Copernicus Legacy: The Five Hundred Years Revolution

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Copernicus' Legacy: The Five Hundred Years' Revolution

Rede uitgesproken door

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bij de aanvaarding van het ambt van hoogleraar
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aan de Universiteit Leiden
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Mijnheer de Rector Magnificus, zeer gewaardeerde toehoorders,

I remember very well the first time I was confronted with an astronomical problem. I was five years old and attending Kindergarten, the German flavor of pre-school in which children are not supposed to be exposed to intellectual challenges. We were read a story about an Eskimo child, the content of which I have largely forgotten. When I came home for lunch, I told my mother that we had been told a story which was very – I think the Dutch translation of the word I used is “stom”. My mother asked why I passed such harsh judgment on the story, so I explained that the writer had taken the liberty to tinker with the laws of nature, which I strongly disliked. The poor Eskimo child was cast in a plot that played in complete darkness, because the Sun did not rise for several weeks. I knew all too well, of course, that the Sun rises every morning, and was appalled by the fact that the storyteller had chosen to ignore this simple fact of life.

When my father came home from work, he was consulted about this less than satisfactory state of affairs, and it was decided that it was time for my first lesson in celestial mechanics, to be given in the dining room. A plastic ball and a felt pen were produced from the playing room, and the lecture could begin. The ball was declared to represent the Earth. Two points were marked on the ball opposite to each other, and it was decided that these should designate the North Pole and the South Pole, respectively. Two additional spots were painted on the ball, one representing the place where we lived, the other representing the land of the Eskimo child in the story, duly located very close to the point that had been declared to be the North Pole.

During this basic introduction into geography it had become dark outside, and the lamp hanging down from the ceiling above the dining room table had to be switched on. This was convenient, because the lamp could now do double duty as classroom illumination, and as a stand-in for the lamp of lamps, our Sun. Now we were ready for the main part of the astronomy lesson: the ball was held up close to the lamp and set into rotation about the two points that had been declared to be the poles. Keeping my eyes focused on the spot representing our home, I could watch with awe how the rotation of the Earth led to a periodic change between brightness and darkness at this point as the Sun (that is, the lamp) rotated into and out of view: I had understood how the rotation of the Earth leads to the change between day and night.

The next part of the lesson consisted of an explanation that – for no particular reason whatsoever – the axis of rotation was not vertical but inclined by some angle. The original experiment, setting the ball into rotation close to the lamp, was now repeated with the more realistic orientation of the axis. I could see with great satisfaction that this slight change of geometry had not changed significantly the periodic change between day and night for our home. But when my father drew my attention to the

Eskimo-spot I realized with amazement that – although this spot also made a small circle around the North Pole – it never rotated into the illuminated half of the ball: the Sun did not rise in Eskimo-land.

But the story got even better. In the next part of the lecture my father and I formed a parade, marching around the dining room table, while holding the ball up at the height of the lamp and keeping it in constant rotation. The rotation of the ball was quite fast, representing the quick succession of night and day, whereas the march around the dining room table took place at a dignified slow pace; in our imagination it would take a full year to complete one circle around the table. My father took care of another subtlety that – as far as I remember – was not discussed explicitly at that time: the axis of rotation was carefully kept stable during the procession, with the North Pole always facing in the direction towards the wall to the playroom. (My father was an engineer and knew about the importance of conserving not only energy but also angular momentum.)

Now I discovered, with a little prodding perhaps, that while we were marching close to the playroom our home was longer in the shade than in the light, whereas at the opposite end of the table, close to the kitchen, we got long days and short nights. This insight made a strong impression on me: two simple motions, the rotation of the Earth around its own axis, and its revolution around the Sun, could explain not only the occurrence of day and night, but also the seasons, and why days are longer in the summer than in the winter. That night I went to bed feeling a deep satisfaction: I had understood the physical mechanism behind two important observations of daily life, the writer of the story had been fully rehabilitated, and, as it turned out, the Eskimo child was compensated for the long dark time in the winter by an equally long time of brightness in the summer, during which the Sun would not set.

