain-astronomer on Parry's 1821-23 expedition to find the north-west passage. Navigating accurately in the Arctic oceans was a matter of life-and-death for Parry's expedition.

Fisher's last published work was a chapter on *Circular Arc Sailing* in the 1864 edition of Edward Riddle's *A Treatise on Navigation and Nautical Astronomy*. Riddle (1788-1854) was a mathematician and astronomer who came to attention by contributions on navigation to *The Ladies Diary* in the 1810s, and eventually became a master at the Greenwich Hospital School, where Fisher was chaplain and headmaster. Riddle had died by 1864 but his book was the definitive textbook for navigators in the nineteenth century. The introduction to Fisher's chapter says:

The following article ... contains new and simple methods of modifying the Great Circle track, where the latitude into which the ship would be led is so high as to render the navigation dangerous: to say that this article has been furnished by the Rev. Mr Fisher, late chaplain and principal of the Greenwich Hospital Schools, will be a sufficient guarantee of its value and sound practical character, and the kindness with which it has been contributed is here gratefully acknowledged.

Fisher's article is concerned principally with avoiding sailing to high latitudes – he gives the example of a journey from the Cape of Good Hope in South Africa to Van Diemen's Land (Tasmania), where the Great Circle route would venture into Antarctic waters. His recommendation is to split the journey into a series of shorter arcs; some sailed as Great Circles and some by "Mercator's Sailing" which is Rhumb Lines; for example, sailing at constant latitude. I presume that the navigators on Parry's Arctic expedition did something similar when they were crossing open oceans.

The rather mathematical concepts of Rhumb Lines, Great Circles and Mercator Projections might seem to have little to do with astronomy. Yet they are a reminder when of the days when astronomy was a practical science, enabling navigators to sail around the globe. The concept of the Rhumb Line was first mooted by the Portuguese mathematician Pedro Nunes in 1537, but the mathematics was developed by Thomas Harriott in the 1590s. I've written about Harriot before (MIRA 86) – he is an important but neglected figure from the history of astronomy, who observed the Moon through a telescope before Galileo (Harriott was also connected tangentially to the gunpowder plot, so had to stay out of public view, which is perhaps why he's not better known). It is significant that such an important figure from the history of astronomy as Thomas Harriott should also play such a vital role in the development of navigation. In truth, the two disciplines have been closely connected through most of their history.

The 1864 edition of Edward Riddle's *A Treatise on Navigation and Nautical Astronomy* can be found online in Google Books.

Erwin Finlay Freundlich

By Mike Frost

In addition to my lecturing to astronomical societies, I am a STEM ambassador, talking about Science, Technology, Engineering and Mathematics in schools. My employer supports this activity and so I can cover all four of the STEM branches, talking about my day job in engineering as well as my interests is astronomy, physics, and maths. Indeed, many of the STEM activities, such as Robot Day at the Coventry Motor Museum, are organised by the Institute of Engineering and Technology (of which I am a Fellow), and run by their STEM coordinator, an inspirational man called Derrick Willer, who has received an MBE for this work.

When I was just starting to do STEM work for the IET, Derrick organised a networking evening for STEM ambassadors at one of the schools in Rugby. I wasn't keen to go, as I didn't think I would know anyone there and I can find these sorts of events quite intimidating. However, I have also come to realise that it's worth persevering; if you don't know anyone, go talk to someone! So I went, and of course, I had an enjoyable evening: I did already know a few people, as it turned out.

One new friend I enjoyed talking to was a chap called Willy Goldschmidt, who also lived in Rugby. Willy is retired now from a career in the IT industry and is an enthusiastic speaker on careers. But when he found out that I was an astronomer, he dropped a bombshell.

