HORIZONS

Jan Hendric Oort

When we were young we may have watched how ships gradually disappeared when they were farther and farther away from us. We saw first the hulls disappear, while the masts remained visible. Finally, as they sailed away, even the tops of the masts dipped under the “horizon.” As children we were intrigued by this horizon. What was behind it? Grown-ups have a similar curiosity. They sailed to the horizon, and found there were new horizons behind, and that this was repeated almost eternally. Until at last they found they had circumnavigated the Earth, and had discovered the whole world.

But there remained the space above us: the realm of Sun, Moon and stars. From the earliest times from which writings have come to us it has been thought that the heavenly bodies formed the outer limit of the world. As there were no space-ships, they were unreachable. Nobody knew their distance.

However, Greek thinkers conceived models of the world which incorporated the heavens. Among many other things they understood that the eclipses of the Moon were due to the Moon’s coming into the shadow of the Earth. The observation that this shadow was round taught them that the Earth must have a spherical shape. They also used observations of this shadow to obtain a measurement of the distance to the Moon: because the Moon moved so fast, going around the sky in a month’s time, while the Sun took a year to do this, it was generally, and correctly, thought that the distance of the Sun must be considerably larger than that of the Moon. The shadow of the Earth over the range concerned must then be almost a cylinder, with a radius equal to that of the Earth. By measuring the angular radius of the shadow of the Moon one can therefore find the distance to the Moon, once the Earth’s radius is known. The latter had been determined by Eratosthenes from a combination of the linear distance between Syene in Egypt and Alexandria with the angular distance between the stars going through the zenith at the two cities. The resulting distance to the Moon was 60 times the radius of the Earth, or 400,000 km: the first measurement of a distance in space: It was a tremendous step.

Almost 2,000 years had to pass before the next jump, to the distances of the planets and the Sun could be made.

The Greek astronomers had conceived a model of the world in which all heavenly bodies were attached to rotating spheres. The outermost sphere, the “primum mobile”, contained the fixed stars. Inside this was a sphere containing the planet Saturn; it rotated around its own axis which was attached to the outer sphere. Then came the Jupiter sphere whose axis was attached to that of Saturn and again had its own rotation, and so on for Mars, Venus, Mercury and the Moon. At the center was the immovable Earth. The spheres were crystalline and transparent, so the inner ones did not obstruct the view to the outer planets. The model was fully described and transferred to later generations by Ptolemy in his famous work the Almagest, which for many centuries remained the standard textbook on astronomy. It was only in the 16th century that Ptolemy’s system was seriously challenged by Copernicus. He pointed out that it was more plausible that the daily rotation of the stars was only an apparent motion; that it was the Earth which was rotating and the stars were at rest. Furthermore, the Sun did not describe an orbit around us, but that we described an orbit around the Sun. An entirely new model of the planetary system was constructed by Copernicus and his followers, Tycho Brahe, Kepler, and Galileo. It was in this era that by technical refinement of instruments and the passionate devotion of scientists like Tycho and Kepler a second tremendous leap in measuring distances in the Universe was made. It was accomplished by measuring the direction towards a planet from two different positions. Due to the Earth’s rotation the observatory swings around, and will alternately see the planet in slightly different directions. Knowing the radius of the Earth the observer also knows the distance between A and B. Precise measurement of the angle between the two directions AP and BP then enables us to construct the triangle APB and thereby derive the distances AP and BP. It was a marvelous accomplishment: the angle between AP and BP, which was the essence of the measurement, being less than a minute of arc. In this way, the scale of the planetary system became known and the foundations were laid for the magnificent theory of gravitation by which Newton finally crowned the exploration of the Solar System.

But what about the fixed stars? Because they are fixed they should be much further away than the planets. But how much further? Some original scientists had already speculated that they might be similar in nature to the Sun. If this is so, their distances must be a million times larger than of the Sun, far beyond any distances that could be measured in Kepler's time. Once more, as in Brahe's and Kepler's time, three centuries earlier, it was an enormous advance in precision brought about by technical developments, and in particular the construction of large telescopes, the "spaceships" of those days which enabled man to measure the distances to the fixed stars. Just as in the case of the planets the measurements were based on trigonometry. But this time the basis of the triangle was not the diameter of the Earth, but the 25,000 times larger diameter of the Earth's orbit. Nevertheless, the measurements were at the extreme verge of what could be accomplished. The angle between AP and BP was less than a second of arc (which is the angle under which you would see a small coin at a distance of 2 km).

The observations confirmed that the stars were indeed of a brilliance comparable to the sun.

