The Smallest and the Biggest of the Universe

INAUGURAL SPEECH BY PROF. DR. OLGA IGONKINA

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Our picture of the Universe and its evolution since the Big Bang is full of mind-boggling questions. Does the Universe have a boundary or is it infinitely large? Was it ever smaller than the proton, the basic building block of matter? What are the constituents of the Universe? What is Dark Matter, which is more abundant than normal matter but which does not seem to interact with us? And where is the anti-matter that was created during the Big Bang? In her lecture, Professor Olga Igonkina will review the current understanding of the evolution of the Universe and how the particle physics experiments at the Large Hadron Collider (LHC, CERN) could shed light on these problems.

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Inaugural speech delivered at the acceptance of the post of Professor by special appointment of The study of proton-proton interactions at the Large Hadron Collider at CERN at the Radboud University Faculty of Science on Friday, 4 September 2015

by Prof. Dr. Olga Igonkina

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Mijnheer de rector magnificus,
Geachte aanwezigen,

THE SPACE BOUNDARY

Today I would like to review two aspects of the Universe. First, I would like to look at the boundaries of the Universe, either in space or in time (past or present). I will give a few examples of such boundaries or related infinities and how mankind deals with them. What do we actually know for a fact and what are hypotheses?

The second aspect that I would like to review is the connections between the smallest and the biggest objects we know – the elementary particles and the Universe itself. Although their scales are so different, the processes affecting the elementary particles also govern the evolution of stars and galaxies. There are a number of unexplained effects in the Universe, where seemingly tiny physics processes or scales have a big impact on the evolution of the Universe.

THE EARTH DISK

The problem of infinity was important already to ancient people. Many early civilizations, for example ancient Chinese and Mediaeval Europeans, believed that the Earth is a flat disk. What was at the edge of the disk was unknown. We have inherited nice stories and fairytales speculating what would happen if one would go to the edge. The 'disk world' of Terry Pratchett is the latest most entertaining series. Even now, it is interesting to imagine yourself, somewhere in the middle of the flat Earth and trying to accept such a picture as a description of the world. I did so while writing this lecture. Imagine this vast space, and a mystery at the edge of this. I am not sure about you, but I would have this urge to find out for myself, if the Earth disk has an edge, to test it experimentally.

Now, let me also remind you how the Earth was discovered to be a sphere. The ancient Greeks (Pythagoras and later philosophers) discussed in their lectures that the Earth is spherical. Aristotle observed "there are stars seen in Egypt and Cyprus which are not seen in the northerly regions". Since this could only happen on a curved surface, he too believed the Earth was a sphere 'of no great size, for otherwise the effect of so slight a change of place would not be quickly apparent' (De caelo, 298a2–10). From the literature, it is not clear how they have arrived at this conclusion. Some historians believe that travelling by sea allowed ancient Greeks and others to appreciate the slow disappearance of mountains behind the horizon, which would not happen on a flat Earth. Another argument is said to derive from a round shadow of the Earth on the Moon during the lunar eclipse, with the curvature that is the same at the beginning and at the end of the eclipse. Eratosthenes, a chief librarian of the Library of Alexandria, performed measurements of the length of the shadow of a stick in different cities. When in Syene (the present-day Aswan), there was no shadow, in Alexandria the shadow was made by sunlight falling at angle of 7°. From this measurement, he calculated the circumference of the Earth to be equal to 250 000 stadia, which agrees with the actual value better than 15%.

Well, here is another experiment, which could have been done by Greek philosophers who were also great mathematicians. In fact, the same argument is used nowadays to describe the flatness of the Universe. Let us make a triangle. One person each will stand in one of the three corners and will connect to each other using a rope lying on the ground. If the surface is perfectly flat, then the sum of the angles of such a triangle amounts to 180°. If the surface is not flat, for example, if one person stands on the North Pole while the other two are on the Equator, the sum of the angles will be larger than 180°. So, if you perform such a measurement on a surface large enough (and solid enough), you could in fact measure that the Earth is not flat, at least not in the local place of the measurement.

