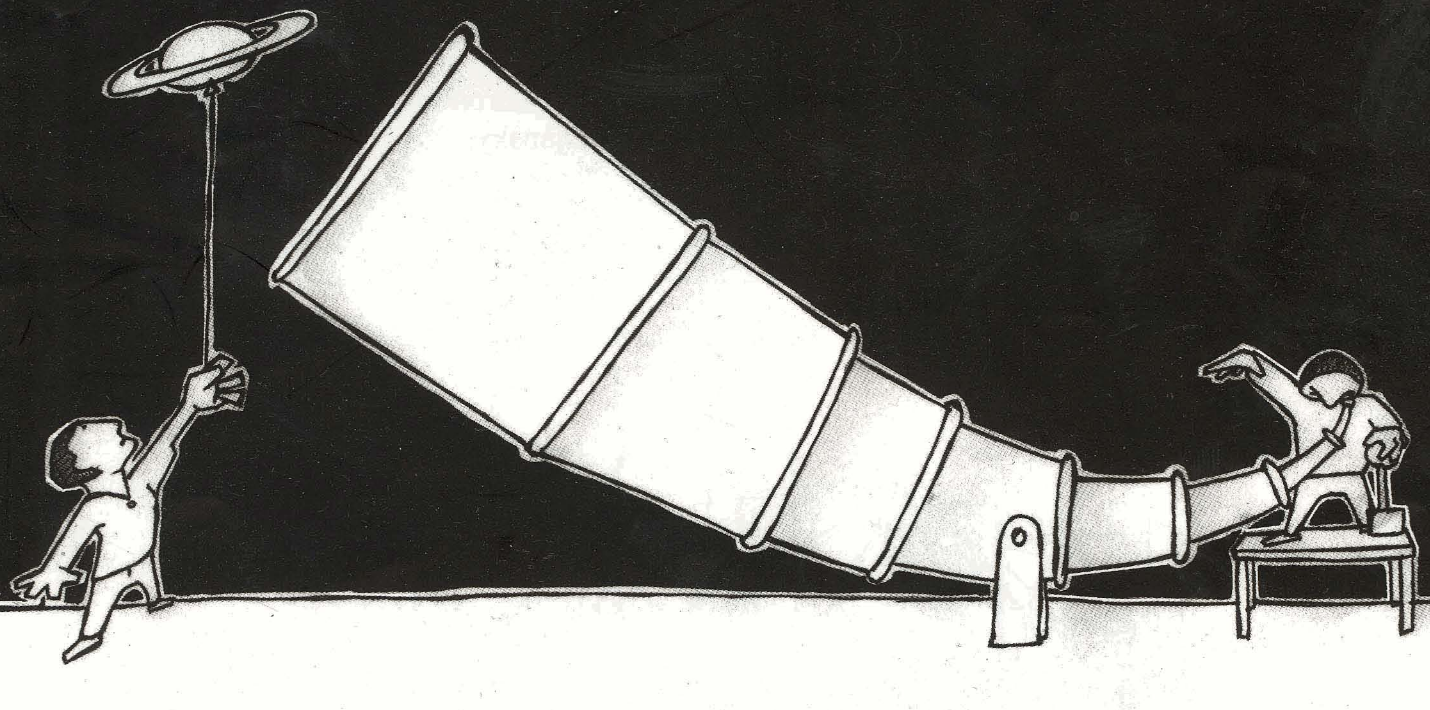
Astronomy's Devices



V. Radhakrishnan

Jansky lecture 2000

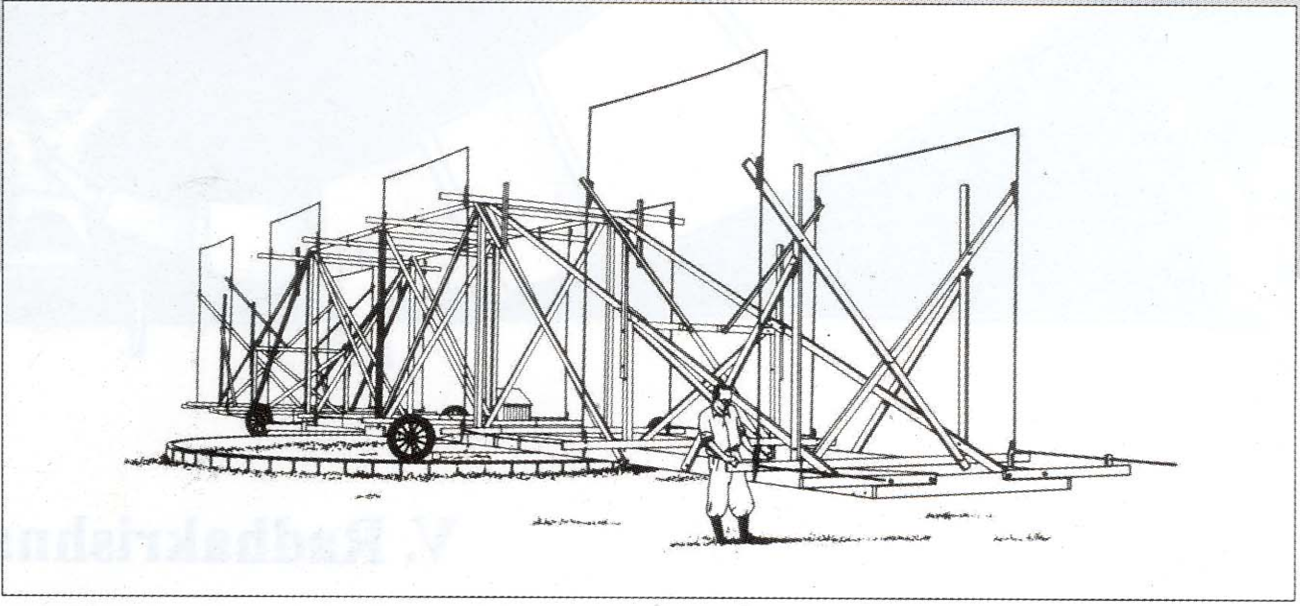
Karl Guthe Jansky (1905-1950)

Born in Norman, Oklahoma, in 1905, Karl Jansky attended the University of Wisconsin. After graduation in 1928, he joined the Bell Telephone Laboratories in New Jersey. His work there dealt with the problems of the shortwave radio telephone. In 1931 he was assigned the task of tracking down the crackling static noises that plagued overseas telephone reception. At the Holmdel station he constructed a large directional antenna system.

Jansky recorded two well-known kinds of atmospheric static: crashes from local thunderstorms and noise from distant thunderstorms reflected from the ionosphere. From his records he later singled out a weak third kind of static that could hardly be distinguished from the internal receiver noise. Through headphones the weak noise sounded like a steady hissing. At first Jansky thought that the interference came from the Sun, but after a year of careful measurement he concluded that the radio waves came from a specific region on the sky every 23 hours and 56 minutes. Suspecting that the radiation was coming from an astronomical source, he attempted to trace its origin. He knew from his study of astronomy that the period of the Earth's rotation relative to the stars was 4 minutes less than its 24-hour period relative to the Sun, and this was the clue that the radio noise originated in space beyond the Solar System. He found that its direction coincided with the constellation Sagittarius toward the center of the Milky Way. In the publication of his work he made two very perceptive comments: He suggested that the radio emission was somehow connected to the Milky Way and that it originated not from stars but from ionized interstellar gas.

At the age of 26, Jansky had made a historic discovery--that celestial bodies could emit radio waves as well as light waves. But his results, published first in 1932, received little attention. Not until the end of World War II was the significance of his achievement widely appreciated.

Jansky's serendipitous discovery gave birth to a new branch of astronomy, radio astronomy. In Jansky's honor, astronomers named the unit of radio flux the jansky.



Astronomy's Devices

V. Radhakrishnan
Raman Research Institute, C.V. Raman Avenue, Bangalore 560 080, India

Starting from antiquity and exploding in the Post-World War II period, astronomical discoveries have revealed a whole gallery of objects and phenomena that could hardly have been foreseen before they were found. Any news from above seems to make good press, and so, there is public awareness of many of the spectacular discoveries in astronomy, and earlier Jansky lecturers who have been fortunate enough to make such discoveries have chosen appropriately to talk about them. For my talk however, I have chosen a topic, inspired by the man after whom the lecture is named, and that surprisingly has not been picked before. I have in mind the devices, most often made or intended for other purposes, but which when turned upwards have shown to us the wonders of the universe, that popular lectures and television programs are usually all about. For me, they are the unsung heroes that have made these discoveries possible.

As a supreme example, I shall begin with one made by Nature herself, and which was the *only device* used in Astronomy for many thousands of years – the human ***eye.***

Apart from some sticks and stones stuck in the ground to sight along, it was the naked eye that followed the motions of the Sun and Moon against the background, and predicted their eclipses to astonishing accuracy. It observed thousands of stars that twinkled, a phenomenon one came to understand only relatively recently as caused by turbulence in the sea of air above us, an effect that continues to plague ground-based observations. Against the fixed background of the stars was the wandering of the planets, whose study led to our knowledge of the solar system, and from it, the theory of Universal Gravitation. Among the transients, that were naked-eye discoveries, were the comets which put on such a spectacular show, some of them returning for more encores, the sporadic brightening of some stars called Novae, and the super spectacular guest stars, which we now call ***Supernovae***.

The eye, a tiny marvel with an opening less than a centimeter in size (Figure 1), is a truly superb detector with a resolution of a hundredth of a degree and a sensitivity that allows us to find our way around by starlight, a feat unequalled by anything until quite recently. If you brag to your friends about the number of pixels in your latest digital camera, note that the eye has over a hundred million receptors on the retina, whose function incidentally was first explained by an *astronomer*, Kepler himself. If you are impressed with your fancy Camcorder that takes the shaking of your hand out of the picture, think of what the eye must be doing to keep the ground fixed while you are moving your head and your eyes about. There is so much of the brain in the eye, doing what is called signal processing in the jargon, that one million nerve fibres carry away the information from over a hundred million receptors.