The measurements had also shown that the stars were not fixed but had considerable motions. A young Dutch astronomer J.C.Kapteyn of Groningen had even discovered a systematic trend in these motions which became known as "star streams." They were the first discovery of stellar dynamics.

A gigantic new world had become accessible to exploration. The research was started vigorously in a few centers. One of these was the University of Groningen.

It had long been recognized that the world of stars did not extend indefinitely; but it was unknown how far it extended and what shape it had. Kapteyn had set it as his task to find out. He also wanted to investigate the motions of the stars and the forces which held them together.

It was in this early stage of reconnaissance of the Milky Way system, or Galaxy, as the star swarm was called, that I began my University studies. Drawn to Groningen by Kapteyn's fame I was soon fascinated by the inspiration which radiated from his lectures. So much so that in my first year I tried to make my fellow students in law and medicine share this inspiration. And what luck it was for a student to grow up in an environment where through hard work and enthusiasm the first traces of a new world were being revealed!

This world contained so large a number of numbers (in fact, some hundred thousand million) that it was impossible to study them all. For this reason Kapteyn had proposed to concentrate out observations on some 200 small fields distributed over the whole sky, in which observations would be made down to the faintest observable stars. He managed to instill his enthusiasm in his colleagues, and persuaded a number of observatories spread over the world to join in this Plan of “Selected Areas.” The Groningen Department itself had no telescopes. It made its contribution by measuring plates obtained at other observatories. But its staff was too small to cope adequately with the enormous number of measurements required.

But Kapteyn was undaunted. He found a successful solution by asking and obtaining permission to get prisoners to assist in the work. During my student years the great project had already led to a provisional result. In this bold first model, the so-called “Kapteyn System.” the Sun was assumed to lie not far from the center of a spheroidal swarm which had an outer diameter of some fifteen thousand light-years, and a thickness of one fifth of this. The equatorial plane of the swarm coincided with the plane of the Milky Way, which gave it its name “Galaxy.” Of course there were no abrupt boundaries, the star density falling off gradually towards the outside. The distances suggested the density was about one tenth of that near the center.

My own work during the years in Groningen was directed to the motions of stars. A fellow student had drawn my attention to an article describing a peculiar property of the motions of stars which had high velocities relative to the mean of all stars measured. The phenomenon proved to be interesting. The investigation led to my first article in an astronomical journal, and later became the basis for my doctor’s thesis.

I was of course also involved in thinking about the Kapteyn System and its place in the Universe. In the “school” of Kapteyn the big swarm of stars surrouding us was the Universe. It ended at the outer surface of the swarm.

In this same period the Universe was also being studied at the Mount Wilson Observatory in California by a younger astronomer, Harlow Shapley, in a quite different manner. Shapley concentrated entirely on the so-called globular clusters. These are concentrated groups of stars, with some hundred thousand members each. By studying a special sort of variable star in these clusters, and by various other means, Shapley succeeded in finding their distances. These came out to be very large: several ten thousand light-years. If correct, the globular clusters would therefore lie well beyond the frontiers of Kapteyn's Universe. The roughly hundred clusters formed a swarm, much like Kapteyn's star swarm, but of some five times larger dimension. It was concentrated towards a center some 20,000 light-years away, far outside the Kapteyn system. What was remarkable was this distant center lay precisely in the plane of Kapteyn's disk, i.e. the plane of the Milky Way!

Shapley imagined that the actual Galactic System was outlined by his globular clusters, and that the Kapteyn "Universe" was one of a large group of "islands" spread around through the much larger swarm of globular clusters. At the time this picture seemed far from satisfactory: Why did we not see the other islands, and why did the center of the large system coincide exactly with the plane of our local island?

The final solution came (somewhat later) through the realization that the real world was entirely different from what either the Kapteyn group or Shapley had imagined. It did stretch out over the entire diameter of the swarm of clusters but it did not resemble it. While the globular clusters formed a nearly spherical system, the real star swarm was a thin disk, whose thickness was not more than a hundredth of its diameter. At first sight, this model would appear to contradict the Groningen investigations. Actually, it does not. The Groningen astronomers had principally investigated their 206 areas distributed evenly over the sky, but in concentrating on these regions, had practically overlooked the thin band of the disk system. An important other factor was that the major part of the disk was hidden by absorption through dark interstellar clouds, whose overruling importance was not realized at the time, due to the fact that they were entirely confined to the thin disk. Actually, the whole of the Galactic disk outside the circle was invisible.