There are two lessons that I would like to point out in this story. First, that such abstract questions like 'do we live on flat or curved surface' have very practical consequences. It was a rather abstract, curiosity-driven, question for the ancient Greeks but it is quite essential for our society now. The discovery of America was motivated in part by this curiosity and it did affect history.

The second lesson from the disk story: it is also possible to understand the boundaries of the world by exploring the local space more carefully. If we ask the right questions, we might find the right answers, even if travelling to the outer boundaries is beyond our powers today.

So now we are several centuries further, the problem of the edge of the Earth is solved. Actually, no, it is not solved – it is just pushed to a next dimension. The question that we face now is: what is the boundary of the Universe, or to be more precise, what are boundaries on both large and small scales and in time. But let us have a careful look at the Universe and its evolution today.

While discussing this I would like to give you numerical estimates, in order of magnitudes. So each number is expressed as 10 to a given power, for example 10^3*m is a thousand meters (or a kilometre), and* 10^{-3} *is a millimetre, a 1 over thousand fraction of a metre. So* 10^9 *is a billion (or 'milliard' in Dutch) and* 10^{18} *is a billion billion.*

THE BIG BANG

Today the size of the observed part of Universe, the biggest known object, is 93 billion light years (or close to 10^{26} m). The whole Universe is probably 10^{30} times bigger, although we cannot measure it, or it could be infinitely large. The part that we can see is 93 billion light years large. The height of Mount Everest is 8.8 km. The size of a person is about 2 m. The smallest objects are elementary particles such as electrons and quarks. The size of elementary particles is unknown. It is measured to be smaller than 10^{-19} m and assumed to be zero. Three quarks make a proton (or a hydrogen atom), the smallest stable non-elementary object. The size of a proton is about 10^{-15} m. So the ratio of the height of Mount Everest to the size of proton is only a thousand times smaller than the ratio of the observable part of the Universe to Everest. Notice that the whole Universe can have a finite size. What occupies the space outside the boundaries of the observable part of the Universe, if anything – we do not know.

The Universe is not constant in time. The experimental evidence suggests that the Universe is about 14 billion ($\sim 10^{10}$) years old and that it is slowly expanding. Its diameter grows by 2 light years per year. It is interesting to look at the evolution of the Universe and its past.

Our most favourite model of the evolution is the Big Bang theory. This theory postulates that, about 14 billion years ago, the Universe was extremely hot and dense. At that moment in time, everything that is contained in our observable Universe occupied an extremely small volume. And then, in a very short time, it expanded by a huge amount, after which it continued to expand somewhat slower. This first, very short (less than a second) but very intensive period is called Inflation. We need this very intensive period to explain why the observed Universe is so flat and homogeneous except for stars (and people) and how the stars (but not people) could have been formed. So here are the numbers for this Inflation period. At the beginning of the Inflation, the Universe was about 10^{-26} m or less (smaller than a proton). Then, in less than 10^{-32} of a second, it expanded to a size of 1 mm (so about the size of a grain of salt). The rest of the expansion took 14 billion years. The expansion caused the Universe to cool down. What happened before the Inflation (the first 10^{-36} s) – nobody knows. Actually, we do not know for a fact that the Inflation took place, but this is our best guess that allows us to describe all experimental facts.

There are a number of interesting statements hiding in this short description of the timeline of the Universe. First of all, the Universe has a finite size. Second, 14 billions years is a long time, but only three times longer than the age of our planet. Third, the elementary particles are claimed to be ‘size-less’. So the proton consists of three point-like quarks plus a lot of empty space. But how small are the quarks (or electrons) really?