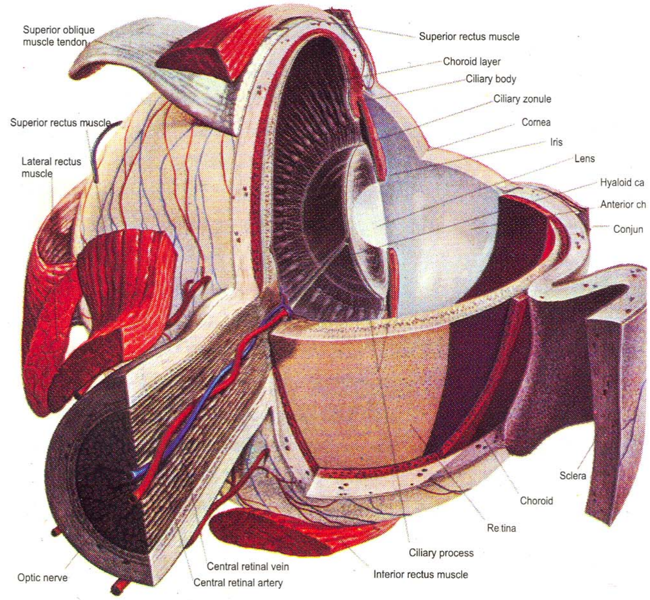


Figure 1.

It takes just about the minimum physically possible amount of light to trigger the eye, and I find it amazing that anyone with good vision can actually discern an object a million light years away. That is the distance to Andromeda, our neighbour galaxy which looks we believe, as our Milky Way would if seen from there.

But as with hearing and other faculties, inherited defects and the effects of age take their toll with our vision, and already many hundreds of years ago, spectacles were invented to help those so handicapped (Figure 2). Bits of

A spectacle peddler in the 16th century

Figure 2.

glass were ground to bulge both inwards and outwards to compensate for both near and farsightedness. In fact it was the act of a Dutch spectacle maker, or his kids, putting the two types of lenses used in his job at the ends of a tube and looking through, that resulted in the invention of the telescope, the next and among the greatest of astronomical devices. It was considered for use in early warning of enemy ships approaching one's harbour, but it took the genius of Galileo to first point it upward and to recognize celestial evidence of the universality of physical laws. The cratered surface of the Moon had shadows formed just as they are on Earth, and Jupiter had moons that went round it just as our Moon goes round our planet. More difficult to observe was that Venus had phases like the Moon, dramatic evidence that it went round the Sun and not the earth. With the telescopes you see in the picture (Figure 3), Galileo accumulated sufficient evidence in eight months to demonstrate that the Book of Genesis, the philosopher Aristotle, the astronomer Ptolemy and the theologian St. Thomas Aquinas were all wrong. He shouted his findings from the rooftops, and as we all know, got himself into serious trouble, including house arrest for life. The brighter side, if you can call it that, was that he did not get burnt like Bruno.

The required magnification was achieved with a large separation between thin lenses at the two ends of a telescope, resulting in a long and unwieldy object to handle. Attempts to shorten the length by having fatter lenses produced impossibly blurry images, for reasons *not* understood at the time, and for a century and a half, astronomical telescopes were long and lean and of poor quality. An example of how extreme this got is

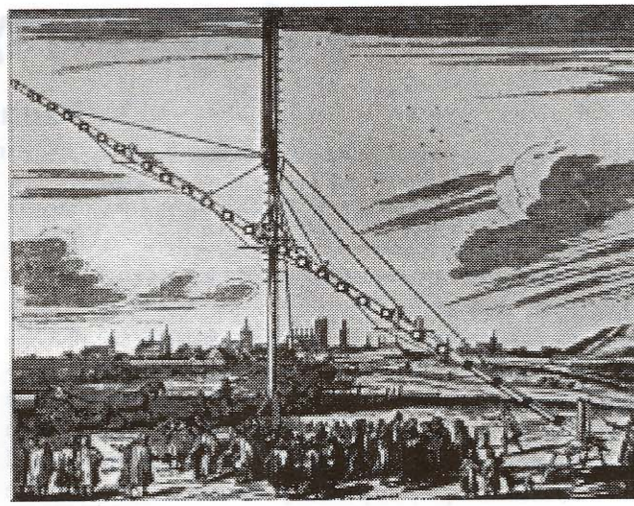


Figure 4.

seen in the picture (Figure 4) which shows one 150 feet long!

Newton was born in 1642, the year Galileo died. Among his many discoveries was that sunlight, if passed through a wedge-shaped piece of glass called a prism, would split up into the colours of the rainbow (Figure 5). The connection with telescopes is that the lenses were in fact prisms, and suffered naturally from what is technically called chromatic aberration. (White objects produced coloured and blurred images). And so, Newton invented a new kind of telescope (Figure 6), where a curved *reflecting* surface would do what the lens did, but now *identically* for all colours. Although this concept is

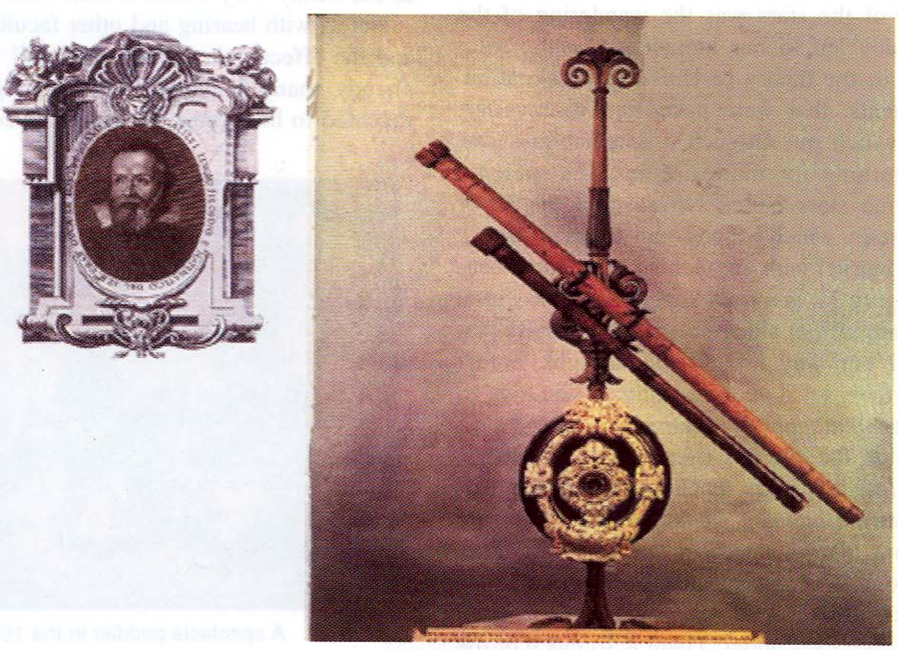


Figure 3.

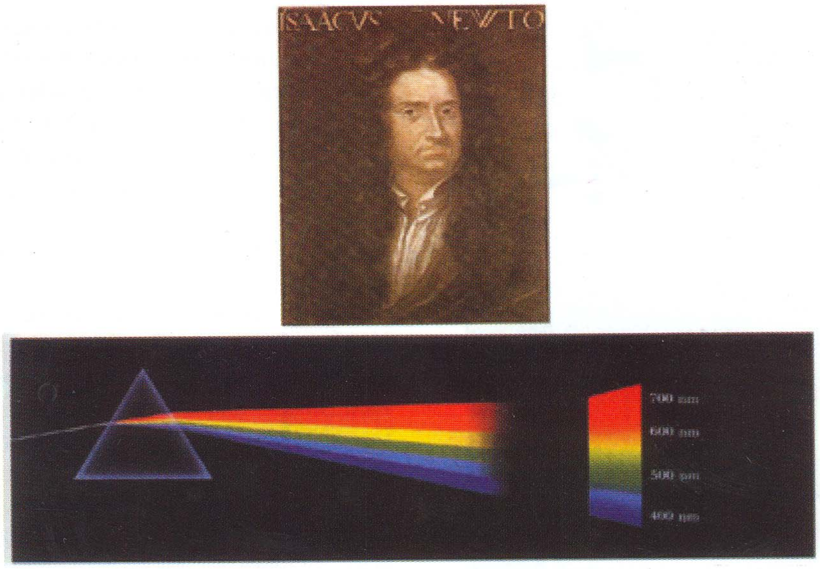


Figure 5.

Box 1.

"There is no fact in the history of science more singular than that Newton should have believed that all bodies . . . separated the red and violet rays to equal distances when the refraction of the mean rays was the same. This opinion, unsupported by experiments and not even sanctioned by any theoretical views seems to have been impressed on his mind with all the force of an axiom. . . . When, under the influence of this blind conviction he pronounced the improvement of the refracting telescope to be desperate, he checked for a long time the progress of this branch of science, and furnished to future Philosophers a lesson which cannot be too deeply studied."

The Life of Sir Isaac Newton, by David Brewster, 1831

Figure 6.

used in every contemporary major astronomical telescope, its original motivations were interestingly erroneous.

Newton believed and stated explicitly (see Box 1) that the bending of light, and its separation into its constituent colours **had** to go together. Wrong statements by great men can never stop the progress of science, but they can delay developments, which in this case, was the emergence of combinations of lenses made with different types of glass, called **achromats**, that bend light, but equally for all colours. They put refracting optics back into the game, especially since the metal reflectors like Newton's were very poor mirrors, and silvered glass was 200 years in the future.

