1966 Karl Jansky Lecture.

First, I must acknowledge the honor bestowed on me by the University of Virginia, the Trustees of the Associated Universities Incorporated and my friends and colleagues at the National Radio Astronomy Observatory who invited me to give the first Karl Jansky memorial lecture.

Being the first lecturer I am of course fortunate in having an unlimited choice of subject intimately associated with the man to whom this lecture series will be a continuing memorial. I do not face the difficulty faced for example by the Halley Lecturer at Oxford — where the lecturer has a struggle to involve Halley in his first few sentences — and then changes the subject as quickly as possible. I think it would be true to say that few scientific discovers in history have seen their initial discovery proliferate so rapidly ~~[illegible]~~ At the beginning of the modern era of radio astronomy in 1946 — the year I started work in the field — some six papers had been published on the subject. Nowadays some six new papers on radio astronomy arrive on my desk each week. From this you can see that ~~if my~~ with a topic were to be Jansky's work and where it has led us, I could only hope to cover a very small fraction of the consequencies. For this small faction I have selected four objects to talk about ranging from one of our solar system's planets through our own Galaxy — the source of Jansky's discovery to the most distant object known to man. Hence our lecture title.

I regret that I did not know Jansky personally, he died a few months before my first visit to this country (in 1950 at the age of 44) and the Bell Telephone Laboratories where his work was carried out. In 1928 as a new recruit, he was assigned to an investigation of the source and seasonal variations in the static which at times severely limited transatlantic communication in the 15 meter band. For this purpose he built a receiver and a moderately directional antenna looking horizontally over the sea near Holmdel, New Jersey. A replica of this antenna stands near the museum at the National Radio Astronomy Observatory at Greenbank, as does a reconstruction of a parabolic dish used by Grote Reber – another American pioneer in radio astronomy.

Having completed his equipment Jansky began his study of the diurnal and seasonal components of the radio static and its direction of arrival. He recognised three distinct sources, one due to local thunderstorms whose nature was clearly obvious, one which he attributed to disturbances of the same nature but at much greater distances and a third which on audio monitoring produced a steady hiss – similar to that which you may hear on your TV receiver if you turn up the volume when the stations are off the air. Part of the hiss you hear is electrical noise generated in the first stage tubes or transistors and part – particularly for the low number channels – is Jansky's hiss

Jansky soon found that this third component was strongest at a certain time of day when his antenna was directed towards the south east. He further noted as the weeks went by that the time of day when it reached a maximum was steadily getting earlier. After some months it was clear that this rate would amount to a whole day after a year had gone by. This discovery was not however as simple and straightforward as it perhaps appears because his records were not of the third component alone but were often dominated by the very variable thunderstorm activity.

However a years observations definitely confirmed that the source of the mysterious hiss ~~was~~ had an apparent motion similar to that of the stars and was coming from space. The earth rotates on its axis 366 times each year. The number of days in the year defined by the Sun's rising and setting is one less — the missing day is due to the earth's orbital motion round the Sun each year ~~on~~ If the orbital motion were in the opposite sense we would have one extra day. The stars being at much greater distances rise and set with the true rotation period — in other words 366 times a year and the times of rising and setting occur 4 minutes earlier each day. From the time at which the maximum of the radiation passed through his antenna beam and the azimuth Jansky was able to establish that the source of the radiation coincided with the brightest band of stars we call the Milky way It was strongest in the direction in ~~whose~~ which astronomers believed the center of this system lay.

Thus radio astronomy began — however it did not really prosper for another fifteen years. During the early war years Jansky's hiss made its presence felt in radars working in the one to five meter wavelength range. The sensitivity or ability to detect the weak echoes from aircraft or ships varied considerably ~~with the~~ depending on whether the antenna beam intercepted part of the Milky Way. It was these effects and the occasional very strong signals received from the Sun when there were large sunspots present that started British radar scientists in England and Australia on a systematic investigation of Jansky's hiss after the war.

