The Extreme Structures of our Universe

Vincent Icke

Sterrewacht Leiden & Alien Art

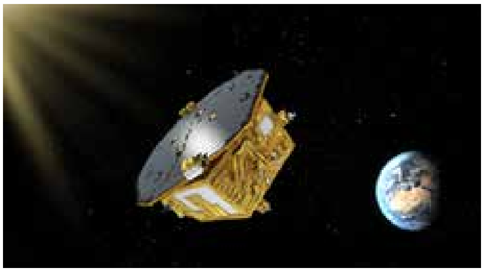
icke@strw.leidenuniv.nl

My story is a tale of extremes. Extreme artificial structures that we have built on and around planet Earth. Extreme natural structures that exist in our Universe, and extreme structures in our mind, when we try to understand how this all works.

Of all the possible artificial structures, consider telescopes. The first one, invented by Johannes Lipperhey of Zeeland, was soon copied by Galileo Galilei, which dramatically changed our understanding of the Universe. The object itself did not look very dramatic, but its human impact was extreme. Currently, engineers in Chile are building the European Extremely Large Telescope, which will contain a segmented mirror with a total diameter of 39 meters. The building of this extreme instrument could more than cover the full grounds of the original Leiden Observatory, which is the oldest still operating observatory in the world.

Even more extreme in size are the modern radio telescopes, such as the ALMA interferometer, built for the European Southern Observatory in Chile. In such giant instruments, computer signals are used instead of steel girders and copper cables to connect the components. These are wonders of engineering. I find them much more impressive than the pyramids of the pharaohs, because our amazing scientific structures were built by free people for the benefit of all humanity.

Modern telescopes are carried into our Solar System by spacecraft, placing the wonders of engineering far outside planet Earth. They have observed our planets, their moons, and landed on many of them, revolutionizing our understanding of the history of our Solar System, and thereby the history of ourselves. Several such probes have already left the heliopause, and are heading for the stars.

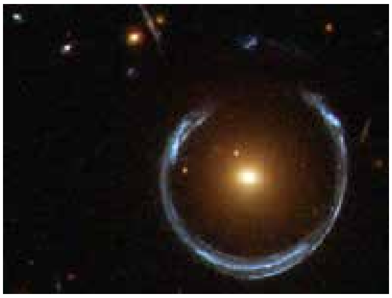


The next decade will see the launch of an even more exotic instrument, designed to detect the trembling of space-time caused by catastrophic collisions of compact cosmic objects. These tremors are called gravitational waves. The three spacecraft of the Laser Interferometer Space Antenna (LISA) experiment, built by the European Space Agency, will be linked by lasers over millions of kilometers. These structures are among the most extreme that have ever been built, because even though they are only a few meters in size, they are precise enough to detect displacements of the size of an atom, one hundred billion times smaller than a human being. With this sensitivity, LISA can detect gravitational waves throughout the Universe.

Let us now look at natural structures, the shape and disposition of the things that the world is made of. First, consider the structure of matter. The extreme structures are found way below the more or less everyday scales of atoms and molecules. It is amusing that some of the biggest instruments have been built to study the smallest particles we know. The ATLAS detector built at the European Center for Nuclear Research (CERN) is housed in an underground cavern about 40 meters high. It is 46 meters long, 25 meters in diameter, and weighs about 7,000 tons; it contains some 3000 km of cable.

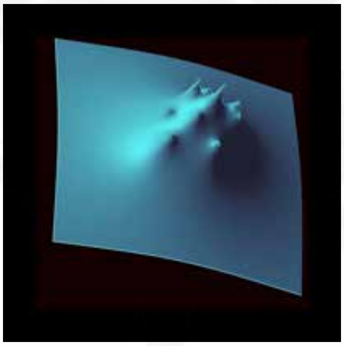
The purpose of this imposing machine, one of the focus points of the 27-kilometre underground tunnel ring of the Large Hadron Collider, is to study the structure of matter on the smallest attainable scale. At present, the giant CERN collider has probed the structures of particles to sizes that are ten thousand billion-billion times smaller than a human being. It would not be helpful to try and make images of these structures, because they are so totally extreme that we are incapable of recognizing or appreciating them. Mathematics will do the job. Nevertheless, every image of whizzing balls and flashes does not do justice to this extreme world, and is no better than a story, one that would at best give a false feeling of familiarity.

Totally on the other side of extremes are the most distant structures we have ever seen: young groups of stars near the beginning of the Universe. These flecks of light are not stars but galaxies, each one containing a hundred billion stars or more. The faintest are about 11 billion light years away from Earth, which is almost billion-billion-billion times more than the size of a human being. That is about as far as we can see at present, because the age of the Universe is 13.8 billion years, wherefore we cannot observe anything beyond that distance.