Is there a minimum size, like the size of a proton, that makes sense, and there is nothing sizable but smaller? If electrons and quarks are really elementary particles that have no substructure, this is indeed so. That there could be very small objects that do not have structure is fascinating. Also it is interesting that there could have been a moment when the whole Universe was smaller than a proton. Well, it is unlikely that it was full of quarks or other particles at that particular moment, but it was not empty. It was full of energy (or was very hot). It is also interesting that we can describe the evolution of the Universe only from a certain moment, sometime shortly after the Big Bang. But we cannot describe the Big Bang itself (was it a specific moment in time, when the Universe was just a point, size-less?). And what was there before the Big Bang? Was there a starting point in the time, or is the time axis infinite? Did the Universe exist before this well-accepted point in time and perhaps had collapsed into an extremely small space before expanding? Or not?

There is yet another question – if the Universe had such a small volume, what was occupying the bigger volume then? Or is the volume itself also finite? Does it make sense to talk about the border of this volume like talking about the border of the Earth disk? Can we fall from the Universe disk?

The evolution of the Universe has also a few interesting features. So during the Inflation, the expansion was very fast and has inflated the Universe by huge factors. However, at the end of the Inflation, the Universe was still very small if compared to the size of a person. The expansion of the Universe after that was extremely slow. Nevertheless, this very slow process resulted in an increase in size from about 1 mm to 10^{26} m in 14 billion years. Furthermore, if this theory is true, and the Universe will keep expanding, eventually we will lose any contact with faraway galaxies and the sky will become very dark, as the stars too far to be bound by gravity will disappear from sight. In many billion years, but still.

Well, this is a sad picture, but we do not know it for a fact. This is our best scientific bet today, but we need to research this further to make any definite statements here. And I will not speculate any further, except that I would like to point out that such a sad future is driven by a very small physics parameter. So very small physics quantities still matter even for objects as large as Universe.

EXPERIMENTAL EVIDENCE SO FAR

Now, let us now review the experimental evidence for the Big Bang theory and the Inflation:

- The stars move away from us. And the stars far away are moving away quicker.

- Except for stars and planets, the Universe is very homogeneous. Wherever on the sky we measure the temperature, it is 2.7K.
- There is a relative abundance of light atoms (such as helium, deuterium and lithium) that accurately agrees with the predictions of the Big Bang theory. The observed abundance of helium could not have been produced in stars.
- There are no known objects, stars, galaxies or isotopes that would be older than about 14 billions years.

However, there are a few experimental measurements that remain unexplained. In particular:

- Presence of Dark Matter: The stars and the galaxies move around each other like they have more mass than we estimate based on the amount and distribution of light from these galaxies. This extra mass is often attributed to Dark Matter, or a new type of elementary particle, unknown to us. To be more quantitative, the amount of Dark Matter is five times larger than amount of ordinary matter, that is stars, planets, people and quarks.
- Lack of anti-matter: Then there is a problem of the disappeared anti-matter. Anti-matter is very similar to matter, like a twin brother. For each particle, there is an anti-particle, which has the same mass and the same lifetime, but has an opposite electric charge. For example, the anti-particle of the electron is the positron and the anti-particle of the proton is the anti-proton. The same physics laws apply to anti-particles as to particles. We know anti-particles very well: they are copiously produced in collisions at high-energy accelerators. In fact, we practically always produce an equal amount of particles and anti-particles at accelerators. Even more striking – we cannot produce only matter or only anti-matter. From the evolution of the Universe, we conclude that, also during this short period of Inflation, there were equal amounts of matter and anti-matter, otherwise the Inflation hypothesis would not match the observations. However, something happened to the anti-matter since then, and now we find only matter in its free form. Thanks to this disappearance of anti-matter, the stars, Everest and humans can exist, but there is no experimentally confirmed explanation of this basic fact.
- Dark Energy: The stars are moving apart quicker and quicker, as if a force opposite to gravity repels them. This is called ‘accelerated expansion of the Universe’. From a theoretical point of view, such acceleration or deceleration is acceptable. In fact, Einstein added a constant, the so-called ‘cosmological constant’ into equations of general relativity, to allow for a static Universe that expands at a constant speed. Well, the evidence is that the expansion is not static; nevertheless, this cosmological constant allows for the observed expansion. However, why the Universe expands, or what is the physical meaning of this constant, remains unknown.