Nowadays we are aware of many sources of Jansky's radiation and of the very different ways in which it is produced. We know that there are at least ~~three~~ four basic mechanisms for its generation. Firstly we receive radio waves from any solid body that is warmer than its surroundings. With ~~radio~~ sufficiently sensitive radio telescope you could make a radio map of this hall showing the bodies, the seats of the chairs you are sitting on and the lights around the hall. Similarly looking into space we can see the Moon and the planets. This type of radiation we call black body radiation. It has the characteristic that it is strong at very short wavelength and ~~[illegible]~~ weak at long wavelengths.

A second type of radiation is hot ionised or electrified gas. This we call thermal radiation. On earth fluorescent light tubes are a well known source. In the sky the Sun's outer envelope called the corona and the vast interstellar clouds of gas surrounding very hot stars are well known sources. This radiation can also be recognised as its intensity is independent of wavelength until the gas becomes opaque at long wavelengths when its characteristics change to those of the first type.

The third type of radiation is known as plasma radiation and it arises from a gross oscillation of ionised gas. This can be produced in the laboratory and at times of high sunspot activity it greatly increases the radio output of the Sun. Its characteristics are that it is restricted to fairly narrow wavelength ranges and it varies rapidly with time. Its emission from the Sun often coincides with explosions on the Sun's surface which give rise to the streams of particles responsible for the aurora, in fact we can trace the passage of these bursts of particles through the Sun's atmosphere by studying the plasma radiation it generates at the various levels in the atmosphere.

With the exception of certain nearby stars which have something akin to sunspots but on a much larger energetic scale, even with large modern radio telescopes we cannot detect radio emission from the stars. Most of the radiation from our galaxy comes from the tenuous regions of interstellar space, from objects such as supernova remnants and it is due to our fourth process. This is synchrotron radiation, generated by relativistic electrons — electrons which have almost the speed of light. When these encounter a magnetic field they are constrained to orbit round the field lines. In doing so they radiate some of their energy and the wavelength range of this radiation is determined by their energy. If it is very high — as in a laboratory synchrotron — from where the process gets its name — the radiation is in the form of light. For lower energies it occurs in the radio band. This is the most powerful source of the cosmic radio waves that we detect with our telescopes and it is this radiation that enables us to detect objects into the distant reaches of the universe — some beyond the biggest optical telescopes. The characteristics of this radiation are that its intensity generally increases with wavelength and that it is linearly polarised. The plane of polarization gives us the direction of the magnetic field and so enables us to determine the structure of the field in the sources of synchrotron emission.

So much for the mechanisms of radio emission. Now let us look at some of the radio sources and do it in what I believe is the order of increasing distance.

This next slide shows two of them, one which was at the time these observations were made, a well known radio source and the other an amazing chance discovery. The observations were made by Burke and Franklin at the Department of Terrestrial Magnetism in Washington D.C with a cross type radio telescope operating at a wavelength of 15 meters. The record shows the signal increasing and then decreasing as the sources in turn crossed the antenna beam. Close inspection shows that the radiation from the left hand source is a series of short bursts and that the time of crossing the beam changes relative to the right hand. This is rather like Jansky's observation of the time difference in his observations. From this motion Burke and Franklin were able to deduce that the burst emission was coming from the planet Jupiter and in the following months found that it was restricted to rather long wavelengths and varied considerably from day to day. As it happened, this radiation had been observed but not recognised by CA Shain in Australia several years before. Due to his very wide beamed antenna ~~and~~, the sporadic nature of the radiation and the similarity to ordinary static from thunderstorms, he had attributed it to thunderstorms. However, knowing of Burke and Franklin's result he was able to make good use of his pre-discovery observations. By studying the time at which the burst radiation occured together with the appearance of the visible spots on Jupiter's surface he was able to show that the burst source was rotating a little faster than the visible features. Now these visible features are not on the surface itself but in the atmosphere of which on Jupiter is believe to be methane and ammonia. Now the atmosphere probably can lag behind the solid surface and Shain believed that his faster rotation period probably represented that of the solid planet. By observing the burst radiation for nearly 10 years astronomers have been able to determine a very precise period for the planet.