I told you this story about my childhood experience with astronomy because I think that it leads nicely into the topic of the talk that I want to give today, which is entitled:

Copernicus' Legacy: The Five Hundred Years' Revolution

We associate the dawn of modern science with a small number of great astronomers, who changed our picture of the world, and that of our role within it: Copernicus, Brahe, Kepler, Galileo, and Newton. Each one of them must have experienced the same joy and excitement about understanding a new aspect of nature that I felt after the march with the rotating ball, but at a much deeper level: while children discover new aspects of the world almost daily as they understand more and more of what the grown-ups have already known for a long time, it is the privilege of the scientist to know for a short while something that nobody ever knew before. But true discoveries and flashes of insight are rare for most of us whose names are not Newton or Einstein, and come only after long periods of hard work.

Around the year 1500 the prevailing view of the Universe was based on a model dating back to classical Greece and formulated fully by Ptolemy in the second century AD [1]. The Earth was at the center of the Ptolemaic system, orbited by the Sun and the planets. The Greeks' strong sense of beauty and mathematical simplicity had led them to postulate that the planets' orbits should follow circles, the most symmetric two-dimensional mathematical shape. Unfortunately it turned out that astronomical observations and predictions of events such as Solar and Lunar eclipses were not in agreement with simple circular orbits of the planets. Ptolemy therefore had to construct a more sophisticated model in which the motion of each planet was described by two circles called "deferent" and "epicycle", respectively. The motion of the epicycle along the deferent was quite complicated, which took away somewhat from the desired mathematical purity and beauty. Nonetheless, Ptolemy's geocentric system was successfully used for many centuries as a framework to describe the motions of the planets, and to predict astronomical phenomena.

During the first half of the 16th century Copernicus developed his heliocentric system, in which the Earth is but one of the planets orbiting the Sun, which in turn remains fixed at the center of the Universe. The publication of these ideas in his book ***De Revolutionibus*** [2] in 1543 marks the beginning of the events that are now known as the ***Copernican Revolution***. Remarkably, Copernicus still used circles and epicycles to describe the planetary motion; the predictions of his model were not significantly better than those derived from tables based on the venerable model by Ptolemy. From our modern point of view it is probably fair to say that Copernicus was largely led by philosophical, not by scientific considerations.

The next large step forward was made by Brahe, who performed a large number of precise observations of the planets, and by his assistant and successor Kepler, who analyzed Brahe's data set. In 1609 and 1618, two generations after Copernicus' main work, Kepler published his books ***Astronomia Nova*** [3] and ***Harmonices Mundi*** [4], which contain his now-famous laws of planetary motion. Kepler's Laws state that the planets' orbits are ellipses, not circles, and give rather simple descriptions of their motions along these ellipses. Kepler's insight into the true nature of planetary motion was very significant, because this allowed him to make predictions that were much more accurate than those of the previous models; unlike Copernicus, Kepler had devised a model that could be shown to be superior to the Ptolemaic system by empirical observations.

At the same time as when Kepler published his first two laws of planetary motion, Hans Lippershey, a spectacle maker who was born in Wesel and worked in Middelburg, the capital of Zeeland, made an invention that would revolutionize astronomy. A letter of the government of Zeeland to its delegation to the States General of the Netherlands, dated 25 September 1608, instructs them to be of help to the bearer, "who claims to have a certain device by means of which all things at a very great distance can be seen as if they were nearby, by looking through glasses which he claims to be a new invention" [5]. On 2 October the States General discussed Lippershey's application for a patent on the instrument; this is the earliest record of an actually existing telescope [6]. One could thus say that the discipline of astronomical instrumentation was founded almost exactly 395 years ago by a German working in the Netherlands.

The news about the invention of the telescope spread quickly across Europe. In 1609 Galileo built his own telescope and used it for astronomical observations. Galileo's discoveries lent further support to the new world model: the existence of sunspots showed that the Sun was not a perfect sphere; the moons of Jupiter clearly did not orbit the Earth; and – perhaps most convincingly – the phases of Venus could only be explained if Venus orbits the Sun, and not the Earth. Galileo's ***Dialogo sopra i due Massimi Sistemi del Mondo*** [7], which summarizes the arguments for the Copernican system, has become one of the most famous books in European history, not least because it got the author into a lot of trouble.