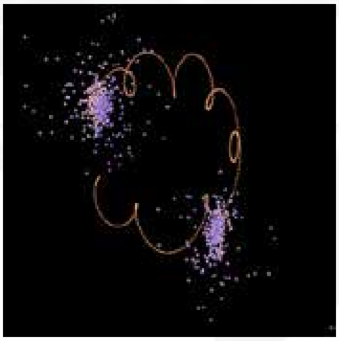
Detailed observations of such galaxies show even more surprising structures, made of something we cannot even see. This blue ring of light is actually a single compact galaxy at immense distance, seen through a huge mass of dark stuff assembled around the bright galaxy in the center of the ring. The matter of the foreground galaxy curves space, so that it acts as a kind of magnifying glass, casting a distorted and enlarged image of the galaxy in the background. This is called the 'gravitational lens effect'. Sometimes this mass is referred to as 'dark matter', but that is presumptuous: we do not know what it is, and there is no evidence that it is even related to the particle-based matter that we are made of. Observations indicate that the most extreme structures in our Universe are made of this dark stuff, which composes about 95% of the content of the Universe – and we have no idea what it is.

If dark stuff is made of some kind of particles, the way ordinary matter is, then we can say: the structures in our Universe are made of particles, space, and time. We must learn to understand these. So we must build theoretical structures, analogous to the mechanical structures of our giant telescopes and immense particle accelerators. The structure of matter is extreme. Therefore, our theories are also extreme. The theory must cover everything we observe about particles, space and time, the extreme building materials of our Universe.

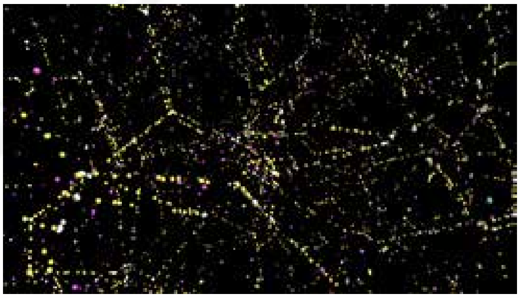


Space-time is real, just as real as concrete and steel. Space structures occur naturally, because matter curves the space around it. Just as in the case of origami, where the folding process determines the shape. For example, the matter of every star curves space, and this curvature we experience as gravity. Therefore, in a sense, gravity does not exist: it is an historical term for the consequences of the structure of space-time. Curved space makes curved orbits. Orbits in space show us what the structure of space-time is. In this way, the orbits of stars in the center of our Milky Way galaxy tell us that the space structure there is so extreme that no light can escape from the centermost area. This very extreme space-time structure is what we call a supermassive black hole.

The shapes that space curvature produces are connected with the shapes of material orbits. The elliptical orbits of the planets are a well-known example. These orbits are so plain and simple because of the almost perfectly spherical shape of the space around the Sun. Much more complicated orbits are followed by the stars in colliding galaxies.



The biggest and most extreme material structures in the Universe are the conglomerates of galaxies and their surrounding dark matter. The Universe expands, because in the course of time space itself expands. Thus, the expansion of our Universe on large scales (beyond a hundred million light years, say) is not a case of matter moving through space, but space itself moving, in the sense that the amount of space in the Universe increases. But the initial distribution of matter, starting 13.8 billion years ago, was not exactly uniform. There was a certain cosmic noise, very similar to low-intensity sound waves. Thus, in the beginning there were small patches where the mass density was smaller than average and others where it was bigger. The deviations from the mean were infinitesimal: only one part in a hundred thousand.



The patches with a below-average density expand a little faster than the average Universe. This produces a distribution of bubbles, from which matter flows away, accumulating on the walls between the bubbles. Where those walls intersect, filaments form, which in turn end up in nodes where four filaments meet. It is possible to approximate this flow of matter in our expanding Universe using a mathematical formalism published in 1908 by the Ukrainian mathematician Gyorgy Voronoi, called a *Voronoi tessellation*. The resulting extreme distribution of matter is currently called *cosmic foam*.

Cosmic structures are always dynamic. Gravity always asserts itself in the long run. Even those that seem static are so only on a human time scale. Seen with a time lapse of millions of years, everything is in constant and often violent motion. Still, I call these things *structures*, even though they are only snapshots in the history of our Universe. But that is also true in the case of human structures: what spectacle would the Egyptian pyramids show with a time lapse of centuries?

A similar dynamic holds in the case of our mental structures. These also evolve, but on a human time scale. The mental structures we have developed for understanding the Universe have also become more and more extreme. Even classical mechanics is not trivial, and quantum field theory and general relativity are yet more extreme. I think that probably our future understanding of the interplay between matter, space and time can fairly be called an extreme mental structure. These extremes we cannot avoid when we try to understand how the Universe works. It is well known that our Universe is extreme, if only in the sense that it is so vastly different from our human scales of mass and size. The search for these extreme mental structures – one may call them theories – goes on forever, because there is so much more to grasp and to understand.

Is there an ultimate theory? A mental structure that is, in a sense, the most extreme, because it encompasses all the phenomena in the Universe? A 'theory of everything'? Of course, we do not know, but I think that it is improbable. What unites particles, space and time? We observe their structures, but what is the underlying mental structure, the theory? We are doing very well on both extremes: elementary particles that are unspeakably small, and the Universe that is extremely big. Should we try to connect these extremes? If we must, can we do it? I wish that we had the answer. Maybe this is the structure that dreams are made of.

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