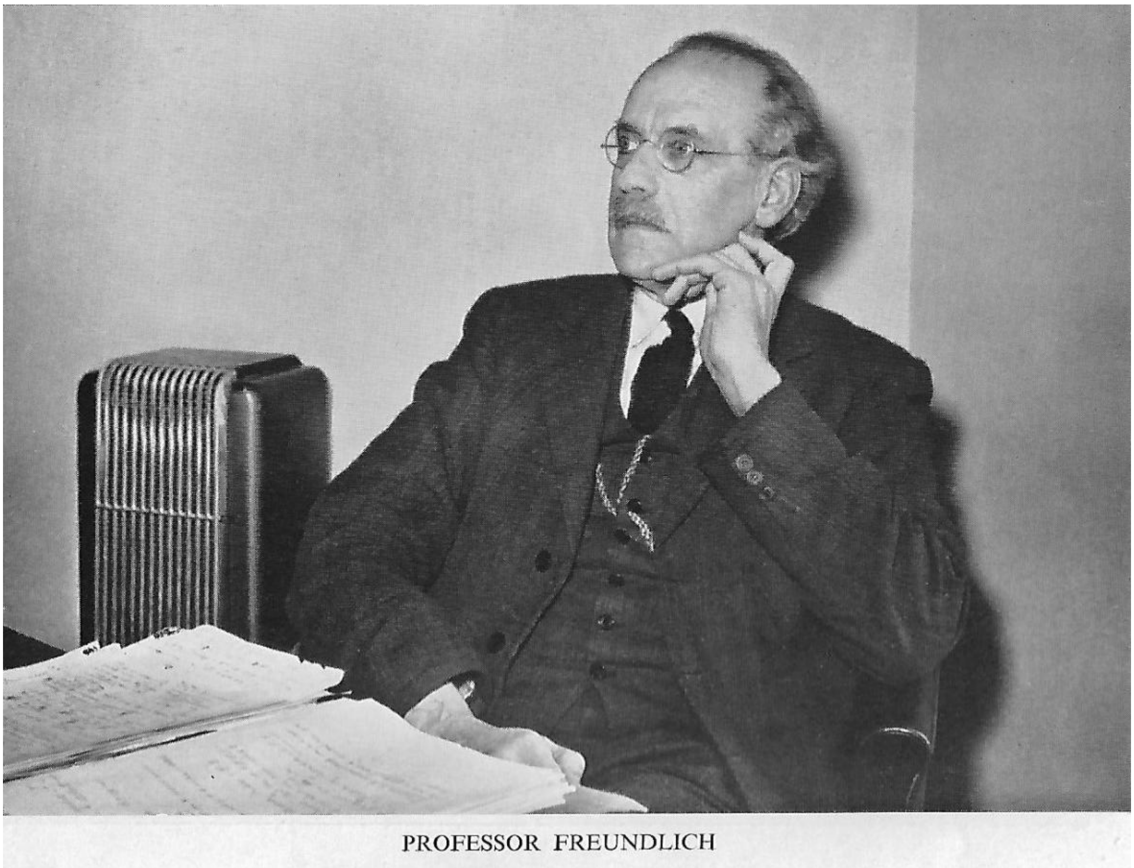
"Oh, you might be interested in my grandfather. He worked with Einstein. . ."

Reader, you will not be surprised to know that I was very interested!

Erwin Finlay Freundlich, it turns out, did not just work with Einstein, but was a close collaborator in the early years. Indeed, Einstein wrote a preface to Freundlich's pamphlet "The Foundation of Einstein's Theory of Gravitation" and concludes with *"he is the first amongst fellow scientists who has taken pains to put the theory to the test"*

Erwin Freundlich (as we'll see, the Finlay was added later) was born in Biebrich, Germany, a suburb of Wiesbaden, on 29th May 1885, one of seven children. His father was Friedrich Philipp Ernst Freundlich, a manufacturer and his mother Ellen Elizabeth (Ellie) Finlayson, a woman of British ancestry. Although Freundlich senior was of Jewish heritage, the family were brought up as protestants.