The true, complex structure of the Galaxy became known only gradually, partly due to the circumstance that not all its populations lay in the disk.

It contained a mixture of various populations with varying degrees of concentration towards the disk, the extremes being the globular clusters which showed hardly any affinity to the disk.

The differences between the populations were strongly reflected in their motions. It is here that the peculiarities of the high-velocity stars which I had investigated in the years at Groningen began to fit in. But I was still too much indoctrinated by the Kapteyn system to take to step to a model in which all stars around us would actually be a part of a much larger continuous disk system. This step was taken in 1925 by the Swedish astronomer Bertil Lindblad by suggesting that all slow-moving stars in our surroundings would share a fast rotating motion around the center of the system of globular clusters, Lindblad thought of a solid rotation. I realized because the mass of the Galactic System was concentrated towards its center, the angular velocity of rotation should increase toward the center, just like the motions of the planets in the Solar System. I had found earlier that distant stars in the Milky Way had unexplained systematic motions, and it dawned on me that these motions were just what one would expect in a rotating system of stars whose inner regions rotated faster than the outer parts. This led in 1927 to the discovery of the differential galactic rotation. The motions confirmed also that the point around which the System rotated lay in Sagittarius, coinciding precisely with the center of the System of globular clusters. It was a wonderful discovery: it showed that the same law of gravitation which had been so successful in explaining the motions of the planets in the Solar System was applicable also in the millions of times larger Galaxy, and that there was a strong analogy between the two systems.

In the following couple of years most of the characteristics of the Galaxy's structure and internal motions became understood, including star Streamers.

However, one serious incompleteness remained: due to the obscuration in the disk the major part remained hidden behind the absorbing clouds. We could not observe the center, which later proved to be the seat of extremely interesting phenomena. Nor could we see whether the disk had any large-scale structure like the spiral nebulae. It was only with the advent of radio astronomy, almost 20 years later, that the enigmas of these regions were revealed.

But long before that time, during the first explorations of the Galaxy, a problem of much wider scope began to present itself; viz. that of the nature of the spiral nebulae. While making the famous survey of the sky with their large telescopes, William and John Herschel had found that besides stars and clusters there existed also a large number of nebulous-looking objects. Because many had a striking spiral structure they were commonly referred to as Spiral Nebulae. There was considerable doubt about their nature. Some astronomers, including Shapley, thought they were objects inside our

Galaxy. Others, who finally proved to be correct, put them at much larger distances and pictured them as individual star systems, “island universes,” much like our own Galaxy. They would be so far away that not even with the largest telescopes individual stars could be discerned, which explained their nebulous appearance.

Already in my student days I was convinced this was the reality and that the world of spiral nebulae opened our eyes to a new Universe. The second half of my lecture will be devoted to this astounding world.

But before entering upon this I must conclude the story of our own Galaxy. Quite unexpected new ways for its exploration were opened by the advent of radio astronomy. An engineer of the Bell Telephone Company, Jansky, who was searching for the cause of a disturbing noise in radio receivers, discovered that the noise was related to the direction of the Sun. It also depended on the position of the Milky Way, and specifically of the center of the Galaxy. Due to a surprising lack of interest by the optical astronomers it took nealy 20 years before the significance of Jansky’s discovery for the exploration of the Universe was realized by astronomers. Exploratory work was started by another engineer of the Bell Company. Around 1945 Grote Reber built in his own yard the first radio telescope for exploring the Galaxy. The advantages of using radio waves for investigating the structure of the Milky Way System were obvious, for radiation at meter-and decimeter wavelengths penetrates unhindered through the dust clouds that obscured our view of the galactic disk. But because of the long wavelengths, telescopes of large aperture were needed to obtain the necessary resolving power. Grote Reber’s results were so promising that the Dutch astronomers who had been so deeply involved in the first exploration of the Galaxy made plans for building a radio telescope that would be sufficiently large for an adequate study of the structure of the Galaxy. We therefore made a proposal to build a radio telescope of 25m aperture which would enable us to determine the structure of the most distant regions of our Galaxy at a wavelength of 21cm. There was a special reason why this wavelength was chosen: The Dutch astronomer Van de Hulst had shown that atomic Hydrogen, which besides Helium, is the principal element populating the space between the stars, will emit radiation at this wavelength. Accurate observations of the inter-stellar Hydrogen clouds at this wavelength would enable us to determine not only their density, but also their velocity. The radio telescope could penetrate to the hidden regions close to the center and measure the rotation velocity in these regions.