A completely different property of a telescope, but all-important for astronomy, is its ability to gather more light from a distant object than the human eye, by having a lens, or reflector, much larger than the size of our pupils. The ability of a pair of binoculars to illustrate this aspect seems surprisingly to be less well known than its ability to magnify. Try looking at a distant tree or bush at night with large diameter binoculars (not opera glasses) and you may be startled to see the leaves as if it were not so dark.

Just seeing astronomical objects was one thing, but what made astronomy an exact science was the ability to fix their positions in the frame that appeared to go round the earth as it spun on its axis. This translated very simply into measuring the precise instant of time at which the stars transited an imaginary N-S line on the sky, called the Meridian, and required two inventions, the first inspired by an insect in 1604. A spider made a fundamental contribution to positional astronomy by spinning its web within a telescope at the focus of the objective lens, exactly where the image of the star or planet was formed, and that was magnified by the eyepiece in the same way as the image. This led to the crosshair which suddenly enabled

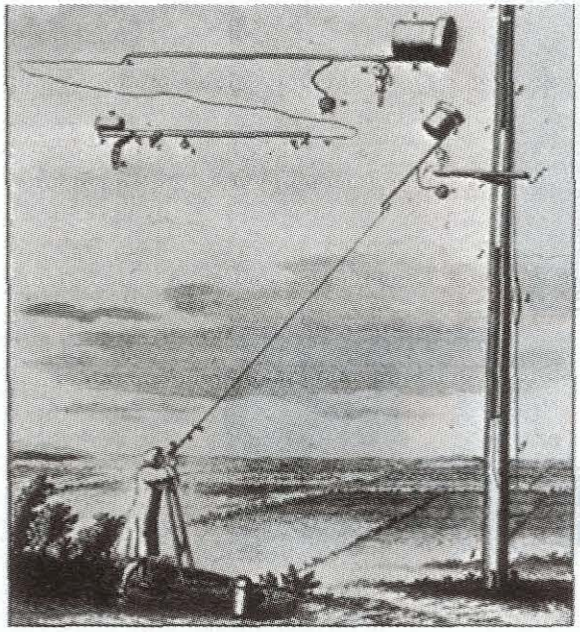


Figure 7.

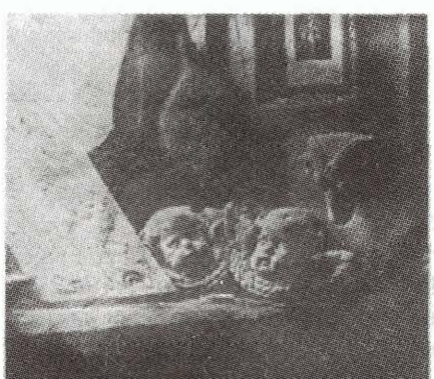
Figure 8.

accurate measurements as it defined precisely (for the first time) the direction in which the telescope is pointed. The other invention was the pendulum clock by Christian Huyghens, which vastly improved the standard and accuracy of astronomical measurements.

For over two hundred years, the function of the astronomical telescope was to collect light from different directions and to squeeze the pencil down to a size small enough to enter the human eye, *the only detector* available. Such visual observations were made with telescopes ranging in size from less than a meter to over ten meters, during this period when telescopes were described by their lengths and not their diameters (Figure 7). (The picture shows a very clever one invented by Huyghens which used the tension in a string to align the lenses at the two ends.) Such telescopes led to the discovery of new planets, and satellites of planets, double stars, clusters of stars, nebulae (clouds of gas) and impressive lists of stars. One famous catalogue listed a third of a million stars, observed with an instrument all of 3 ½ inches in diameter!

But the eye, sensitive though it was, lacked the ability to add new information to old beyond the duration of a tenth of a second or so. The next revolution that was needed to look deeper was the ability to accumulate a weak signal over a stretch of time. And the process that would do this originated from the inspired but empirical meddling of a scenery designer and artist, looking for a way to record the forms and perspectives of nature for the design of dioramas. A diorama is a painting without borders (Figure 8) depicting a panorama and illuminated in a closed room to give an illusion of reality. It was invented by Daguerre in Paris who is also credited with the invention, or discovery of photography – some years later, in 1839. You may have heard of Daguerrotypes, the name

Dagurreotype of Daguerre made in 1844



The earliest known Daguerreotype still in existence, made in 1837

Figure 9.

given to the early photographs. They were made by a process involving plates of silver, trays of iodine and mercury, and slow heating in the dark, more than reminiscent of alchemy, arrived at by unknown means, but which worked and immortalized him (Figure 9).

Quite strangely, for totally unconnected reasons, a well-known astronomer was part of the story. When John Herschell in England heard of Daguerre's success, he too produced a photograph of his famous father's famous 40″ telescope (Figure10), (now the icon of the RAS). He used a completely different negative-positive process that his friend William Fox Talbot (in Bristol) had been experimenting with for years. It so happened that 20 years earlier John Herschell had discovered that (the normally extremely insoluble) salts of silver could be dissolved easily in the chemical commonly called ***hypo***. This discovery, useless at the time, when applied to the very temporary and unstable Daguerrotype, and also to the Fox Talbot neg-pos system, made photography suddenly practical. An astronomer, by inventing a photographic fixer, had made *permanent image recording* possible.

Some forty years or so later, the dry gelatin plate was invented and made long exposures possible. It was in 1883 that a 30 mins exposure of the Orion nebula (Figure 11) made with a home-built telescope, by an engineer famous for constructing the London sewerage system, showed stars too faint to be seen by eye using the same telescope. Ainslee Common had transformed photography from a mere recorder of a visible scene, to a detector of the *unseen*, and was most appropriately given the gold medal of the RAS in recognition. "Long Live Amateurs", I say.

A hundred years later, astrophotography was taken to its peak by David Malin at the AAO, both to make important discoveries as also to popularize astronomy with his fantastic pictures of the heavens in colour. Shown in Figure 12 is his picture of the same nebula.

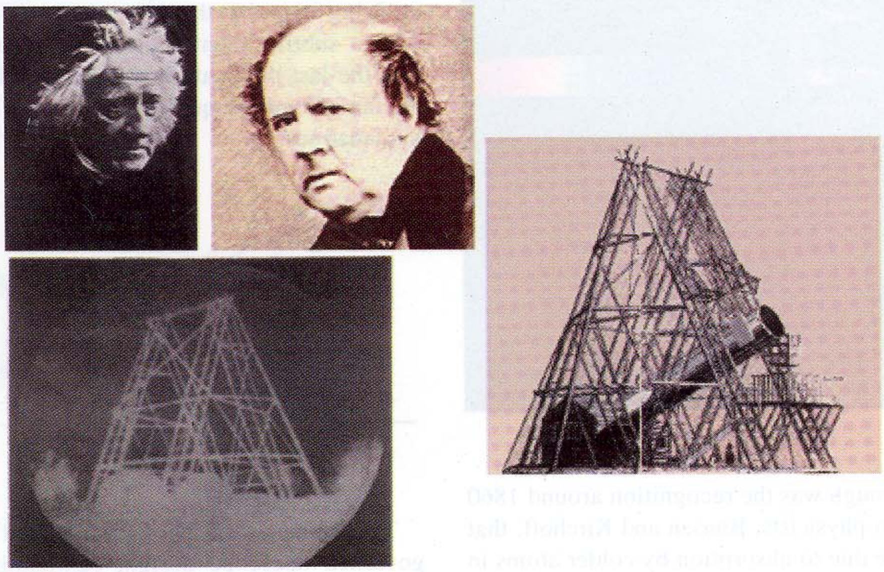


Figure 10.

Figure 11.

Figure 12.

There was no looking back, and photography rapidly replaced the eye as the only detector. It did so not just for images but, equally importantly, for capturing information buried in the spread of wavelengths of light. As we saw earlier, Newton had separated the apparently white light from our nearest star, the Sun, into a range of colours called a spectrum, by passing it through a prism. A century later, the German physicist Fraunhofer placed a narrow slit before the prism and invented the spectroscope, the next great device (Figure 13). Suddenly, it was seen that Newton's spectrum of sunlight was not smooth, but in fact penetrated by a series of narrow dark lines, that came to be named after Fraunhofer.

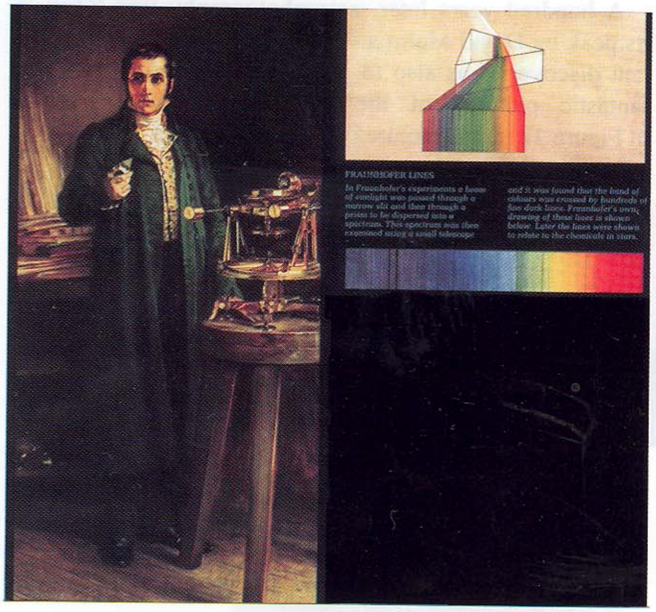


Figure 13.