So, although we have a reasonable description of the evolution of the Universe, there are difficulties to explain the content of the Universe. We need a better understanding of the smallest parts such as elementary particles and their physics law to explain the biggest objects in the Universe – the evolution of the galaxies, and the movement of the stars. So the current estimate is that more than three-quarters of matter of the Universe consist of unknown particles, and half of the known particles, the anti-matter, have disappeared.

So far, we have not found a way to approach Dark Matter. It seems not to interact with ordinary matter in any other way than via gravity. One might question, then, if this is really important to worry about, given that we have such a difficulty to register Dark Matter or identify any interaction of the Dark Matter with ordinary matter. Perhaps, one could say, it does not have any impact on our life. Perhaps. We do not know. But here is another rather illustrative example from our history, the discovery of ultraviolet and X-ray radiation. In the past, people (physicists) did not realize the presence of radiation in everyday life. You cannot see it, taste it, feel it. Sure, the light from the Sun was well known, as well as heat emitted by fire. But the fact that there is also invisible radiation from the Sun, or from radiative materials, was not recognized until the end of the 19th century. Although we do not see or feel radiation, we are not protected against it by our lack of knowledge. The discovery of the radiation was very important in both avoiding its negative effects as well as benefiting from it. To give a few examples: using our knowledge about its interaction with elementary particles, molecules, materials, allows us to recognize and cure cancer, as well as to monitor air pollution or to explore our past with carbon dating of archaeological artefacts. So even if we do not know today how Dark Matter interacts with ordinary matter, it is important to find out. I have a rock here with me. Could you tell if it emits dangerous radiation? Well, we can easily measure it with this Geiger counter. It does not radiate. Could you tell if dangerous Dark Matter surrounds it? So far we have no tool to check it. Ignorance could be dangerous.

The next point is the disappearance of anti-matter. That was an important event or process, as it allows the existence of structures, humans, mountains. Nevertheless, it is important to understand what has caused that. Was it some specific process active right after the Inflation? Or this is something that is constantly and slowly changing the Universe. So far, we assume it has happened at the early times; otherwise it is hard to explain the existence of galaxies. But we do not know for a fact that there is no additional slow process that would turn matter into anti-matter. As we have seen, slow or small processes matter for evolution. Thus, it is important to understand this puzzle to be able to predict the future evolution of the Universe.

Here is the experimental knowledge about anti-matter:

- It is not present in the Universe in its free form in any significant amount; neither is there an anti-Universe anywhere at a visible distance.
- Dark Matter does not consist of ordinary anti-particles; it is comprised of a different type of particle altogether.
- The physics processes are symmetric between matter and anti-matter with high accuracy.
- Yet, there is a slight difference between these processes, in particular, between quarks and anti-quarks, that allows a bit of matter to be generated. However, the trouble is that this amount is too small. Only 10^{-9} or one in a billion of the total amount can be explained this way, or to put this in perspective: only about seven people here in the Aula could be explained by this process, but where the rest of the world population comes from is a puzzle.
- There is a family of particles – leptons and anti-leptons – where no asymmetry seems to be present at a measurable level. If such lepton asymmetry is observed, it could explain the remaining amount of matter in the Universe. Again this would be a very rare process, but rare processes matter…

We, physicists, like elegant and simple theories that solve all problems at once. There are, in fact, a number of hypotheses that could explain both the presence of Dark Matter and the lack of anti-matter. I will not go into technical details, but if these theories are correct, we could understand both problems in one go. Many of these theories assume that the Dark Matter particles contribute to asymmetry between matter and anti-matter under very high energies, or temperatures, for example, as occurred during the Big Bang. At low temperatures like we have now, the Dark Matter becomes inert and does not interact with ordinary matter or anti-matter anymore, except in very rare processes.