The large telescope was only completed in 1958, but 10 years earlier we had the luck that the Postal Service put at our disposal one of the 7.5m radar telescopes salvaged from the dunes where the retreating German armies had left them behind. Observations were started in 1952, and by 1954 a complete map of Hydrogen density and velocity over the entire Galaxy as far as it was visible in the Netherlands was ready. It was the first map of the Galactic disk, and was quite an achievement. The work was in large part done by students who worked almost day and night, with mutually inspiring enthusiasm. It was a good time at the observatory!

The map showed a striking spiral-like structure, confirming again the resemblance between our Galaxy and the spiral nebulae.

However interesting the 21cm Hydrogen radiation was, the radio emission of our Galaxy had other, totally new, things in store for us: A large fraction of the radiation does not come from tiny vibrations in atoms, like the light with which we are familiar, but comes instead from high-speed electrons describing orbits of many light-years radius in the magnetic field of the Galaxy. This sort of radiation had been known from observations in the large accelerators used to investigate the structure of atomic nuclei. It was therefore called “synchrotron radiation.” One of its main characteristics is that it is polarized: the light vibrations are confined to one direction, contrasting to common light, where a random distribution is shown. Synchrotron radiation had never before been observed in nature.

By a curious train of events I became involved in the early history of finding this radiation. It came about through observations of the Crab nebula, which is probably the most remarkable object in the sky. The Crab nebula was born on the 4th of July 1054 by the explosion of a faint, unknown star in the constellation of Taurus. In the first year after its explosion it became so bright, it could be seen in full daylight. The star was almost entirely disrupted. Its fragments were expelled at high velocity, and after several centuries had grown to such a size that they could be observed as a nebulous object. In 1954 I asked Dr. Walraven in Leiden to measure the rate at which its brightness decreased by the expansion. Dr. Walraven, who was a genius in refined observations, did more. He measured not only the brightness, but also the polarization. We had heard that observers in the Soviet Union had found that the light of the Crab nebula was polarized, and wanted to see if this was correct. It turned out that it was not only correct, but that the degree of polarization was so high it could not be ascribed to known mechanisms of producing polarization through diffraction of inter-stellar dust particles. It indicated convincingly that it must be intrinsic to the light emitted by the Crab nebula, and that this light must therefore be of the synchrotron sort.

This was an exciting discovery. The cold February nights I spent with Dr. Walraven at the telescope, watching the construction of the first synchrotron-map were probably the most wonderful times in our lives.

It was Walraven's talent which made it possible to make these revolutionary observations with a small telescope, under the most unfavorable conditions, in the midst of a fully illuminated city.

We now return to the exploration of the universe.

We have explored the limits of the huge star-swarm in which we live, and have found that neither the Kapteyn "Universe" nor Shapley's extended globular-cluster system can be the complete Universe. They are no more than an island in an ocean that extends far beyond; an ocean that contains many other islands. The spiral nebulae are such islands. They are numerous. Thousands of nebulae had already been catalogued by William Herschel and his son John in their large survey of the two previous centuries. The nebulae, or galaxies as we shall call them from now on, are at least as numerous as the stars in our own Galaxy. On a long-exposure plate taken with the 5-meter Hale telescope on Mount Palomar in Southern California. We see two sorts of images: those with sharp boundaries and those with fuzzy boundaries. The first are images of stars, like our Sun, but at distances of several thousand light-years; the nebulous ones are galaxies, swarms of at least hundred billion suns each, lying roughly a million times further away than the sharp-image objects.

The further we look the more galaxies we see. Is there an end? Do the galaxies form a swarm like the stars in our own galaxy, but of a higher order? No evidence has been found for this. There appears to be no end to the world of galaxies.

True, their distribution is far from random: they have a strong tendency to cluster together, in groups of all kinds of sizes, ranging from doubles, triples etc. to groups and clusters containing thousands of galaxies, showing an impression of the complicated structure. There is one large cluster, the Virgo cluster, but it is too large to show adequately.

In general the rich galaxy clusters have roundish shapes, with diameters of the order of ten billion light-years. There exist still vaster structures, with hundred times larger diameters. They are called “superclusters.” Their shapes are far from round. Sometimes they are string-like. Usually they are very irregular. The asymmetrical structure of the superclusters suggest there has been no important mixing since their birth. Apparently, we see them in the stage of their formation. This is exciting: the study of superclusters may then teach us something about the manner in which the large structure has originated. During the last five years I have become deeply involved in their investigation.