After leaving school in 1903, Freundlich originally started working in the shipyards in Stettin, north-east Germany, and studying naval architecture at the Charlottenburg University in Berlin. However, within a year, he had switched to studying mathematics and



PROFESSOR FREUNDLICH

Photograph courtesy of the late Dr Dave Gavine

Rather blurred photograph of Freundlich, Einstein and Prof K Müller searching the site for the Einstein Tower in the park of the Astro Physical Observatory in Potsdam. Photograph courtesy of Willy Goldschmidt.

astronomy at Gottingen University in central Germany. Gottingen has a strong reputation for science – the great mathematician Karl Friedrich Gauss worked there, for example – and Freundlich's lecturers included the geometer Felix Klein and Karl Schwarzschild, another collaborator of Einstein who gives his name to the Schwarzschild radius of a black hole, the point of no return beyond which even light cannot escape.

Freundlich gained a doctorate from Gottingen in 1910 and went to work as an assistant at the Royal Berlin Observatory. Here he made the acquaintance of Albert Einstein. This was not just a casual acquaintance; Freundlich and Einstein collaborated on problems in relativity. Erwin Freundlich features as a character (played by Luke Allen-Gale) in National Geographic's 2017 series *"Genius"* about the life of Einstein (played by Johnny Flynn and Geoffrey Rush). He is also a character in Stuart Clark's 2014 novel *"The Day Without Yesterday"*, about the revolution in cosmology in the early years of the 20th Century.

Erwin Freundlich wanted to see if he could find ways of taking measurements which could distinguish between Newtonian gravity and Einstein's General Relativity. Einstein had thought of three possible tests, and over the next few years Freundlich tried to help him acquire data for all three tests.

The first test was to see if the General Theory could explain the precession of the orbit of Mercury, which couldn't quite be explained by the existing theory of gravity. Freundlich helped calculate exactly how big the discrepancy was between prediction and measurement and came up with the now famous 43 seconds of arc per century. A tiny amount! But Einstein could explain it.

For the second test, Einstein realised that mass bent spacetime, meaning that the path followed by light was not a straight line, although it differed little in all but the strongest gravitational fields. The strongest gravity in the solar system is close to the Sun, but clearly the Sun is so overwhelmingly bright that any deviation of light as it passes the Sun is difficult to observe. Freundlich suggested that the light from distant stars, passing close to the Sun could be observed during the few brief minutes of a total solar eclipse, when the light of the Sun's photosphere is blocked by the Moon. This may be familiar to you, but you will probably know it from Eddington's expedition of 1919. But Freundlich was first to attempt the observation!

Erwin organised and led an expedition, financed by the Krupp family, to Crimea in 1914 to observe the total eclipse of August 21st. However, 1914 was not an auspicious time for scientific expeditions. Even as Freundlich and his party set out, war broke out between Germany and Russia. In Crimea, Freundlich was arrested, and his scientific instruments confiscated.

Freundlich was released a few days after the eclipse in a prisoner swap and was able to return to Berlin. With hindsight, however, his failure to be in place for the 1914 eclipse was a lucky break for Einstein, as his theory of General Relativity had not reached its final formulation at this time. In particular, Einstein's prediction for the amount of deflection by the Sun changed (doubled) between 1914 and 1915. Had Freundlich managed to measure starlight deflection in 1914, he might have proved Einstein's 1914 theory wrong, and dealt a blow to his reputation. Freundlich travelled to the total eclipses of 1922, 1926 and 1929 to try to repeat the experiments he couldn't conduct in 1914. He was clouded out in 1922 and 1926, but in 1929, he believed he had measured a deflection greater than that predicted by General Relativity, although the consensus is now that his measurements had a systematic error in them. Nonetheless, this meant that he never fully accepted General Relativity, even though he had been so closely involved in the early tests of the theory.