Much has been said and written about Galileo's trial. Therefore I don't want to dwell on in, but rather move on to Newton, who was born in 1642, the year of Galileo's death. Newton formulated the general physical laws of motion, which form the foundation of classical mechanics, and the law of gravity; he showed that Kepler's Laws describing the planetary orbits could be derived mathematically from these more general principles. In this way Newton's ***Philosophiae Naturalis Principia Mathematica*** [8], which appeared in 1687, unified terrestrial and celestial mechanics – the motion of an apple falling from a tree is governed by the same physical laws as the motion of a planet orbiting the Sun. This may appear almost self-evident to us today, as we apply our modern knowledge of physics to distant galaxies and even to the events immediately following the Big Bang, but the insight that the Laws of Nature are universally applicable must certainly be counted amongst the greatest intellectual achievements of mankind.

It is also interesting to note that Newton's explanation of the planetary orbits as the consequence of his laws of motion and gravity is of an elegance and simplicity that comes closer to the classical ideal of mathematical beauty than any other model before. More modern developments in theoretical physics – Maxwell's theory of electromagnetism, Einstein's general relativity, Heisenberg's formulation of quantum mechanics, local gauge theories of elementary particle physics, and supersymmetry to name a few – share that same guiding principle of mathematical elegance that was first formulated by the great Greek philosophers. Although Aristotle's world system has been replaced by Copernicus, Kepler, and Newton, I believe that he would be deeply satisfied to see his aesthetic ideals live on in modern physics.

The term "Copernican Revolution" is normally applied to the nearly 150 year period from Copernicus' ***De Revolutionibus*** to Newton's ***Principia***. During that period the heliocentric view of the world was formulated and put on a firm footing, and the scientific method, with its interplay between theory and empirical tests of working hypotheses, was established as the way in which research is still done today. But I would argue that the Copernican Revolution was far from complete at the end of the 17th century, and that it has in fact not been completed until today.

The birth of modern astronomy during the Renaissance had moved the Earth from its central position to a non-privileged position amongst the planets, but the Sun was still at the center of the Universe, and man was still the undisputed Pride of Creation. The subsequent history of astronomy, however, encompasses a number of developments that have removed one of the remaining perquisites after the other from Earth and its proud inhabitants.

The first such development concerns the proper motion of stars. In 1718 Halley discovered that the positions of several bright stars were different from those recorded 2000 years earlier by Hipparchus [9]. By the end of the 18th century stellar proper motion had become a generally accepted phenomenon, and William Herschel wrote in 1783: "Now, if the proper motion of the stars in general be once admitted, who can refuse to allow that our sun, with all its planets and comets, that is, the solar system, is no less liable to such a general agitation as we find to obtain among all the rest of the celestial bodies." [10] This is a truly Copernican argument as it appeals to the notion that the Sun should not be privileged among the other stars. But Herschel actually went further: in the same 1783 paper he showed that any motion of the Sun should lead to a systematic pattern in the observed motions of stars, very similar to the apparent "motion" of trees as seen from a moving train. Herschel could thus demonstrate that while the Earth moves around the Sun, the Sun itself is not at rest, but moving in the direction of the constellation Hercules.

Herschel was also interested in the structure of our Galaxy. On a clear night, one can see the band of the Milky Way stretching across the sky from horizon to horizon. With his telescope, Galileo had already been able to resolve this band into myriads of stars. Herschel counted how many stars he could see in different directions and concluded that the Galaxy, which was assumed to be the whole Universe at that time, was a flattened structure similar to a lens [11]. Within the plane of the Galaxy, the number of stars did not vary much with direction; this led Herschel to believe that the Sun was very near the center. So was the Solar System in a preferred location after all?

The issue was resolved only at the beginning of the 20th century, through the efforts of Kapteyn in Groningen and his contemporaries. Kapteyn used the Copernican argument – the Sun should not be at a preferred place – and argued that the light from distant stars is absorbed by interstellar matter (dust, as we know today) [12]. Herschel could not determine whether the Sun is at the center of the Galaxy any better than you could see whether you are the center of a large open field in very dense fog; the fact that the field looks the same in all directions does not mean that you must be near its center: the edge might in fact be just beyond the distance to which you can see.