Meanwhile at the Naval Research Laboratory, radio astronomers had been studing the very short wave end of Jupiter's radio emission. At wavelengths shorter than 10 cm they had observed steady radiation in agreement with the optical measurement of Jupiter's temperature ~ 130° K. However at 10 cm they found a temperature of ~ 400° K. A much greater excess was found at 20 cm at Green bank and at 30 cm at Caltech. This occurred very shortly after the discovery of the earths Van Allen belt and many astronomers simultaneously suggested that Jupiter could possibly have a much greater Van Allen Belt Of the high energy particle density were much higher and the magnetic field much greater this would radiate by the synchrotron mechanism. Proof had to wait a further year for the completion of the two 90' antennas at Caltech when J A Roberts and V Radhakrishnan were able to show that the radiation did come from a belt about three times the diameter of Jupiter and that the radiation was linearly polarized – evidence for its synchrotron origin. Later Morris and Berge showed that the plane of polarization the fraction of polarization and the radiation intensity all changed ~~with~~ in step with Shain's rotation period. These ~~observations~~ effects as observed by Roberts with the Parkes telescope are shown in the next slide and they are interpreted as showing that

Jupiter's magnetic axis is inclined by about 10° to its rotation axis – as is the earth's. As the planet rotates the angle of the belt tips back and forth by a total of 20°

Some astronomers believe that the long wave radiation is due to the dumping of electrons from the Van Allen belt due to local disturbances from perhaps the Sun and a similar phenomena may happen near the earth poles during aurorae. It is perhaps interesting to reflect that some of the "distant thunderstorms" that Jansky observed possibly came from Jupiter or from similar activity on our earth.

While my own interests are principally on the much more distant radio sources I have spent considerable time on Jupiter. It is of great interest in showing just what can be accomplished by radio techniques and it is the one object ~~in~~ which ~~a~~ is near enough for space probe observations ~~could~~ to help greatly in obtaining data on the detailed processes in an extraterrestrial sychrotron emitting object.

My next object takes us out a few thousand light years rather than the few light minutes of Jupiter. Around 1946 Australian and British radio astronomers showed that Jansky's broad band of emission could be resolved with interferometers into discrete sources and the first of these sources to be positioned accurately enough to permit its optical identification was the Crab nebula (slide) This is an object with a long astronomical history in fact the first observations were made in 1054 by Chinese astronomers. This nebula was once we believe a star – a star that exploded and whose explosion was seen by the Chinese. It suddenly appeared as a brighter daytime star in 1054 and gradually faded over the following year. By studying the Chinese records Baade and Minkowski were able to show that the remnant here is at the same position as the Chinese superstar or supernova as we call them. Photographs taken at about ten year intervals show that this nebula is expanding and the expansion rate suggests it started about 900 years ago. From spectroscopy we know the expansion velocity and hence the size and distance. The nature of some of the light was a puzzle for many years. From this and the radio emission Soviet astrophysicists predicted that the radio and light might both be synchrotron radiation and that the light might be polarized, This polarization was found in the late 1950's and from its study optical astronomers have been able to map the magnetic field of the nebula. More recently Xray astronomers working with Xray detectors in rockets have been able to locate a strong Xray source in the nebula. The Crab is the only such supernova remnant with easily visible radiation, however up to fifty of these objects have been located in our Galaxy by the radio astronomers and in a number of cases the faint visible remains detected.

