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On the frontiers of physics

The expanding universe of knowledge

Mr. Rector Magnificus,
Dear listeners,

To measure is to know. This adage is one of the cornerstones of physics. The interesting thing about our field though, is that with the advancement of theoretical insight on the one hand, and technology on the other, the boundary between what is measurable and what is not measurable is continuously shifting. Thus, the domain of physics is constantly expanding, and fundamental research is therefore literally breaking new ground: not only is new knowledge obtained; whole new areas of knowledge are opened up.

I will give you an example. Large parts of science and technology, with all their applications in the everyday world, originate from research with which, in the past century, the world of atoms and molecules has been uncovered. This research provided the key to understanding of such varied subjects as the structure of solid matter, semiconductors, the laser principle, and the molecular basis of heredity. It is impossible to imagine life today without for example electronics, telecommunication, computers or modern medical diagnostics. Yet a hundred years ago, even the existence of atoms and molecules was not generally accepted among serious and well-respected scientists, and remained a subject of scientific debate. Famous names are linked to this debate, amongst whom Boltzman, Maxwell, Mach, Oswald, Thomson and last but not least also the names of our fellow countrymen Lorentz, van der Waals and Zeeman. As a young researcher Albert Einstein made his reputation with, among other things, a theoretical explanation of a reasonably obscure phenomenon Brownian motion, the chaotic movement of particles suspended in a liquid in which the existence of molecules played an essential part.

This is not an isolated example. In the course of time other worlds of phenomena and new horizons have come into view through fundamental research. On an even smaller scale for example, we study the world of nuclei and subatomic particles with super microscopes consisting of particle accelerators and particle detectors. In contrast, radio telescopes on earth and infrared- and Röntgen-telescopes on board of satellites, provide us with new eyes to look at the universe and see spectacular phenomena of which the existence was not even suspected in former times. A recurring aspect of this process is, that phenomena which originally are an object of fundamental research themselves, as they become better understood slowly turn into tools, into instruments to look better or deeper. In this way, fundamental research leads to an expanding universe of knowledge, in which there is ever more room for new areas of research and applications.

I would like to clarify this process in more detail for you by telling you something about developments in an area of physics in which I'm involved myself. It is an area of research of a purely fundamental character, where questions arise from science itself. In this case it concerns questions about the nature of gravity, on the one hand as a geometric effect of

space and time, on the other hand as a field of force and carrier of physical quantities like energy and momentum.

Through experience and research, we are familiar with four fundamental forces of nature, which, until now, are not reducible to other forces or to each other; the electrical and electromagnetic forces together belong to a single category, which maybe the most influential one in shaping the world and the universe in the epoch we are witness to it. In addition, there are two kinds of forces which determine the properties and behaviour of subatomic particles: the colour force which binds quarks to nuclear particles, and the weak force which is the source of transmutations of nuclei and nuclear particles, for example in the fusion of hydrogen nuclei into helium in the sun. The fourth force, the weakest of all by far, is gravity.

Gravity is responsible for the motion of the planets around the sun, and of the moon round the earth. It is also the force that keeps us bound to the earth. In the seventeenth century, Newton was the first to give a general description of gravity, with which the orbits of the planets can be calculated and predicted. The same law could explain the motion of free fall of objects and the trajectories of projectiles on earth. As a result Newton's law of gravity was not only successful from a mathematical perspective; it also provided the insight that celestial mechanics and the mechanics of free fall could be explained from one and the same physical principle. The insight that there exist universal laws of nature, which are comprehensible to the human mind and which posses validity far beyond our own place and time in the cosmos, has been one of the most important contributions of seventeenth century science to our modern worldview. It is a *Leitmotiv* that is firmly rooted in the conceptual universe of physicists, and which is taken for granted to such an extent that researchers often barely render account of it.