The question of our true position within our Galaxy was resolved a little later by Shapley through observations of ancient star clusters. These so-called globular clusters are believed to have formed very early in the history of the Milky Way and reflect the initial shape of the cloud which formed the Galaxy. Using variable stars known as RR Lyrae stars as distance indicators, Shapley determined the distribution of globular clusters in the Milky Way galaxy and demonstrated that the Sun was located in the disk of the Galaxy, about 30,000 light years from the center [13].

The overall structure of the Universe was still uncertain around 1920, when it was still unclear whether all stars belong to our Milky Way, or whether other galaxies exist. This question was resolved in the 1920's and 30's, when Hubble showed that spiral "nebulae" were in fact whole galaxies outside our own Milky Way, each one containing billions of stars [14]. The resulting picture of the humble position of mankind in the cosmos has remained valid until today: we live on the third planet orbiting an average star, at a non-descript position in the disk of a normal galaxy, amongst an uncountable number of other galaxies, each one containing numerous stars by itself.

But recent progress in astronomy has shown that our role in the Universe is even less significant. By analyzing the matter and radiation that was created shortly after the Big Bang (the beginning of the Universe, that is), we can infer that the composition of the Universe is very strange. Only about 1% of the content of the Universe consists of stars and gas that can be observed with telescopes [15]. A further 3% or so is usual matter, consisting of protons, neutrons, and electrons, but hiding in objects that have not yet been observed directly [16]. About 25% of the content of the Universe is so-called "non-baryonic dark matter"; this means that it must consist of strange un-known particles, which the high-energy physicists have not yet been able to produce in their large accelerator laboratories [17]. And 70% of what fills the Universe is not matter at all, but "dark energy", a mysterious substance that provides a ubiquitous repulsion, counteracting the gravitational attraction of the galaxies and the dark matter [18, 19]. This is perhaps the ultimate step on the Copernican ladder: after robbing the Earth of its privileged position among the planets, the Sun of its position among the stars, and the Milky Way of its position in the Universe, we must now concede that even the very matter we are made of is only a small ingredient in the cosmic mixture of substances.

Whereas the first phase of the Copernican Revolution stirred bitter controversy, these later developments were followed by the public with interest, but not much emotion.

This cannot be said about the parallel events in biology, epitomized by Darwin's 1859 book ***The Origin of Species by Means of Natural Selection: Or, the Preservation of Favoured Races in the Struggle for Life*** [20]. While Darwin did not have to face a trial, his theory of evolution was met with similar hostility as the heliocentric world model two and a half centuries earlier. In the middle of the 19th century the human race had to come to the realization that it was but one species in the class of mammals in the kingdom of animals on a branch of the Tree of Life that was hardly more significant than the position of the Sun amongst the stars: the Copernican Revolution had swept biology with full force.

The confluence of Copernican concepts in astronomy and biology has spawned a set of intriguing questions about our origin and position in the Universe: How did Life originate on Earth? Could Life have formed at other places in the Galaxy? Has evolution led to other civilizations? Or is our Solar System special? Are we alone?

Applying the Copernican principle boldly, we might claim that intelligent life should be common in the Galaxy. Searches for signals from extraterrestrial civilizations have indeed been performed with a number of radio telescopes, so far without success. This is not very surprising, however, because only a relatively small number of nearby stars have been looked at, and because our ideas of what exactly to look for may simply be wrong. Much more extensive searches with larger telescopes and higher data rates are planned for the near future. It may soon be possible to survey a large chunk of the Milky Way for signals beamed intentionally towards us, and for the stray radiation from internal communications systems used by extraterrestrials [21]. But are such searches science? One problem with them is that we do not learn much from non-detections. If we do not receive a signal, is this because we have looked at a star that does not have a planet? Is there a planet, but no life on it? Is there life, but only dumb bacteria or dinosaurs? Is there a sophisticated civilization like that of Aristotle's Athens, which just has not invented the cell phone yet? From receiving nothing, we can't tell.