Freundlich pursued a third means of testing Einstein's predictions. General Relativity predicted a doppler shift of the frequency of light in a gravitational field. Freundlich had already suggested that a small positive bias (the K-term) in the redshifts of stars which were meant to be at rest relative to the Sun were actually due to gravitational redshift; his interpretation was not widely accepted. Erwin further proposed to use the Sun's gravity to test Einstein, this time by careful measurement of the wavelength (and thus frequency) of emission lines in the solar spectrum. To do this he proposed to build a quite extraordinary telescope, the Einstein Türm (Einstein Tower) a solar telescope at the Kaiser Wilhelm Institute in Potsdam, to the west of Berlin, and resigned from the Berlin Observatory to pursue this work. Willy Goldschmidt has a photograph of Erwin and Einstein walking together in the grounds of the Potsdam Observatory (annotated *"Freundlich, Einstein and Prof K Müller searching the site for the Einstein Tower in the park of the Astro Physical Observatory in Potsdam.")* Unfortunately, the photograph is taken from behind, so it is impossible to recognise any of them! Freundlich's plan was realised by Erich Mendelsohn, who built the Einstein Tower as a solar observatory between 1919 and 1921, becoming operational in 1924.

I visited the Einstein Türm in 2016 and wrote about it in MIRA 100. This peculiar and distinctive building looks like an observatory as envisaged by Salvador Dali. Einstein, when he toured it, described it as "organic", perhaps because many of the walls of the building are curved. It's a four-story tower, surmounted by a dome, all sat on a multi-level base. A coelostat in the dome reflects the solar image down the tower to the base, where a spectroscope splits the light into its constituent colours for analysis. All the moving parts are at the top of the tower and the height of the tower means that the effects of atmospheric turbulence at the top are negligible at the base. The original plan to use concrete for the building was hampered by a lack of building materials and the building was eventually built using brick and white stucco, leading to a redesign of some of the scientific layout, though without a loss of sensitivity. In recent years, the tower has been restored to something approaching its original design.

Unfortunately, it turned out that the Einstein Tower wasn't able to carry out its set task of verifying General Relativity. The problem was the turbulent outer layers of the Sun, which added unpredictable redshifts due to velocity on top of the predicted redshift due to gravity. It wasn't until the 1950s that scientists were able to tease out statistically the small gravitational redshift of solar radiation from the larger turbulence effects. Nonetheless, the observatory was used successfully as a solar observatory for many years. In particular, Walter Grotrian carried out work of international importance on the solar corona during the 1930s. He determined that a particularly impressive spectral line in the corona, which had been suggested was due to a new element, "nebulium", was actually due to heavily ionised iron.

The careers of Einstein and Freundlich drifted apart during the 1920's (Freundlich is only in one episode out of ten of "Genius"). Additionally, world events once again interfered with Finlay Freundlich's life. Erwin had married Kate Hirschberg, who was Jewish, in 1913. His Jewish connections began to make life increasingly difficult as Hitler rose to power through the early 1930s, and Freundlich decided to move elsewhere.

The Einstein Tower in Potsdam

In 1933 he accepted a post as astronomer at the Istanbul Observatory. Turkey, under Ataturk, began to modernise during the 1930s, and science was favoured. Freundlich wrote an astronomy textbook, which became the first such to be translated into Turkish. However, Freundlich did not stay long, moving on to the Charles Observatory in Prague in 1937. This may have been better for his career, but once again world events foiled his plans; it became clear that central Europe was no longer safe. Freundlich had been making enquiries about a job in Britain, adding "Finlay" to his name to emphasise family connections to the UK through his mother. Freundlich travelled to England in 1939 and with the help of Eddington, was able to secure an academic position at the University of St Andrews. When Germany occupied Czechoslovakia in 1939, Erwin's wife and family fled, on one of the last trains out. Willy Goldschmidt's family have testimony from Freundlich's wife and daughter about how terrifying the journey was; in particular, a day spent at the German-Dutch border, where the passengers on the train had to prove that they were entitled to leave Germany; many were left behind.

Freundlich's brother, a professor of chemistry, also came to the UK and worked at UCL before emigrating to America. Erwin, however, was happy at St Andrews. During the war he taught Aircrews how to navigate by the stars when flying at night.