Meanwhile, our knowledge of the Universe has undergone a radical change. The technical development in building telescopes and spectrographs had, early in this century, enabled astronomers to obtain spectra of galaxies of sufficient quality to measure Doppler shifts of their spectral lines and to derive their velocities. Their radial velocities revealed something very remarkable: the galaxies all moved away at high velocities, higher than any velocities observed within our Galaxy. The velocities increased the further away the galaxies were. Hubble succeeded in showing that the motions were proportional to the distances. This indicated that they were not only moving away from us, but also from each other. The Universe appeared to be expanding. This remarkable phenomenon was amply confirmed by subsequent observations. It is called Hubble expansion; the rate of expansion is called the Hubble constant.

At earlier epochs the galaxies must thus have been closer together, and there must have been a time when they all started at one point. If the rate of expansion had been constant, this time (the so-called Hubble time) would have been about twenty billion years ago. Actually, the expansion velocity could not have been constant. It must have been decelerated by the mutual attraction of the galaxies and the matter between the galaxies. The expansion must therefore have been faster in the past, and the time elapsed since its start must have been shorter. Present estimates are about 13 billion years. This is the age of the Universe.

The more distant a galaxy is, the fainter it will appear. In principle we can determine the distance from its apparent magnitude.

In observing objects that are far away in space, we also look far back in time.

But there is a limit beyond which we cannot look. This limit is the age of the Universe, which at present corresponds to 13 billion light-years. It is a new horizon, of another kind than the one behind which ships disappear when they sail away from the coast. This horizon can only be surpassed by patience. A billion years from now we can see the light emitted by galaxies a billion light-years further away than the most distant ones we can observe today. The number of observable galaxies is thus continually increasing.

Let us now look the other way, and ask how the Universe was in the past. In order to penetrate as far as possible into the past we should evidently choose the most luminous objects. Such objects can often be recognized by their exceptionally strong radio emission. Particularly powerful objects for studying evolution in the Universe are the so-called Quasars. These galaxies are characterized by having exceptionally bright nuclei. They are so luminous, and often so distant, that the light waves we now receive from them were emitted at times when the Universe was between five and ten times younger than at present.

The Universe cannot always have consisted of stars and galaxies. At earlier epochs it must have been a more or less continuous medium of radiation and particles. It must have had a very high density and such a high temperature that no condensation into stars could have taken place. It gradually cooled proportionally with the expansion. When it had cooled to a few thousand degrees, formation of galaxies and stars became possible. We cannot directly observe the high-temperature stage of the Universe, but there is one valuable piece of information on the properties of the early Universe, viz. the abundance of helium relative to hydrogen. It is generally accepted that no large amounts of helium can be produced from stars, and that the 25 percent of helium observed today must therefore have been formed in the very early Universe. Three minutes after its origin, in the “Big Bang,” when the temperature of the expanding medium had dropped to 1,000 million degrees the conditions of pressure and temperature had become such that helium nuclei could form. Due to the rapid expansion the interval of time when conditions were suitable was short. The resulting number of helium nuclei was determined by the length of this interval, and the exact temperature and density.

The temperature, or the radiation density, continued to drop in proportion with the expansion. At the present time, roughly 13 billion years after the Big Bang, it has been reduced to three degrees Kelvin.

It is one of the big triumphs of science that astronomers have been able to measure this temperature. In 1964 Penzias and Wilson of the Bell Telephone Company succeeded in showing that the Universe is indeed filled with radiation of 3K, and that, therefore, at the age of three minutes the temperature must have been 1,000 million K, just what was needed for the formation of helium.

This was an eminent success. It was one of the greatest discoveries of cosmology. But it should not close our eyes for the big enigmas that remain unresolved. For instance, where did the very large structures observed in the present Universe come from? How can the three-degree background radiation coming from opposite directions be so nearly equal if, due to the expansion, the two regions could never have been in contact? And, finally, what caused the "Big Bang?"

It is interesting to contemplate how cosmology has become interwoven with particle physics. Physicists have taught us to understand the evolution of the Universe in the first fractions of seconds of its existence. In exchange, the expanding Universe, in diving into energy regimes far beyond those attainable in the largest accelerators, might ultimately contribute to a better understanding of some of the deepest problems of physics.

In the very beginning the whole observable Universe was contained in a tiny space, no more than a dew drop, but perhaps comprising the solution to all enigmas, like the dew drop in Issa's haiku

A world of short-lived dew,
And in that dew-drop,
What violent quarrels!

The actual Universe would have occupied only a minute fraction of the dew drop, but this would contain the seed for all the intricate phenomena in the immense Universe which was to grow out of it.