FINDING ANSWERS

So here we are in the middle of a flat Universe, not knowing if our Universe is infinite or finite, not knowing what most of the Universe consists of and not knowing what has happened to its known constituents. I do not know about you, but I feel the urge to find out the answers to these questions. Yes, we cannot travel (yet?) to the boundaries of the Universe. But as we saw, one could perhaps answer some questions by performing the measurements of the local space. As history shows, there is a potential here. In particular, one could try to test if the smallest objects are, indeed, the smallest; if the quarks and leptons are elementary particles, or have substructure. Also the asymmetries of matter and anti-matter could be looked at, searching for the rare discrepancies, like those in lepton sector. This is a direction of my research – the experimental study of elementary particles.

Let me now talk a bit about my study of elementary particles and modern tools that we can use. To probe big objects, like stars and galaxies, we use telescopes. To probe the smallest objects, we use accelerators and particle detectors. These accelerators collide two particles together. In each collision, the initial particles (or part of them) vanish, and new particles and anti-particles are created. Most of the collisions are quite similar to each other and therefore not interesting. However, in some of them, heavy particles could be created or some unusual process could take place. The larger the energy or 'speed' of particles in the accelerator, the more massive new particles could be created – similar to what happened during the Big Bang or the Inflation period. The more collisions there are, the larger the statistics that we have to analyze. So, in a sample with very many events, even very rare processes could be searched for, for example, an asymmetry between particles and anti-particles. The Large Hadron Collider at CERN is the biggest accelerator built today. It has achieved both: the world's largest energy and the largest sample of collisions.

The next ingredient is the detector to register the collisions, a sort of a huge camera, sensitive enough and quick enough to capture what happened in each of these collisions. There are a number of such detectors at the Large Hadron Collider, built for different purposes. The ATLAS detector that my colleagues at Nikhef and Nijmegen IHEF groups and I use is particularly well suited for this line of research. The ATLAS detector could be visualized as a very big 100 megapixel camera with a shutter speed of 40 million shots per second. In fact, the ATLAS detector is so big and quick that the recordings of all these shots would take a huge amount of disk space. Instead, we put software in place that analyzes the collision online. So at the moment the shot is made, the software processes each collision, a sort of 'face recognition' of each collision type. The well-known processes are then thrown away, and strange occurrences or events with interesting particles found are recorded for more careful analysis. One has to be careful here not to throw away a baby with the water, not to throw away an interesting but unrecognized event. We record only one in 10^5 events, but this still gives us a huge sample of collision photographs to look at. Well, they are no longer the two-dimensional photographs of around two decades ago, but they are three-dimensional digital images containing information of each event. Here is an example. Each stable particle produced in an event goes through a detector and leaves a particular type of track. They are shown on this picture as a dot, a line or a thick square. Analyzing these tracks in various parts of the detector, combining lines and squares, we can deduce the type of the particle and exact origin. The reconstructed stable particles also provide information about the properties of the unstable particles that they originate from. In this way, we can understand what happened in each event. This particular image is one of a number of famous events with a Higgs particle candidate that we discovered three years ago. Once we have a sufficient number of interesting events, we look at them in detail.