Newton's theory of gravity was thus both substantially and conceptually an important development, with which the frontier of what can be known was suddenly moved into the realm of the stars. And yet, the theory was not wholly satisfactory in the long run. On the one hand, there were a few small problems with the orbit of Mercury, the planet nearest to the sun, which could not be explained. On the other hand, new developments in the physics of electrical and magnetic phenomena led to a much subtler notion of the concept of *field of force*, which Newton's theory did not satisfy. The most important of these insights was, that fields of force do not expand instantaneously through space, but with a finite velocity, and in any case not faster than light. Further, expanding force fields can transmit energy and information between the source and receiver. In the case of electric and magnetic fields, this led to the prediction of the existence of electromagnetic waves, like radio waves; it also led to the insight that light itself is a similar wave phenomenon of the electromagnetic field.

In 1915, Einstein published the Theory of General Relativity, in which he gave a description of gravity in accordance with the new insights in the nature of force fields. According to this theory, disturbances in the gravitational field propagate with a finite velocity, to wit the speed of light; energy is then transmitted from the source creating the disturbances, to the receiver which detects the changing gravitational field. In other words: the Theory

of General Relativity predicts the existence of gravitational waves.

Besides, it is a characteristic of this theory, as well as those of other forces of nature, that in empty space the speed of light has the status of a universal physical constant, a quantity which has the same value for every observer. That implies that in this description of nature, there is a special connection between space and time: when either light or gravitational waves travel through empty space, they always, and in every frame of reference, cover the same distance in the same time, independent of the state of motion of the observer. I won't dwell on the strange phenomena and paradoxes which result from this physical fact and its implications, but for my argument it is important to understand that space and time do not exist independent from each other, and that in connection with this, a geometric interpretation of the gravitational field can be given; in this geometric view, gravity is attributed to a deformation of space and time, through which objects move either toward or away from each other.

That an interpretation like this is possible has mainly to do with a special quality of gravity, which distinguishes this force from all the others: gravity is the only *universal* force. With that I mean, that all objects are influenced by gravity, and moreover, to the same extent. Electric fields exert forces on charged particles, but not on non-charged objects. Similar claims can be made about colour forces, which act on particles in the atomic nucleus such as quarks, but not on electrons which form the outer shell of the atom. The acceleration which an object undergoes under influence of gravity is however independent from the nature of that object. Maybe you have seen a demonstration of this phenomenon in high school: in a vacuum, a feather falls just as fast as an iron ball. This universality of the gravitational acceleration forms the foundation of the geometric interpretation of gravity. After all, to ascribe a dynamic effect exhibited by objects to the qualities of the space in which the object moves, instead of to the qualities of the object itself, the effect must occur for all objects irrespective of their nature.

A direct consequence of the universality of gravity is that in principle, all objects undergo the influence of gravity to the same amount. While you need a special antenna in which electrical currents can flow to pick radio- or television signals from the ether, and a human eye to perceive light, every material object is sensitive to gravitational waves. The effect of gravitational waves is that the distances between all matter particles, as well as their relative velocities change. For bigger objects consisting of many particles, the net result is that these objects deform and may for example start to vibrate mechanically. The effects of gravitational waves are more like those of sound than of light in this respect.

The Theory of General Relativity makes other predictions than just the existence of gravitational waves. According to this theory, planetary orbits deviate slightly from the orbits calculated on the basis of Newton's law, exactly as much as needed to explain the observed deviation in Mercury's orbit. Also, as a result of his own theory, Einstein predicted that light rays would be bend in a gravitational field, because gravity is universal and the propagation of a light signal is determined by the geometry of space and time as well. By now this effect has been observed many times; for example during solar eclipses when stars are still visible that should have disappeared behind the dark moon's disk. The phenome-

non has even turned into a tool instead of an object of investigation, to track down dark matter in the universe. That is matter which does not radiate light, or insufficiently to be visible with a telescope, but which can betray itself by the deformation of images of more distant galaxies. Their light is bent in the gravitational field of the dark matter, and the dark matter thus functions as a lens for the light of sources lying behind. In this way, the existence of non-luminous matter in the universe can be registered. From these examples it may be concluded that the Theory of General Relativity is extremely successful as a description of gravitational phenomena; until now it has been proved right on all points in which it predicts measurable deviations of Newton's old theory.