The first and one of the strongest radio sources – Cygnus-A took a further four years to identify. Its final identification was due to an extremely accurate position by Cambridge radioastronomer Graham Smith and the follow-up by Baade and Minkowski with the 200" telescope. Direct photographs showed that the Cygnus-A source was a galaxy but a spectrogram showed that it had a very unusual nature. In a spectrograph the light is spread out over its wavelength or color range and spectra of stars or galaxies are generally characterized by emission or absorption lines due to the individual elements. In the case of a distant galaxy these lines are displaced towards the long wavelength or red end of the spectrum by an amount which depends on the velocity at which the galaxy is receding from us. This red shift or recession velocity is used a measure of the distance of the object. In the nearby universe where there are alternative methods of establishing distance Hubble many years ago showed that the velocity or red shift was directly proportional to the distance. ~~The~~ For reason it appears that the universe is in a state of expansion. Now, due to the finite speed of light as we look out into space, we also look back into time, a galaxy we see now at a distance of say a million light years, we see as it was a million years ago — and so on. By going to bigger and bigger distances the astronomer or cosmologist has as one of his aims an understanding of the evolution of the universe, whether it be in terms of individual galaxies or of the expansion itself. One of the things he looks for is deviation from the linear law of the redshift, the relation between the distance measured by velocity and some other means such as the brightness or diameter of a galaxy. Such deviations predicted by the various cosmological theories are not expected to show for the relatively small redshifts of the order of $\frac{1}{10}$ of the velocity of light — as were available 15 years ago. Until the advent of the Cygnus-A identification the detection of distant galaxies was a difficult task — just by examining an faint image on a photographic plate you cannot be sure whether you are seeing a bright galaxy a long distance away or an intrinsically faint one quite nearby. Moreover many hours or even nights on a large telescope were required to obtain a spectrum.

The importance of the Cygnus-A object is shown in the next slide which is a schematic representation of the spectra of a normal galaxy and Cygnus-A. In the normal system

The measurement of distance depends on the location of such features as the two faint absorption lines indicated. Their wavelength are measured against a laboratory spectrum exposed on the same plate. In the Cygnus-A spectrum in contrast to the barely visible absorption lines there are a series of very bright emission lines which can easily be seen with a much shorter exposure. From other closer identifications of radio sources with galaxies we knew that the galaxies concerned were amongst the brightest – optically of all galaxies and so we had two important results. First that the radio sources could select intrinsically bright systems and second that the measurement of their distance was a far less difficult task. However it was not until 1960 – eight years later that a really big step was made – a step which involved a new generation of radio telescopes and contributions from 3 radio observatories and one optical observatory. First the Jodrell Bank Observatory of the University of Manchester had detected a number of very small diameter radio sources using long baseline interferometry. As the apparent size of a source could reasonably be expected to decrease with distance effort was concentrated on the smallest diameter sources. For one, 3C 295, the Cambridge and Caltech observatories provide very accurate positions – in good agreement with each other, indicating very small likelihood of experimental errors. A search of the 48" Sky survey plates yielded two objects within the radio position errors and a spectrum of one of these galaxies by Minkowski showed it to be of the Cygnus-A type with the then incredibly large red shift of 0.416 – a recession velocity of about 100 000 km/sec. For this galaxy the light travel time is of the order of the age of the earth (4 billion years), the Sun and the stars of our Galaxy

For the first time the astronomer was close to overtaking the geologist.

For a galaxy, Minkowski's record still stands. Calculations suggest that it would be possible to detect similar systems with velocities of 0.6 c. The difficulty in going further is that most of the radiation from a galaxy is in the visible band and the bigger the redshift the further this radiation is shifted into the invisible infra red which is cut off by the earth's atmosphere and does not register on photographic plates.

However although there was a halt in the direction of more distant galaxies, the advance to bigger and bigger red shifts went on. For the very next identification — 3C48 — revealed a new class of objects which do not suffer the disadvantage of the galaxies. Again a small diameter radio source, again two independent position measurements in good agreement but this time not a galaxy but what appeared to be a star. Analysis of the light showed a spectrum quite unlike any normal star and one which defied interpretation for nearly ~~eighteen~~ two years. Several more of these objects were found in these two years but the most important was the identification of 3C273 by Hazard Mackey and Shimmins using the 210' telescope at Parkes. It is interesting to note that each advance into space has resulted from an improvement in the position determinations by radioastronomers. The most accurate method is that of lunar occultation where a source is seen to disappear behind the limb of the Moon and some time later reappear. However it is only possible with large steerable telescopes with very precise motion control. Hazard had pioneered this method with the 250' telescope at Jodrell Bank but his first major success was with the Parkes instrument