The next breakthrough was the recognition around 1860 by two other German physicists, Bunsen and Kirchoff, that these dark lines were due to absorption by colder atoms in the Sun's outer layers of hotter radiation from inner regions. By visual inspection they identified the elements sodium and iron in the Sun showing – as someone quipped – that stars were made of people stuff. More significantly, they ushered in astronomical spectroscopy, the way to detect what was out there, sometimes, even before we knew it was here. Helium was first discovered in the solar spectrum, and named appropriately, before it was found on earth, and much longer before it would play a crucial role in devices that would enable major astronomical discoveries.

There was also now the possibility of determining the motion of distant matter through the Doppler effect, popularly described as the change in the tone of the whistle of a train approaching and then receding from the listener (Figure 14). To achieve this would require a means to detect spectral lines perhaps so weak that one would need long exposures and accumulation of the signal. And this was just what photography could do for spectra, as it did for images. In fact it became such a powerful tool for studying stars that the *Astrophysical Journal* was founded with a subtitle mentioning spectroscopy (vol. 136, 1962 was the last publication which carried this subtitle before its famous editor quietly removed it without a word of explanation).

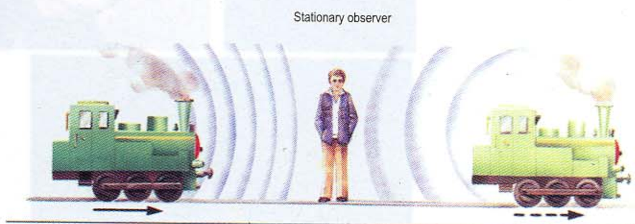


Figure 14.

The demands of photography and spectroscopy now governed telescope design, culminating in the 60″ and 100″ telescopes on Mt. Wilson (Figure 15) in the early

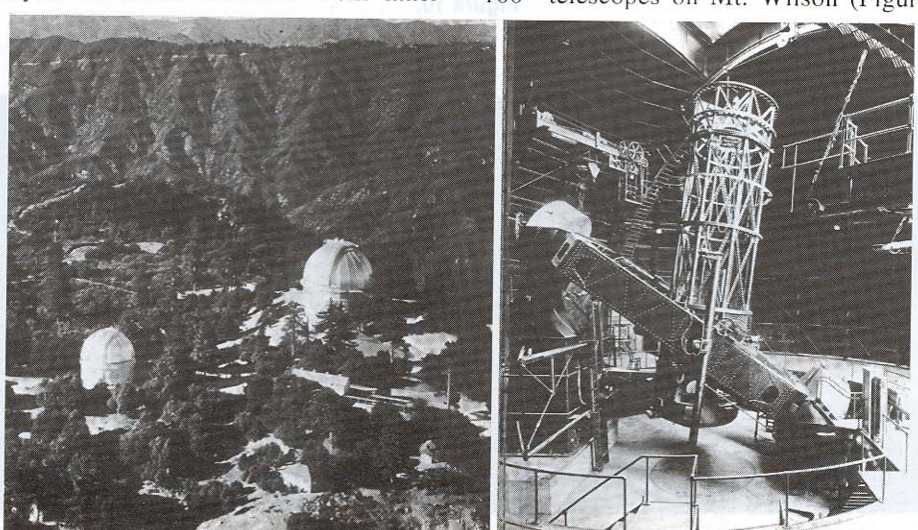


Figure 15.

1900s. From these flowed discoveries as momentous as that the Milky Way was just one galaxy among many, and that they were all going away from each other with a speed proportional to their separation, the expanding universe. Both astrophysics and cosmology were made possible by something invented to make dioramas.

Astronomical spectroscopy had revealed so much by just looking in little windows, within the one octave – from red to violet – that our eyes are sensitive to, that it should have been obvious that whole new views of the universe were waiting to be discovered in the vast expanse of the electromagnetic spectrum, if only we would look. But it didn't happen that way. Bell Labs wanted to improve radio communications and put a young physics graduate on the job of studying the so-called **static** that was a cause of interference. This was just before World War II. Nobody in his senses could have imagined that the antenna he used (Figure 16) would bring us news from thousands of light years away. It is a tribute to his superior quality as a scientist that although Jansky found what the Company had asked him to find, he persisted in accounting for something weak that was left over, and made a historic discovery at the age of 26.

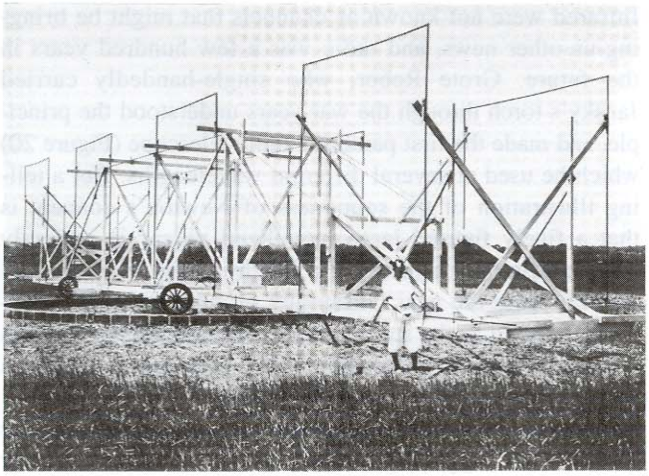


Figure 16.

Radio astronomy was born, and there were now decades of radio spectrum just waiting to be explored as and when the right devices and people got together. And World War II, for all its ills, provided just such a golden opportunity. The desperate need for effective radar, both ground-based and airborne, led to intensive development (by physicists on both sides of the Atlantic) of devices that would operate in different regions of the radio spectrum making possible, among other things, the microwave oven you have at home. Radar equipment, and expertise in operating them, led, after the war to several groups in different countries doing, what Galileo did, looking away from approaching enemy craft and up at the sky. England and Australia were the leaders in the field, but at several places in Europe like Holland and France, and even Sweden where I worked for a while, one used the so-called giant Wurzburg radar antennas (Figure 17). They had been moved from the coasts where the Germans had installed them, to **Radio Observatories**, a new post-war phenomenon.

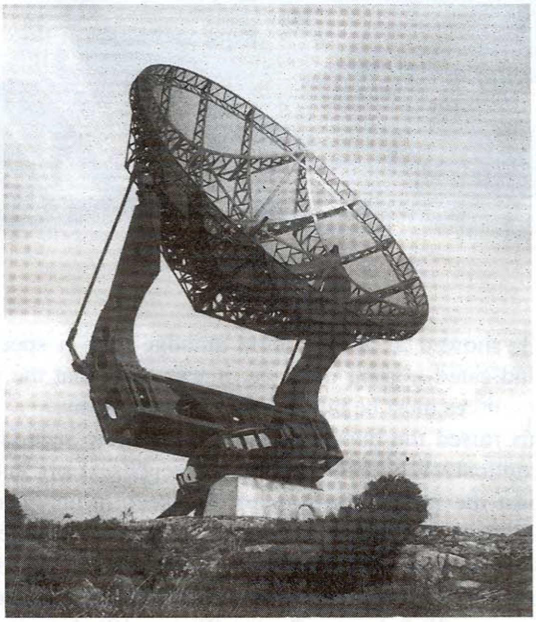


Figure 17.

Radio astronomy revealed innumerable sources dotted all over the sky, but the defining moment was when the first Jansky lecturer John Bolton, and collaborators in Australia, using antennas like our familiar TV ones (Figure 18), detected and identified two strong ones with far away Galaxies.

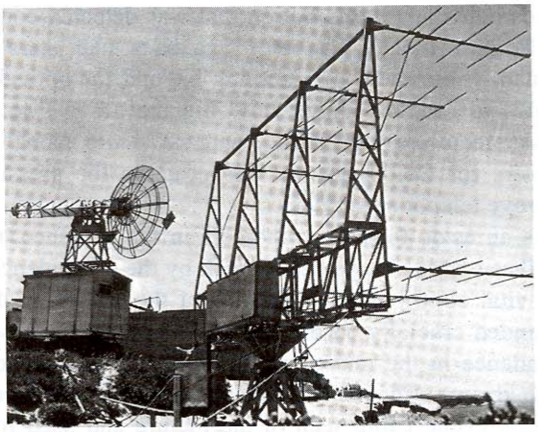


Figure 18.

Radio signals were revealing a different and distant universe, and when sometime later, the second brightest radio source in the sky was identified with what the biggest optical telescope in the world then, (the Palomar

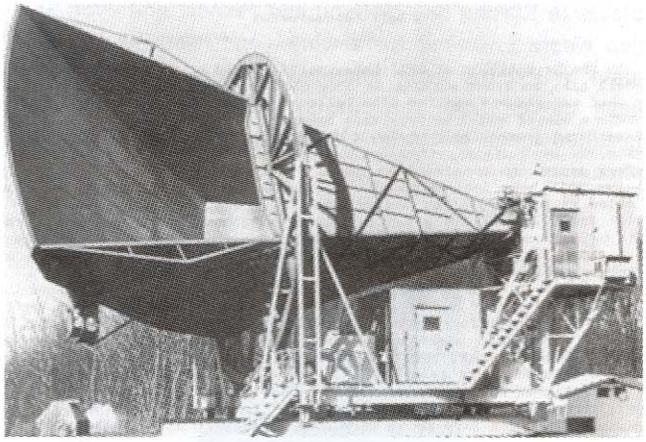


Figure 19.

200″), showed as a very faint smudge with a spectrum that indicated a great distance, it was clear that the weak radio sources must be billions of light years away.

This raised the question "How come radio sees farther than optical? Why can't optical telescopes, if big enough see past the faint radio sources now seen in untold numbers?" Both questions were answered in a strange but decisive way by the next major astronomical discovery made at Bell Labs, 35 years after the first one. The **device** used was a 20-ft horn-reflector (Figure 19) designed for ultra low-noise communications, and insensitive to stray radiation from unwanted directions. It had an unblocked aperture, the principle the new Green Bank Telescope (GBT) has adopted. More than one aspect of the second discovery was like a replay of the Jansky story. All known things accounted for, except a little annoying leftover to explain. No longer annoying mind you, once it was realized that the leftover was not due to what the pigeons had dropped in the antenna, but from the Big Bang. According to cosmologists, the radiation that was detected comes to us from a time long before galaxies and stars were formed. If so, there *was* nothing beyond for optical telescopes to see, no matter how big they are. Two more Jansky lecturers for NRAO, and two more Nobel prize winners for Bell Labs, but no let-up in the pressure to improve telephone services.