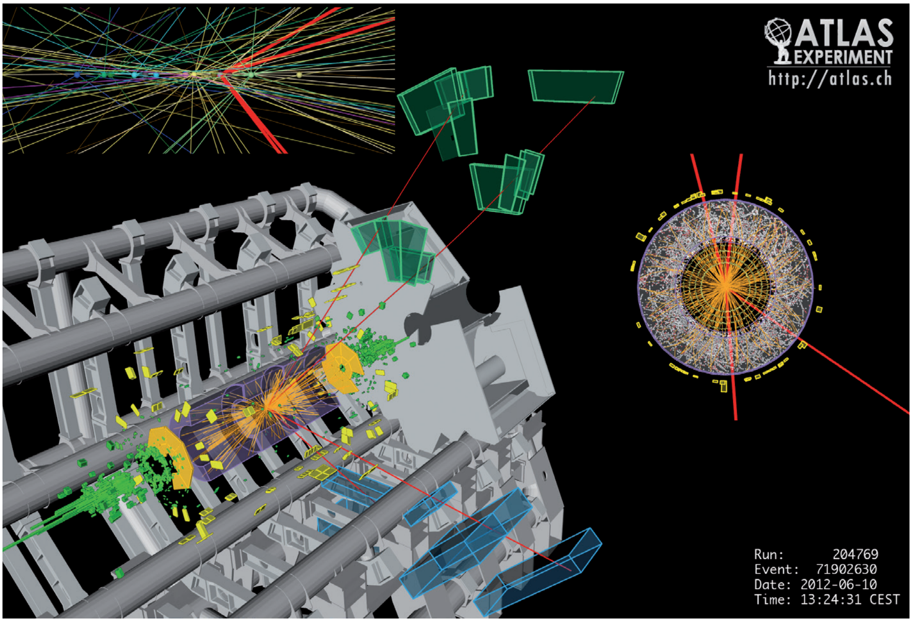

Figure: ATLAS event display of event with a Higgs candidate

So how could we solve the two problems that I focus on – the possible substructure of the elementary particles, and the lepton matter–anti-matter asymmetry? Based on our hypothesis, we look at collisions with a particular particle composition. Such a composition could happen accidently, when several ordinary events overlap. The probability of such ordinary events is easy to calculate. If we see significantly more events than expected: Hurray! A discovery is made. And then we would need to understand if this discovery really confirms our claim, or have we found something totally new, a surprise, a new puzzle in our picture of the Universe?

So, here we are in the middle of un-understood Universe, with unclear content and an uncertain future, but with powerful tools that could shed light on the evolution of that Universe. Enlarging our horizon and deepening the knowledge about our environment are essential for both progress and, perhaps, for the survival of humankind. No doubt, once we solve these problems, we will have new boundaries to cross, but, by then, we will advance in our knowledge. So, let's explore the data that we have to understand our world better.

EDUCATING OURSELVES AND OTHERS

There is one more aspect of my work, next to the research, that I would like to highlight today. This is education. In some sense, research is education. In a first approximation, it is a personal education – I learn first myself. Then, it is education of society – when the results are published in papers and shared in public presentations and discussions. But the third step is most important, when the knowledge is shared with the next generation of scientists, with students. The knowledge and education are two sides of the medal. So, anyone who would like to succeed in research necessarily needs to invest in education. It is both very important but also very pleasant, as there is a huge feedback coming from such an investment. In discussion with students, many new ideas are born, the excitement of research work increases and much more work is accomplished. I thank all my current and past students for all their help and trust, and I am excited to start new education/research projects within Radboud University of Nijmegen. I thank the University for giving me the opportunity to do exactly this.

ACKNOWLEDGEMENTS

With this I would like to conclude my lecture. In the remaining few minutes, I would like to express my gratitude to the people and institutions supporting my research.

First of all, I would like to thank to the Faculty of Science, the Institute of Mathematics, Astrophysics and Particle Physics and the Executive Board for their trust and support of my professorship. I would also like to thank the HEP group of the University for their involvement and support and, in particular, Professor Nicolo de Groot. Every day I come here, I am overwhelmed with an outburst of new ideas – if only we would have enough hands to test them all. Being a part of Nikhef, I was already working closely with my Nijmegen colleagues and am looking forward to intensify our collaboration.

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Thank you, Wouter, for being both a fierce critic and enthusiastic supporter of my ideas, research and life. Lev and Artjom, thanks for your existence in spite of the known laws of particle physics. Thank you, my family and my mam, for your continuous support and curiosity in my research.

Thank you all for joining me today.

Ik heb gezegd.