The occultation of 3c 273 showed that the radio source was double, one component coinciding with a faint dot of light and the other with a comparatively bright star. From its spectrum Maarten Schmidt found that the lines could be identified if it had a red-shift of fifteen percent of the velocity of light — almost 3 times as great as the Cygnus galaxy. Moreover he could interpret the spectra of the other objects by assuming much larger redshifts. The next slide shows a schematic spectrum of a typical quasi-stellar object or quasar as these are called and how the identifying lines move from the far ultra violet into the visible as their velocity or redshift increases. The ~~most distant~~ largest red shift implies a velocity of nearly 80 percent of that of light — 240.000 km per sec. The identification of these lines and the redshifts has been one of the most exciting pieces of scientific detective work in history and has potentially enlarged our knowledge of the history of the universe by a very large factor. I say potentially for there are problems associated with the quasars. 3c 273 for example appears 10 times brighter than the Cygnus-A galaxy and if its redshift is interpreted as indicating distance it is 3 times further away. Thus its intrinsic energy output is 100 times greater or equal to the output of 10^{13} stars like our Sun. It appears as just a point of light — it cannot be resolved in the largest telescope and its volume must be less than a millionth of that of a galaxy. Other considerations suggest that quasars are in fact very much smaller than this for their light output has been observed to vary by factors of 10 over just a few months. If we assume that the whole object is involved, then it cannot be larger than the distance light can travel in ~~a few~~ this period, ie a few light months — in other words its size is quite small compared to the distance from the Sun to the nearest star. If the quasars are at vast distances and if they exist for any reasonabley fraction of the age of the universe then we require an energy source which is more efficient than ~~that which~~ the most efficient we presently know — the conversion of hydrogen to higher elements.

There are two possible alternatives to the interpretation of the redshifts as cosmological ie ~~as~~ indicators of distance based on the general expansion of the universe. The first is that the red shift is due to gravitational effects — that the quasars are extremely massive objects of very small radius and that the light is slowed down in the huge gravitational field. However Maarten Schmidt has shown that if all their observed features are to be consistent then in order that their gravitational effects on other nearby bodies are to be beyond detection, they have to be placed at distances so great that at least part of the redshift would be cosmological and the energy supply problem would still be present. From gravity effects alone the largest redshift possible would be 2 and already four objects have been discovered with red shifts in excess of 2.

The other alternative is to say that the redshifts are due to the velocity of the objects – as in the cosmological interpretation, but that they are quite close objects which have been accelerated to these velocities in an explosion. Because we don't see any quasars with blue shifts, ie coming towards us, the center of this explosion has to be quite close to us, ie in our own Galaxy or certainly in a nearby system. However as we see equal numbers in all directions their distances must be greater than the radius of the galaxy. From their apparent brightness we can estimate their masses, then from their number and velocities we can estimate the energy involved in the explosion. This theory while feasible for the time when only a few quasars were known is now almost certainly untenable for as the numbers discovered run into the hundreds, the energy required in the explosion begins to exceed the total energy available in our own – or any other galaxy.

At present I believe that the cosmological interpretation – that there are indeed very distant objects – must be accepted and the problem of the energy source must be faced. I should probably remind you that the same problem of the source of energy to keep the Sun and stars shining was a mystery only 30 years ago. Even though the quasars can be detected at distances much greater than can the galaxies we have not so far been able to use them for investigations into the evolution of the universe – at least not by investigation of their red shift luminosity relation. In order to do this we need objects which have essentially the same luminosity and what we observe is that the brightness of quasars with the same redshifts differ considerably – and as I mentioned before some show rapid changes with time. For certain types of

over.

quasar, however, the intrinsic radio luminosity appears to show much less variation from object to object than does the optical — and time variations in an individual object are certainly smaller. So perhaps a combination of radio discovery, radio luminosity and optical red shift may be our main hope for cosmological investigation in the future.