As an aside to the astronomers in the audience, may I say that I have always been struck by the coincidence that this vital contribution in support of the Big Bang theory depended crucially on the use of helium, whose observed abundance in the universe was another prediction of the same theory. The world's then most sensitive receiver, located in the cabin seen in the picture and used for the observation, was called a maser and required cooling with liquid helium to achieve its performance. I have much more to say about Bell Labs and their devices, but wish now to digress and say something about waves and particles.

As the great William Bragg said early last century,

> **Light brings us news of the universe.**
>
> Coming to us from the sun and the stars, it tells us of their existence, their positions, their movements, their constitutions and many other matters of interest.

We have just seen that news of the universe is also brought to us by radio waves. Thanks to the genius of Maxwell who unified electricity and magnetism, we think of both kinds of messages as just electromagnetic radiation, and differing only in the length of the waves. For light, this is of the order of a thousandth of a millimetre, for the waves that Jansky detected it was 15 metres, and most radio astronomy being done today is at wavelengths in between.

The prime motivation for Newton's invention of the reflecting telescope was to make it Achromatic over the range of wavelengths that the eye responds to, a *mere* two-to-one ratio. At that time, even the Ultraviolet and Infrared were not known as channels that might be bringing us other news, and radio was a few hundred years in the future. Grote Reber, who single-handedly carried Jansky's torch through the war years understood the principle, and made the first parabolic radio telescope (Figure 20) which he used at several different wavelengths. But a telling illustration of the soundness of Newton's concept is that a finely figured large metallized mirror is perfectly **achromatic** over a factor of a hundred million to one, all the way from the near Ultraviolet through the radio spectrum. As long as the surface is smooth and the wavelength is *smaller* than the dimension of the reflector, it will be a perfect collector of any radiation that falls on its surface.

The biggest modern optical telescopes today are the Kecks, each bigger than, and capable of doing superbly

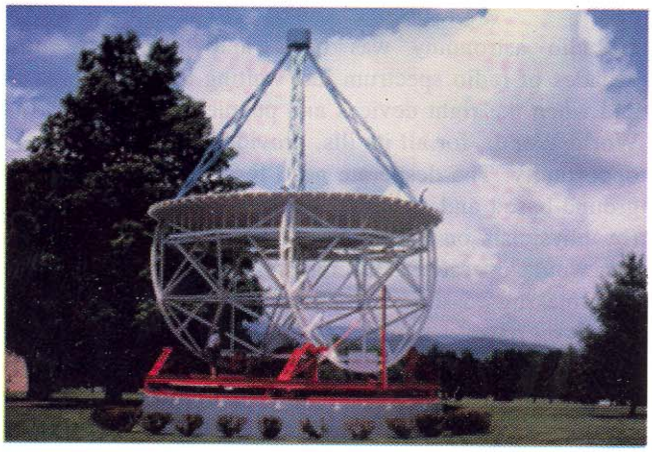


Figure 20.

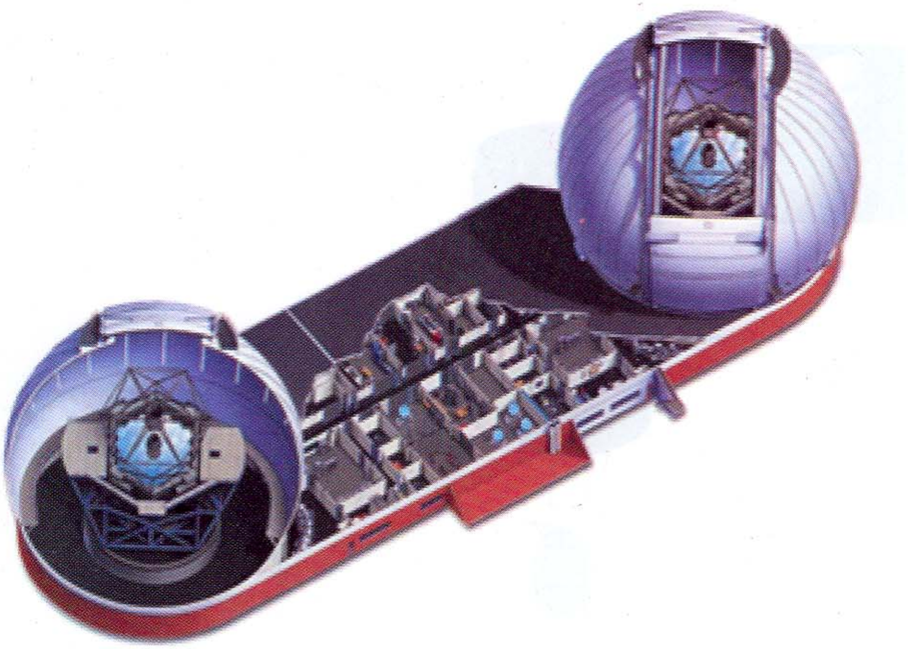


Figure 21.

anything that Reber's antenna could do* (Figure 21). I know they cost somewhat more, ($ 100 M each), but the point I am trying to explain is that when you change wavelengths, by say a factor of a million in such a telescope, it is what you put at the focus that needs to be different.

The functions required are that of receiving the message, and storing this information for later analysis. (Moses must have appreciated the importance of this aspect when he lugged all that heavy recording gear up the mountain.) For operation at light wavelengths, we have already discussed two kinds of devices that can be used. We can put a human eye at the focus, and use our memory to draw pictures of canals on Mars say, or a photographic plate which would be more sensitive, more faithful, and permanent in its memory. In both cases, the process of detection belongs to **photochemistry** and involves a different aspect of radiation that we can no longer ignore.

When electromagnetic radiation goes from one place to another, it behaves like a wave. Phenomena like refraction and reflection, diffraction and interference are all wave properties and basic to the design of both optical and radio telescopes. But there is a Jekyll and Hyde behaviour when it comes to radiation giving up its energy. Einstein got his Nobel Prize not for Relativity, but for showing that the energy of radiation arrives only in packets called photons, no matter how weak the radiation (see Box 2). An analogy is that of a dripping faucet where tightening the tap will only change the time interval between drops, but not the amount of water in each drop.

Photochemical detectors, like the eye and photographic emulsions, need photons with a certain minimum energy to activate them (Figure 22). They are thus colour sensitive, and radiation of wavelength longer than a certain limit cannot initiate the required chemical changes (like

*The reverse is obviously not possible because of the wire mesh surface which cannot reflect anything shorter than decimetric radio waves.

Box 2.

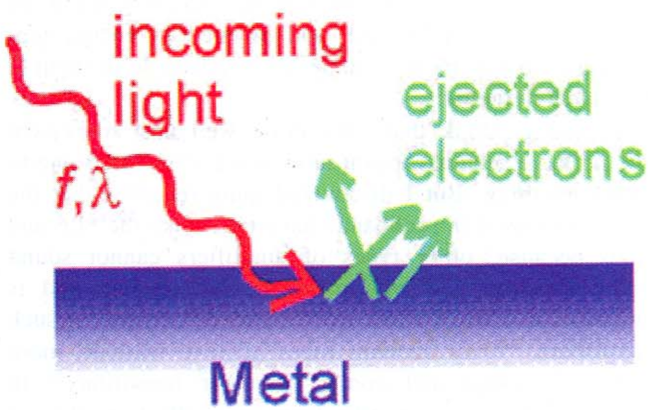
The energy of electromagnetic radiation arrives only in packets called photons.

The energy in each packet is $h\nu$.

h is Planck's constant and ν is the frequency.

So energy is proportional to frequency.

One light photon has the energy of a million radio photons.



Electrons will be emitted only if λ is shorter than a certain limit

Figure 22.

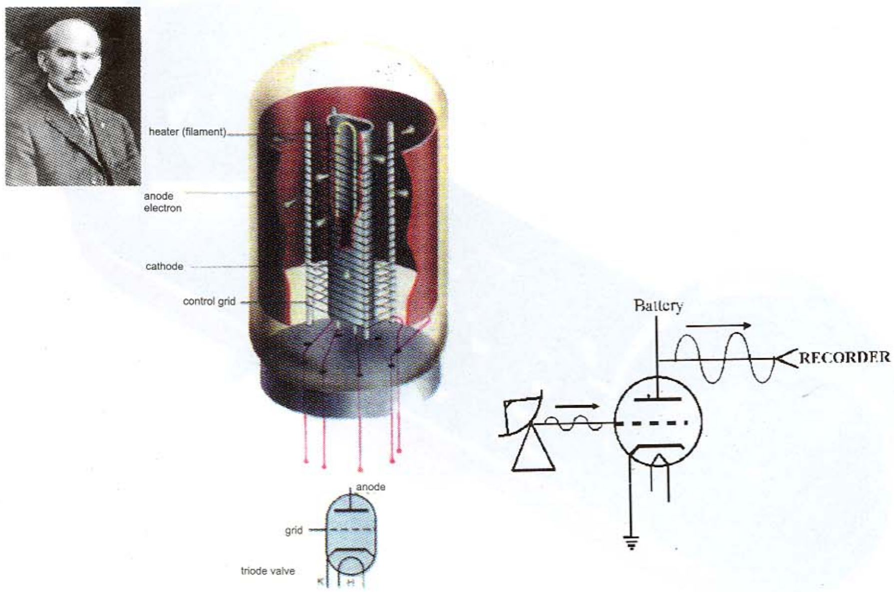


Figure 23.

the red light in a photographic dark room). This is just as in Einstein's effect, when electrons are emitted from the surface of some metals only if the wavelength of the light is shorter than a certain limit. Electrons so emitted can be accelerated by batteries to operate a recording instrument.