The significance of a theory like the Theory of General Relativity is therefore not only that it describes the observations better than the older theory, but above all that it predicts new phenomena, which were not within the scope of the older theory. I would like to highlight three of these kinds of phenomena here, as they are a focus of scientific interest at present. First of all, the theory predicts the existence of black holes; these objects are so compact, that they collapse under the influence of their own gravity and are unable to stop this process. The field of a black hole is so strong, that within a certain region around the object even light falls in and is unable to return, which explains the name of these objects. Astronomers suspect a large number of black holes in the universe; some with the mass of a robust star, others with a mass a million times as big as that of the sun. Such a black hole could be in the centre of our own Galaxy.

Secondly, the theory predicts that the universe is not static, but is evolving in time. This is in full agreement with the observations of astronomers, that all galaxies far away in the universe move away from us, and on average with a higher velocity the farther away they are. The inevitable conclusion is thus that the universe is expanding, and that it must have been much smaller, more compact and hotter in the past than it is now. There are more indications for this than only the expansion of the visible universe. The most important one is a background radiation of microwaves, the same kind of waves heating your kitchen oven. This microwave radiation which is present in the whole universe was discovered thirty years ago by accident and is a remnant of a time when stable atoms did not yet exist, simply because the temperature in the universe was too high. The first atoms could only come into existence, in the form of neutral hydrogen and helium clouds, when the average temperature in the universe was lowered to a mere 3000 degrees Kelvin; the universe was by then approximately 300 000 years old, very young in comparison with the 10 billion years it is now. However, the light and heat radiation which mainly filled the universe then, are still present in the background. The big difference is, that since then the universe has become many times bigger, and the temperature has dropped from 3000 degrees to a mere 2.7 degrees above absolute zero now. This residual radiation is in a way by far the oldest phenomenon ever measured with scientific instruments. The investigation of this radiation, especially the small temperature variations that occur, teaches us something about the structure of the universe in a time long before the first stars came into being. The instruments with which this radiation has been discovered and studied have thereby pushed back the frontier of time. They tell us something about a period in the past of

our world of which we not only thought that it would remain a closed book forever, but of which a century ago, no one even knew it had existed.

The third important prediction of the Theory of General Relativity is the existence of gravitational waves discussed before. Such waves, also known as gravitational radiation, have not been observed directly until now. The most important reason for this is that the gravitational force is so incredibly weak in comparison to all other forces of nature we are aware of. For example, let us imagine a gravitational wave with a frequency of 440 Hz; that is the frequency of the fundamental, the A, of our western tonal system. When such a gravitational wave passes by, everything becomes alternately longer and thinner, and then shorter and broader. In the physicist's jargon this is called a quadrupole oscillation. Let's assume that the gravitational wave has an intensity of 120 dB, equivalent to one watt per square meter; in the case of sound, this is close to the pain threshold of our hearing; a very strong signal. In the case of gravity though, this intensity means that your length reduces and increases 440 times a second with approximately 1/10000 of the size of a nucleus. If you consider that the atoms in your body already, owing to body heat, move across distances about ten million times as big, you realise that the effect of a gravitational wave is negligibly small. That's why, during the first fifty years after the development of Einstein's Theory of Relativity, this phenomenon was thought to be immeasurable; there weren't even any attempts to prove the existence of gravitational waves.

Nowadays, the measurements of such small effects are rather seen as a challenge: difficult but certainly not hopeless. For the detection and observation of gravitational waves, special techniques are developed to strengthen the signal of the gravitational wave while all other vibrations in the detector are suppressed. A method invented by Joseph Weber, much elaborated and improved since, uses a big metal resonator, which is suspended freely, so as not to be disturbed by the environment it is placed in. The resonator is equipped with very sensitive motion sensors registering any motion of the metal surface and amplifying it. To suppress the effects of heat motion of the atoms in the metal, the resonator is cooled to below the temperature of liquid helium, only a tenth or maybe a hundredth degree removed from absolute zero.