Another refugee from Germany, Max Born, also settled in Scotland. Max Born and Erwin Finlay Freundlich worked together in the 1940s and 50s on an attempt to explain cosmological redshift by means of "tired light" theories, another indication of Finlay Freundlich's unhappiness with relativity. Max Born, a Nobel prize-winner in Physics, is not a central character in this story but his story is similar to Freundlich's in a number of intriguing ways. Born also studied at Gottingen, though he managed to annoy Felix Klein by not entering a prize competition Klein had suggested (they made up and Born eventually won the prize). Like Finlay Freundlich, Born had Jewish heritage which forced him to leave Germany for the UK; he became a British citizen the day before WW2 broke out. He worked first at St Johns College, Cambridge, but became a professor at Edinburgh University. One of Max Born's grandchildren is the singer Olivia Newton-John.

At St Andrews, Erwin Finlay Freundlich constructed a new observatory and commissioned a Schmidt Camera to his design. The ultimate aim was to give the observatory a professional-class instrument, but first of all a smaller prototype camera was built. To test the camera, he installed it at the Mills Observatory in Dundee. This was a curious decision as the Mills Observatory is a public observatory, and it isn't possible to look through a Schmidt Camera! Eventually Freundlich brought the Schmidt Camera back to St Andrews and proposed that it be replaced in the Mills observatory by an 1871 Cook Refractor which had been used for training purposes by astronomy students at St Andrews. This was a much better telescope for the Mills observatory, and is still in use, though showing its age. I visited the Mills observatory when the BAA met in Dundee in 2016, and also wrote about it in MIRA 100. Freundlich attempted to commission a larger Schmidt Camera for St Andrews, but this eventually foundered as he neared retirement. Professor Stubbs, who succeeded him at St Andrews, didn't allow him access to complete the project. The camera was never a success.

One of my friends from the BAA in Scotland, Dr Dave Gavine, was a student of Finlay Freundlich's at St Andrews. Dave and I met for lunch a day or two prior to the BAA Historical Section meeting in Stirling in 2018, at which Dave spoke. We had a very enjoyable time reminiscing about his life. Dave is unfortunately no longer with us, and I think he was keen to tell his stories to me and as many other people as possible before he left us. Dave's memories of Finlay Freundlich were of an imposing and distant figure; he particularly recalled a slide from one of his lectures, which was impenetrably annotated in gothic German.

Finlay Freundlich retired from St Andrews in 1959. As West Germany recovered from the war, he decided to move back to Wiesbaden, and so spent his last few years in his birth town, with an emeritus position at the University of Mainz. (In another echo of Finlay Freundlich's life, Max Born also returned to West Germany in retirement). Erwin Finlay Freundlich died in 1964.

Erwin Finlay Freundlich's story is remarkable. He was clearly a talented man, who forged a distinguished career. Yet his most important achievements are so closely yoked to Albert Einstein's career, even though they only overlapped for a few years. And his life serves as a reminder of how lives and careers can be at the mercy of political events completely outside our control. The eclipse of 1914, which could have sealed Finlay Freundlich's reputation, was torn from his grasp by the onset of World War 1. And he was lucky to avoid the terrible fate befallen by so many in World War 2.

The photograph of Einstein and Finlay Freundlich together is courtesy of Willy Goldschmidt. I am very grateful to Willy for his family's insights into Erwin's life.

I am also very pleased that I was able to spend an afternoon chatting with Dr Dave Gavine. We miss him.

`https://en.wikipedia.org/wiki/Erwin_Finlay-Freundlich`

Kragh H. (2007) Freundlich, Erwin. In: Hockey T. et al. (eds) *The Biographical Encyclopaedia of Astronomers*. Springer, New York, NY. https://doi.org/10.1007/978-0-387-30400-7_481

Series 1 of *"Genius"*, directed by Ron Howard, tells Einstein's life story (series 2 is about Pablo Picasso and series 3 about Aretha Franklin). It's a well-written drama, focusing as much on Albert's complicated personal life as on his scientific achievements. Finlay Freundlich appears in episode 6.

"The Day Without Yesterday" by Stuart Clark (Polygon, 2014)

MIRA 100 contains articles on my visits to the Potsdam Observatory and the Mills Observatory in Dundee.

The Mills Observatory in Dundee