Individual radio photons have like a million times less energy, and even in swarms of millions cannot free an electron from its atom, to be accelerated and used further. Astronomical radio sources create currents in antennas too weak to trigger any detector, unless they can be **amplified** in some device. One such called a triode was invented in 1906 by Lee de Forest, in which the electrons needed to do the job were liberated not by light, but by heating a filament in an evacuated tube (Figure 23). The stream of electrons could then be modulated by the weak signal from the telescope, and boosted in energy ten-thousand fold or more by batteries, to adequate strength to operate a **detector**.

I used to think that only those well past retirement would have seen a vacuum tube, leave alone used one to make anything. But I discovered quite recently, that the amplifiers used in rockbands have tubes like the 6L6 and 6V6 because, other types of amplifiers cannot sound right, says my kid who plays the bass guitar, and is bigger than I am. I quote from an advertisement for such amplifiers, "Only vacuum tubes achieve warmer, more attractive sound and cooler smoother transitions"! In any case, here is a picture from my collection of over half a century ago, for the benefit of those not familiar with the variety of vacuum tubes that were in use (Figure 24).

Figure 24.

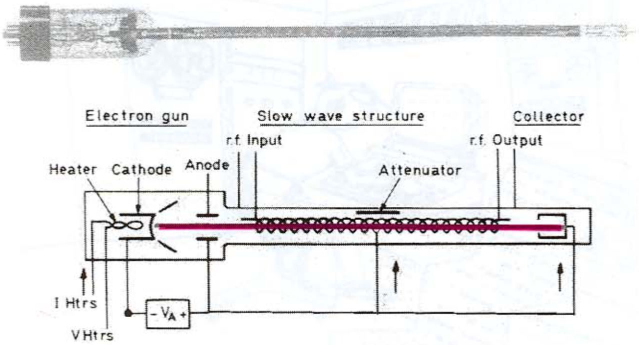
I come now to an important point.

It was *not* the type or size or frequency of Jansky's antenna that was crucial, for his brilliant and historic discovery, but the device that built up the signals to a detectable level. The Radio Universe was made apparent by the *vacuum tube amplifier.*

The lightest of the particles of which all matter is made up, is my friend the electron, undeniably mankind's greatest servant. Evaporating it with heat from a metal in a vacuum enclosure, and accelerating it with electric fields ushered in both the *name* and the *age* of electronics.

The triode was not invented at Bell Labs but they lost no time buying the patent from Lee de Forest, improving its performance, and using it for long distance telephone communications. But wanting something more reliable, less bulky and less heat producing, they launched an unrelenting effort to invent other and better devices to amplify signals which goes on to this day.

The first was the traveling-wave amplifier (Figure 25), a different kind of vacuum tube with an electron gun, and a helix, along which the signals traveled and grew in strength. Although it played an important part in transcontinental communications for a long time, it made only a brief appearance in radio astronomy in the fifties.

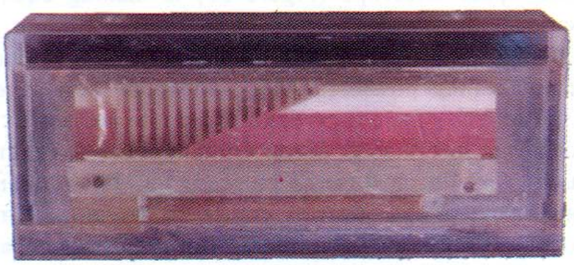


A travelling wave tube amplifier

Figure 25.

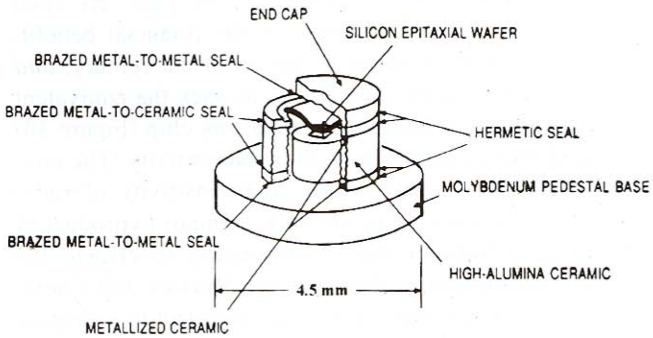
The next major device was the maser (Figure 26) which I have mentioned already in connection with the measurement of the microwave background radiation. Unlike the free electron devices which required heating to several hundred degrees above ambient, the maser required cooling to within a few degrees of zero on the absolute scale of temperature. The signal interacted with a crystal of ruby and was amplified by the energy given to the ruby at another frequency called the **pump**, and not from a DC source like a battery as required by the electron tubes. The price paid for the superior performance, was a heavy, complicated and cumbersome device, despite which, for some years, there were many radio observatories that had a maser receiver. I spent a year in 1961 at Bell Labs building a couple of them for Caltech, during which time I think I learnt more than in any other year of my life.

An almost concurrent development at Bell was the parametric amplifier. Like the maser, the device was a solid, and the energy to amplify the input signal was provided at another frequency also called the pump. But unlike the maser, it was tiny, could work even at room temperature, and for over a decade or two the parametric amplifier (Figure 27) served as the front-end of choice for radio astronomy receivers at many observatories. It has now been totally displaced by the transistor, another device invented by our friendly telephone company.



Cut-away model of Ruby Travelling Wave MASER

Figure 26.



Parametric Amplifier

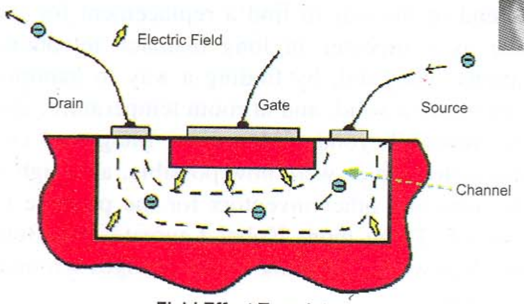
Figure 27.

The history, as some of you may know, was that Bell Labs assembled a bunch of super whiz-kids (Figure 28) towards the end of the war to find a replacement for the vacuum tube as a repeater in long distance telephone communications. They did, by finding a way to manipulate electrons *inside* a solid, and at room temperature, and created a revolution beyond imagination. Integrated circuits and microelectronics were now possible, although it took two decades and other inventors for the promise to be fully realized. Three more Nobel Laureates for Bell, but not a big deal when you think of the changes wrought by their invention.

Bardeen, Shockley and Brattain

Figure 28.

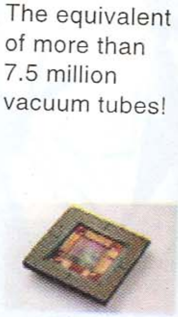
The particular type called a Field Effect Tran$istor (FEET) (Figure 29), now used as the most sensitive amplifier over the whole radio spectrum, is the kind that functions most like a vacuum tube. It was invented in theory by Bill Shockley the brilliant leader of the group when they started their work in the late forties. But by the time it was realized in practice, Shockley's associates had left him as impossible to work with, and the public hated him because he wanted scientific investigations into the possible dependence of intelligence on race. He died without getting adequate credit, or the financial benefit, for thinking up the greatest invention of the century, *and* starting Silicon Valley. The ability to pack the equivalent of many million vacuum tubes into a tiny chip (Figure 30) has transformed every branch of human activity. The consequent change in size, speed, and sensitivity of radio astronomy receivers, is, in my view, a minor byproduct of this major revolution that is continuing to change the world. It is interesting that both the Physics and Chemistry Nobel prizes this year were awarded to scientists who developed devices.

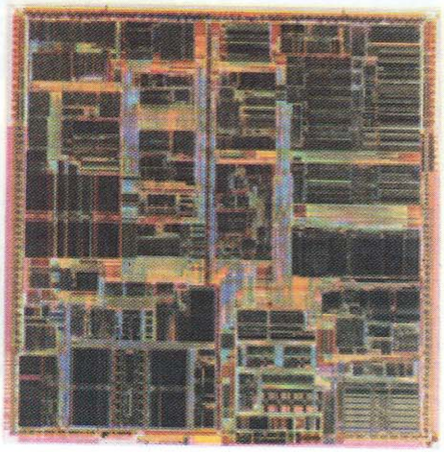


Field Effect Transistor

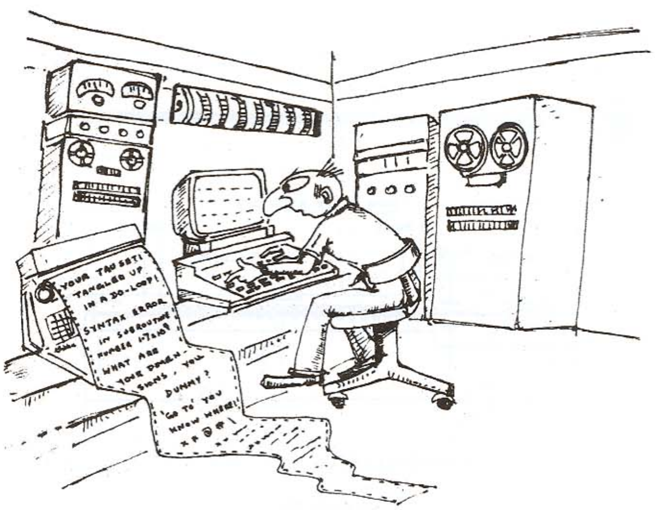
Figure 29.

The equivalent of more than 7.5 million vacuum tubes!