Another technique heavily invested in, makes use of lasers of which the light travels back and forth between two pairs of mirrors in mutually perpendicular directions. In such an interferometer, each arm alternately grows longer or shorter, under the influence of a gravitational wave. Thus, a difference arises in the time of arrival of the two light signals, which you can attempt to measure. Whichever method you want to use, it's of great importance in all cases to improve the technology, whether it is for measuring small displacements, the low-noise cooling of big objects or the stability of lasers.

The question arises then, how sensitive these instruments have to become in order to observe the gravitational waves with some degree of certainty. At the same time this presents the question of the sources of gravitational waves: where and how are these generated, and with which characteristic frequency and intensity? To give an answer to that question, we better look first at the only objects in the universe of we are quite sure that they produce gravitational waves and with which intensity. It concerns an exotic kind

of binary stars: two stars orbiting around each other just like the earth and moon do. In this case, it concerns very compact stars that do not produce visible light; only a typical radio signal; under influence of their own weight they have partly collapsed, but not so far that they have turned into a black hole. Instead, they resemble a gigantic atomic nucleus, largely consisting of neutrons, with a density of approximately a trillion kilograms per cubic centimetre. Such a neutron star contains half a million earth masses in a sphere of 20 kilometres diameter. When two such objects orbit with great speed around each other, they produce a considerable amount of gravitational radiation. Although we can't measure this directly, it has been found that their mutual distance slowly decreases, which means that the two stars lose energy. The energy loss per rotation corresponds to the expected intensity of the gravitational waves which the system has to radiate according to the Theory of General Relativity. This is a strong indirect indication for the existence of gravitational waves.

Because we know approximately how far some binary neutron stars are removed from us, we can calculate the intensity of the gravitational radiation at the moment it passes the earth. These waves have a frequency of about 1/10000 hertz, and intensity corresponding to less than 10 dB; an inaudible rustle below the level of whispering. The change in length they cause in a measuring instrument on earth, for example one of the Weber resonators now being in use, is a hundred times smaller than in the former example; about a millionth of the diameter of a nucleus. Such a weak and low frequency signal is not measurable on earth, but the European and American space agencies ESA and NASA have designed a plan for a laser interferometer carried by three satellites in space, such that the distance between the transmitter and receiver of the laser signal will be 5 million kilometres. The effect of a gravitational wave then becomes ten thousand times bigger than in an interferometer on earth. If this plan will be realized, there is a good chance that the gravitational waves of binary neutron stars can be observed.

To detect gravitational waves on earth, they have got to have considerably higher frequencies, about 50 Hz or more. At lower frequencies, vibrations in the earth's crust interfere too much. Higher-frequency signals are for example expected to arise in the kind of stellar explosion known as a supernova: a heavy star becomes instable at the end of its life; the nucleus collapses and becomes a neutron star, while the outer layers are blasted away. With this, very large quantities of particles, energy and radiation are released, among which there is radiation in the form of gravitational waves. Because the actual collapse happens in a split second, short, intense pulses of gravitational waves are to be expected. Among those there will be waves of all possible frequencies, but mostly between 1 and a 1000 Hz. When such a supernova would be situated in our own Galaxy, the gravitational waves should be measurable with the current generation of instruments. As supernovae are very rare however, you can only expect to observe them with some regularity –say, a few times a year– when you can also detect supernovae in far away galaxies, up to distance of a hundred million light-years. That implies, that the light and gravitational waves of such a supernova have been travelling for a hundred million years before they reach us. These signals are extremely weak; in this case the corresponding displacement of the surface of a resonator is not more than a millionth of the diameter of a nucleus. On

the other hand, at this frequency the energy is higher and the background noise is much lower; moreover, the challenge is not to measure the motion of one single atom, but the common motion of a large number (about 10^{24}) of atoms. A collective motion like that at high frequencies is expected to be detectable. These examples adequately illustrate the challenges my colleagues in experimental physics are facing.