The only vacuum tubes that are still made in the millions are for people to stare at dumbly (Figure 31). It is considered normal to do this all day at work whatever your profession, but if you want a break you can always go home and watch TV.



The typical modern astronomer, a terminal case

Figure 31.

If I may go back to my hang-up about the dual aspect of radiation, then anything shorter in wavelength than visible light like ultraviolet, X-rays, etc, arrives in packets with more than enough energy to rip electrons off atoms they happen to encounter, and disappear in the process. So none of this radiation can get through the atmosphere and reach the ground, and we remained in total ignorance of whole new views of the universe, waiting to be seen at higher and higher energies. World War II rockets and high altitude balloons (Figure 32) carrying detectors gave us our first glimpses of totally different scenes from those we knew. But it was the launch of *Sputnik* and the ensuing politically motivated space-race that made possible bigger and bigger artificial earth satellites that are bringing us a continuous stream of new and sensational astronomical discoveries. Most of these are in windows of the electromagnetic spectrum inaccessible from the ground, but the Hubble Space telescope (Figure 33) is making equally sensational discoveries in the visible range despite its small size by ground based standards. The advantage which makes this possible is **being above the** atmosphere and not suffering from the twinkling I mentioned earlier.

As I was just saying, X-ray photons have more than enough energy to make their presence felt when passing through matter, and when it comes to detectors X-ray astronomers suffer an embarrassment of riches. They have many different ways of using the energy of X-ray photons to liberate electrons to determine the intensity of the radiation. (See Box 3)

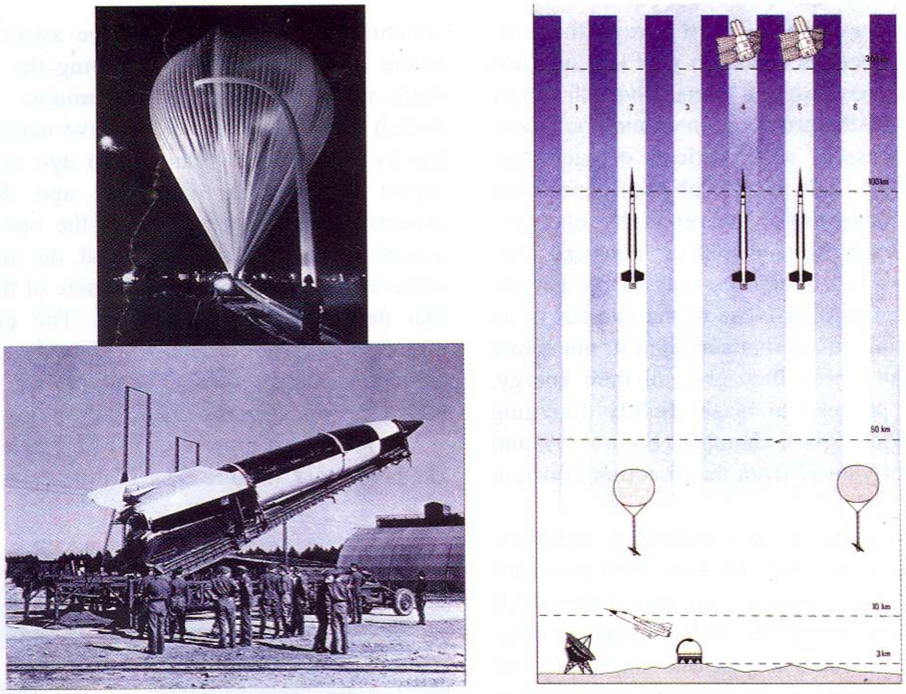
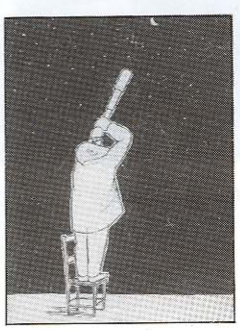
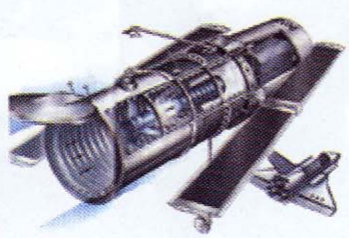


Figure 32.





The Hubble space telescope

Figure 33.

Box 3.

Types of X-ray detectors

- Proportional Counters
- Microchannel Plates
- Semiconductor Detectors
- Scintillators
- Phosphors
- NEADs
- Single Photon Calorimeters

But to know where the radiation comes from would require focussing and imaging as in an optical telescope, something that depends on its wave aspect. And perversely, the more energetic a photon, the more Macho it gets and the less it wants its sinuous aspect to be seen or used. X-rays cannot be refracted by any medium, and even the magnificent Keck mirrors cannot reflect them. Its surface would look like a sieve to radiation whose wavelength is smaller than the separation between the atoms in the reflector surface. But tilt a sieve to your line of sight (Figure 34), and there will be an angle where you don't see the holes any more and the surface will look and act like a continuous sheet of conducting material to give you good reflection. Thus do X-ray telescopes focus radiation that is not of too high an energy. This is not the theory of total external reflection as an X-ray physicist might explain it, but a good enough analogy for today's purposes.

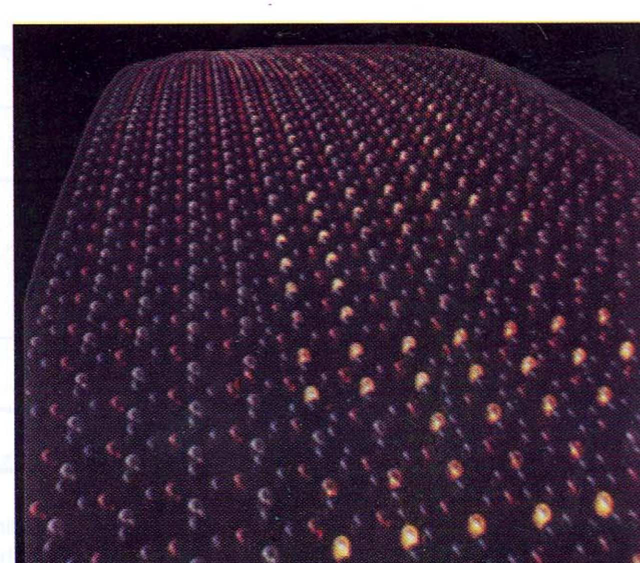


Figure 34.

As you go up in energy, beyond hard X-rays, the grazing angle that will reflect the radiation gets less and less and the efficiency of the telescope starts to vanish. There is no way to manipulate the propagation of such radiation. To associate a wave aspect with particles of such high energy is just an act of faith that no physics experiment can easily, or at all, demonstrate. At even higher energies, the impossibility of building any kind of focussing telescope is made up for in an interesting way by the gamma rays themselves. When passing close to the nucleus of an atom, they ignore the electrons that surround it, but create a pair of new ones to which they give all their energy. These two electrons proceed to blaze slightly diverging trails in a device called a spark chamber (Figure 35), and the swath points directly away from the direction of origin of the radiation.

There are many sources of such extremely energetic radiation and one can make maps showing their positions on the sky. I would like to show you one such, which fascinates me because it is so different from maps at other wavelengths. Each point here is just one single photon! (Figure 36). We have already encountered the opposite situation at the other end of the astronomical spectrum, where there is no way of showing the particle aspect of radio radiation. Right in the middle of this enormous stretch we have light, whose wave nature was demonstrated by Young 200 years or so ago and whose particle aspect by Einstein 100 years ago. Remarkably, both aspects manifest themselves in the operation of the first astronomical detector I discussed, the human eye. It is the wave aspect combined with the size of the lens in our eyes that determines the resolution. The particle aspect, as already discussed, is manifested in the photochemistry of detection. I shall turn now to the most modern device which has replaced the eye in astronomy.

We have here a picture of two gentlemen at work in a US laboratory (Figure 37). No prizes for guessing which

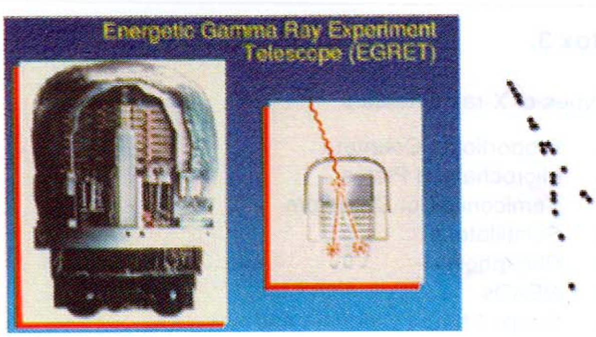
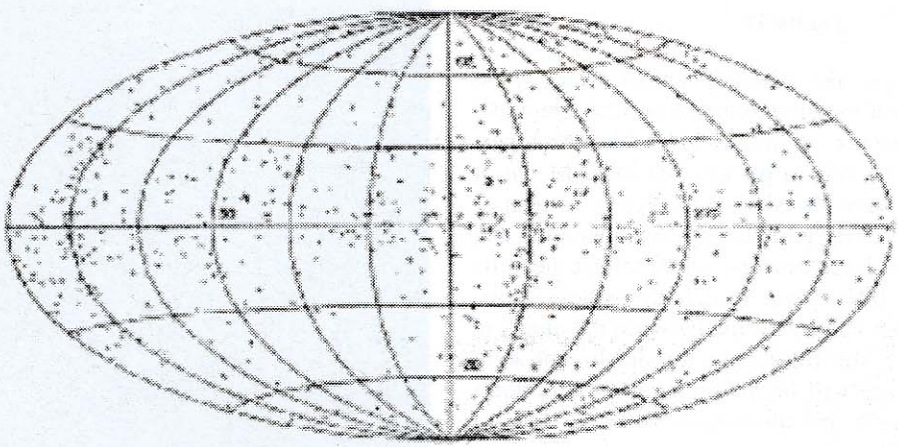


Figure 35.

Willard S. Boyle and George E. Smith, inventors of the CCD at Bell Labs.

Figure 37.



Distribution in galactic coordinates of gamma rays > 50 Mev observed by OSO-3

Figure 36.

lab, or which device they were trying to improve. The sound quality of telephones had been good for decades, so what were they trying to fix? The lack of vision. Boyle and Smith were creating the picturephone so you could see who you were talking to, and be seen by him or her. For this they invented something called a charge coupled device or CCD, based on a new principle. The incident light liberated electrons *within* small but separate elements of semiconducting solid in which the charges were accumulated over the exposure time, and then pushed out one behind the other like a line of boxcars. The contents of each are then used to generate an image with picture elements of brightness proportional to the amount of charge.

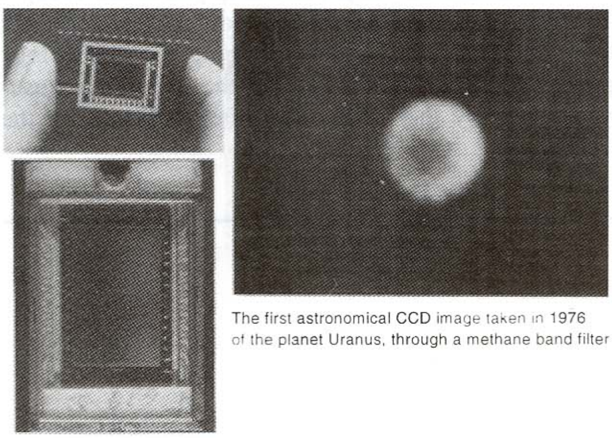
The energy required to make electrons available for *internal* conduction is far less than to release them from the solid surface (as in Einstein's photoelectric effect) and so CCDs could work even at "long" wavelengths like the red, and with refrigeration well down into the infrared. Higher energies like X-rays posed no problem in principle, and technical adaptation was all that was required.

The situation today, thirty years after the first invention, is a revolution in the detection of electromagnetic radiation just as spectacular as the transistor revolution, which it incorporates. Your electronic cameras both video and still, the surveillance devices in supermarkets, banks and big apartment complexes, your scanners and innumerable other applications, all use CCDs (Figure 38). They are the most sensitive detectors at the back-end of every major and most minor telescopes in the world at infrared and shorter wavelengths. Apart from imaging for which they are so obviously suited, they have transformed astronomical spectroscopy, just as photography did when it was first introduced. Space-based telescopes depend on CCDs and use them well into the X-ray band.

One very heartening consequence is that amateur astronomers can put very affordable CCDs on their modest telescopes, and do better than the professionals did with their big telescopes not so long ago, as seen in the picture (Figure 39). There is a lot of useful science that I believe is being done by amateurs today, and I find this some consolation for their sad disappearance from radio astronomy, a field pioneered by radio hams, an ultimate example being Grote Reber. The emergence of national and international facilities, that no single institution or sometimes even nation can afford, spelled the death of the amateur era when individuals who had conceived, constructed or modified their equipment, could feel some justifiable identification with their astronomical findings.

I hope I have conveyed my message that astronomy has depended enormously on the use of devices originally created with no thought of the sky in mind. This supports the view of Jared Diamond, a very perceptive social scientist, that "Invention is the Mother of Necessity", and not the other way around. There are numerous other examples such as the Global Positioning System (**GPS**), set up originally for strictly defence purposes, but now used as time and frequency standards at most astronomical observatories. And much more by pilots, sailors, trekkers and even taxies and rental cars. Another is optical fibre which carries the bulk of the world's communications today, and is finding specialised applications in astronomy. A very clever use in optical spectroscopy is to have a bundle of fibres, each carrying the light from one of hundreds of stars in a given field of view of the telescope. The other ends are arranged in a line to feed into a single spectrograph, and all the spectra are obtained simultaneously, giving a spectacular increase in speed.

Optical fibres are the best way to connect radio telescopes in an array to the central processor as is now being done at NRAO. In 1961, the year I spent at Bell Labs, I remember first hearing about work on developing optical fibres to replace telephone cables, and it sounded then like science fiction. But in this case, one can go much



The first astronomical CCD image taken in 1976 of the planet Uranus, through a methane band filter

Figure 38.

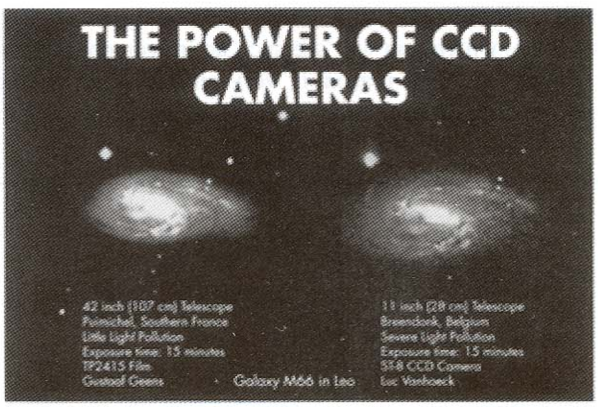
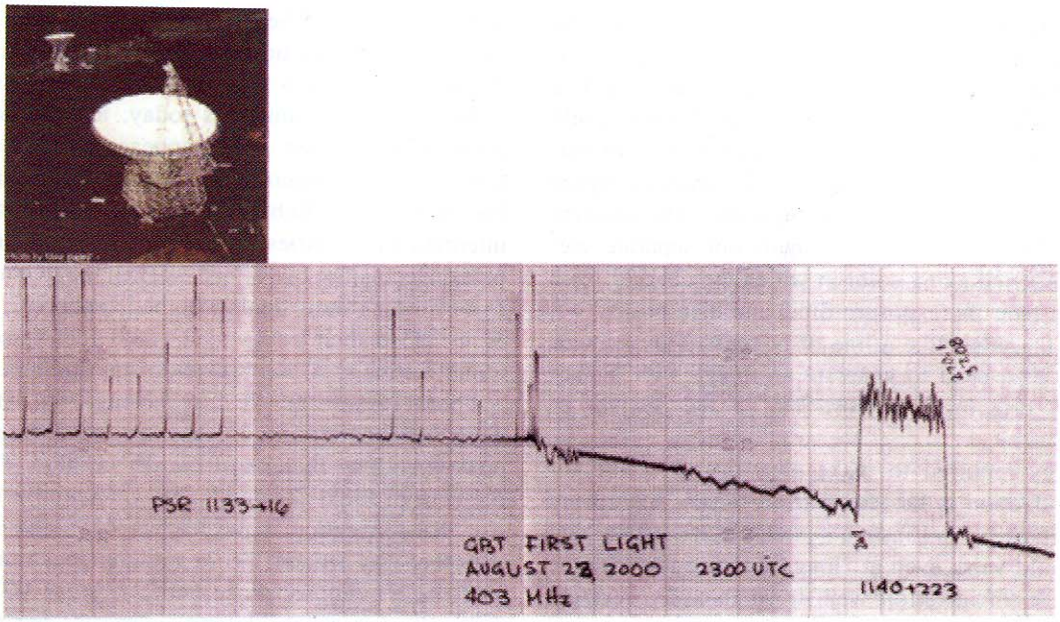


Figure 39.



First light with the Green Bank Telescope

Figure 40.

further back to support the theme of my lecture. A patent for a method of manufacturing optical fibres was taken out in the 1930s, with the inventor's comment, and I quote **in case, someone ever finds a use for it**.

Whatever type of astronomy we are talking about, the ability and importance of being able to record vast amounts of data at high rates will remain paramount. And the last topic I wish to touch upon is the revolution in recording ability, a development motivated in total oblivion of any astronomical implications.

I was very sorry to miss the dedication of the GBT (Figure 40), but my heart was warmed to see that its first light was received on a chart recorder, a most venerable instrument of the vacuum tube era, that I've spent years looking at. Jocelyn Bell in her Jansky lecture described the search through hundreds of yards of paper chart to find little squiggles that were, in that case, eventually worth a Nobel prize. But, there is probably no observatory today where you will see such an instrument in actual everyday use. The reason is very simple. The message from on high arrives today not at the rate of about 1 bit per second, just right for a chart recorder, but millions or billions of times faster. And the reason for that is the existence of the ability to generate, collect and process such data, brought about *entirely* by the transistor revolution.

Very Long Baseline Interferometry was conceived because tape recorders existed, and they did because of the entertainment industry. The staggeringly high recording densities, available today and even more promised for tomorrow, is thanks to Sony's development of tapes and drives for its Camcorders, not exactly astronomical applications.

I think I have said enough to convince you about the extent to which astronomy has been dependent on the use of devices made for applications that normal people can relate to. This should I hope, also help you to see **today's** astronomer in proper perspective as more likely just another consumer, or passenger riding the technology express, than a hotshot explorer of the universe, as usually depicted by the media, and often believed by the astronomer.

The Karl G. Jansky Lectureship

The Karl G. Jansky Lectureship is an honor established by the trustees of Associated Universities, Inc., to recognize outstanding contributions to the advancement of astronomy. First awarded in 1966, it is named in honor of the man who, in 1932, first detected radio waves from a cosmic source. Karl Jansky's discovery of radio waves from the central region of our Milky Way Galaxy started the science of radio astronomy.

The recipient of this award delivers the annual Karl G. Jansky Lecture, to which the public is invited. The lecture is delivered in Charlottesville, VA, and Socorro, NM, and, whenever the recipient's schedule allows, also in Green Bank, WV, and Tuscon, AZ. In Charlottesville and Socorro, professional astronomical symposia are conducted during the day prior to the evening public lecture.

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