Let us assume, with becoming optimism, that they will succeed in their plans, and will be able to measure gravitational waves. The physics of gravitational waves will not be done with that. On the contrary; that is the moment it becomes really interesting. Although we have identifiable sources of gravitational waves at our disposal through binary neutron stars and supernovae, there are possibly other sources which can teach us much more. This would concern phenomena we presently know little or nothing about, because gravitational radiation is the most important source of information about them. In the first place, they could be black holes. If you read the science section of your newspaper with some regularity, you may know that there are indications that there is a big black hole in the central part of our own Galaxy. This black hole would be comparable with the sun qua proportions, but it would contain about a million time as much mass. Other galaxies, such as the Andromeda Galaxy probably contain such massive black holes in their centre as well; some of them even have two: a binary system of two black holes revolving around each other. The gravitational field at the surface of such a black hole is a million times as strong as that of the sun, or even more. This surface is sometimes indicated with the term horizon, because it is principally impossible to look further than this surface from the outside. The relatively strong gravitational field together with the high density of stars and other matter in the centre of our Galaxy enables the dark star to grow slowly by continuously capturing and swallowing other matter from the environment. Most of the time this process is gradual: a disc of gas and dust is formed around the dark star, from which matter falls into the black hole. Every now and then though, it could encounter a bigger object, which will be caught. The surface of the black hole will then be temporarily strongly perturbed, and the only way to regain a new balance is by transmitting gravitational radiation. In this way, gravitational waves could give us information about the dynamics of the horizon of a black hole. For the observation of such phenomena, the ability to detect gravitational waves is a necessity.

A totally different form of measurable gravitational radiation possibly comes from the earliest developmental phase of the universe. I have already told you about the microwave background radiation which roams freely through the universe since this was a few hundred-thousand years old. This radiation still contains a considerable amount of information about the state of the universe in that specific time. It is also likely, that there is a residual radiation in the universe of gravitational waves, coming from an era when the interaction between matter and gravity was much stronger than nowadays. If there has been such a phase, roaming gravitational waves from this time might give us information about this very early period in the development of the universe.

Among theoretical physicists, there is a strong consensus that there must have been such a period of strong gravitation in the early universe. This is partly based on the

grounds that all force fields, nuclear fields, electro-magnetic fields and supposedly gravity, manifest themselves differently at different distance scales. Especially the behaviour of force fields at short distances is qualitatively different from those on larger distances. On a microscopic level, the behaviour of particles and force fields is subject to the rules of quantum theory. According to this theory, the distinction between matter particles and force fields on the level of atomic distances and below, are much less pronounced than we are used to from macroscopic phenomena. It is possible to regard particles as concentrated packages of energy, formed by a field stretching over all of space. These field quanta could carry a charge or other physical quantities. Conversely, in this image a typical wave phenomenon like radiation consists also of such localized energy packages, which have particle-like properties. We are familiar with light particles: photons; particles which relate to colour forces, gluons; and particles that transmit weak forces, the so called weak vector bosons, also known as W- and Z-bosons. A similar description must apply to the gravitational field. Gravitational radiation would then exist of a current of gravitational particles, the hypothetical gravitons.

Especially during short periods of time and over small distances, the dynamic behaviour of such quanta differs from that of classical waves carried by the field. The strength of the interaction between field and matter then becomes dependent on the distance over which the interaction is probed. These effects are actually measured in experiments, both for electro-magnetic as for the colour forces: electric forces become stronger on shorter distances, while the colour forces between quarks become weaker when the quarks are close together.

In all fairness, I have to tell you that there is no generally accepted quantum theory of gravity. Even more, to fit gravity into the framework of quantum theory is one of the biggest problems with which theoretical physics is struggling at the moment; especially because a lot of mathematical problems arise which no one exactly knows how to deal with. Several ideas are circulating; the best known assuming that nature, on a fundamental level, can't only deal with particles and their interactions, but also gives a prominent place to fundamental strings, membranes and other objects with a spatial extension. Be that as it may, even if there is uncertainty about the correct approach to quantum gravity, in all theories a shared element is that quanta like gravitons play a part in it, and their interaction with matter becomes stronger when the distance between particles becomes smaller.

There is still some discussion about what the relevant distance scale is. The standard scenario assumes it is the Planck length; a distance of only 10^{-33} cm. That is as small in comparison with a nucleus, as a nucleus is compared to the earth. In the distant past, when the average separation between particles in the early universe was of this order of magnitude, gravity must have played a dominant role. This must have been during a very small fraction of the first second of the existence of the universe. However, there are some non-standard scenario's, in which for example extra space-dimensions play a part; the characteristic scale of quantum gravity could be much bigger then. With this remark I cross the boundary of science though, and I enter the realm of speculation. I will not proceed further, but it illustrates that a considerable amount of imagination is sometimes

useful and necessary to bring science forward.

In the foregoing, I have given you an impression of an area of physics in development: the physics of relativistic gravitational phenomena. I have emphasized that the interest of scientists in this is mainly driven by scientific questions: the physical character of space and time, black holes, and the conditions of the early universe. An important milestone in this area will be reached when it becomes possible to detect gravitational waves. With that, a new window on nature and on the universe will be opened. New phenomena, which have been inaccessible to research so far, will be made accessible. The instruments that will be developed for this purpose will thereafter doubtless be used in other areas of research; possibly even outside this domain. In any case a frontier, separating what is within the domain of science and what isn't, will have been shifted.

It may be clear from my story that observation and explanation of a physical phenomenon, such as gravitational waves, not only signify progress for physics, but also for other areas of research which make use of physics. In this case, it will mostly be astronomy. At the beginning of my argument, I have given some examples of the momentum physical discoveries have imparted to other scientific and technical developments, with great consequences for society. In this respect one should not only think of economical consequences, but also of the consequences for our worldview and the self-image we humans extract from these developments.

It is far from me to conclude from this, that therefore all areas of science and technology are to be regarded as part of physics. It seems to me that a better and more humble idea is, that physics, by continuously shifting the frontiers of the visible and measurable, also provides other areas of investigation with new tools and avenues of progress. Contrary to lessening the importance of fundamental research in physics, its importance is thereby only increased.

This being said, I would like to say some words of thanks before I finish my speech.

I would like to thank the board of the Foundation of High-Energy Physics for the honour and trust shown to me by appointing me to this chair. I experience it a privilege to teach and further the developments in the area of theoretical physics, especially the theory of fundamental interactions, at this university. This gratitude also concerns all of those who have dedicated themselves to my appointment.

Mr. Rector Magnificus, members of the Board of College and the College of Deans of the Free University, members of the faculty of Exact Sciences: I'm looking forward to the time I will be spending with you. I hope I can add something significant to the spectrum of research and education which the faculty offers. For me personally, the broadening of my perspective on science in a university environment is an attractive prospect.

My home institution: NIKHEF, has not only given me permission to accept this chair, but has even encouraged me to do just that. I am very grateful to NIKHEF for that. I will dedicate myself with enthusiasm to the institute, especially to the theory group.

My scientific education has for an important part taken place at the University of Leiden. It provided me with both the broad basis and with the specialist knowledge needed

to perform independent research. I would like to thank my promoter and co-promoter for what they have added to this. This is the result.

Highly learned Verzantvoort, dear Angelique. You have been my help and stay these past years, but also an inspiring example through your personal and professional effort and integrity. Accept my admiration and gratitude.

My children remind me every day of the importance of curiosity and wonder. Don't lose that: amazement is the first step to insight.

In conclusion, I would like to express my thanks to both my parents, who supported me in all possible ways, and who have always encouraged me to follow my own interest and road.

I have said.

Amsterdam,
June 9, 2000