A more systematic approach to answering the question: "Are we alone?" takes one step at a time. First, one has to determine how many of the stars have planets. A lot of progress has been made on this during the past few years. The first planet outside the Solar System was discovered by two Swiss astronomers, Mayor and Queloz, in 1995 [22]. At present, we know more than 100 planets around other stars, and can start to calculate how many planetary systems of various kinds exist.

The second step is finding out how many planets may be habitable. We have a fairly good understanding of what "habitable" means: mostly a solid surface, and a temperature and climate that allows liquid water to exist. Planets with these characteristics (like the Earth) are small, however, and have not been detected yet; all the known planets outside the Solar System are Jupiter-like gas giants without a solid surface.

The third step is determining whether a planet that ***could*** harbor life is actually inhabited. This bears upon the question about Life's origin on Earth, and whether the processes that lead to it (called pre-biotic evolution) would also likely occur on other planets with similar conditions. This question is one of the most difficult in modern biology, but fortunately there is a shortcut towards detecting evidence of Life on other planets. We know that Life on Earth has totally transformed the composition of the atmosphere; without living organisms performing photosynthesis there would be hardly any oxygen in it. We can thus search for Life from a great distance with astronomical techniques: spectroscopy enables us to analyze the composition of a planet's atmosphere, and can thus tell us indirectly about photosynthetic life [23].

The fourth step is perhaps the most difficult of all: If we could count the planets bearing Life, would we have learned anything about the possibility of intelligence at other places? There is currently a heated debate going on amongst evolutionary biologists about the question of whether any particular evolutionary outcome is inevitable, or whether it is shaped so much by accidents of history that no prediction is possible. The first view, as summarized by Conway Morris, holds that "the evolutionary routes are many, but the destinations are limited"; this would suggest that Life evolves towards intelligence with reasonably high probability [24]. The opposing view, namely that the outcome of evolution depends on many contingencies and is therefore unpredictable, also has forceful supporters. If they are right, the emergence of intelligence might be an "accident" that happened only once in the Galaxy, namely here on Earth.

The fifth step involves the question of whether intelligent beings will develop a civilization that eventually develops the tools for interstellar communication. This may appear quite likely, given our own history that took us from the first primitive tools made from natural materials to a technology that can indeed transmit signals to neighboring stars, in a time that is very short compared to astronomical time scales. The more pertinent question may be how long a "typical" technical civilization will survive. I once found a book in a library about the big open questions in astronomy. One chapter in this book was entitled: "Is there intelligent life out in space?" I read it with interest, and went on to the next chapter, which asked the question: "Is there intelligent life on Earth?" This question is not as ridiculous as it sounds in view of the enormous potential for self-destruction through wars, accidents, or destruction of the life-supporting planetary environment that our technologies have created. The question also has a bearing on the search for extraterrestrial life: If all advanced technologies self-destruct after a few hundred years, we would probably not find one before the demise of our own species. Conversely, if we could ever communicate with another civilization, this would be reason for some optimism about our destiny, as this would demonstrate that self-destruction is not a necessary fate.

In any case, the next step ahead in the ongoing Copernican Revolution should address the questions whether planets like our Earth are common, and whether life forms exist that have originated independently from the origin of Life on Earth. Copernican reasoning would suggest that the answers to these questions should be "yes", but there is a counter-argument, frequently called the "anthropic principle" [25]. The anthropic principle holds that the mere fact that we can discuss the origin of life here in the Academiegebouw implies that our environment is conducive to the origin and survival of living beings. Therefore, if one assumes that very special conditions are required to support life on a planet, these would have to be exactly the conditions found here on Earth, and generalizing from the Earth to possible other planets in the Copernican spirit would constitute a big mistake.

At the heart of the anthropic argument is the concept of selection effects, which are quite common in astronomy, and also in the social sciences. In 1936, the *Literary Digest* conducted a poll to forecast the result of the upcoming presidential election in the US. They predicted that Alf Landon, the Republican candidate, would win by a large margin [26]. In the actual election, the incumbent Franklin D. Roosevelt won a landslide victory. The *Literary Digest* had harvested the addresses of the people they sent the survey to mainly from telephone books and motor vehicle registries, thereby introducing an important selection effect. The poor of the depression era, a group where support for Roosevelt was especially strong, often did not have a phone or a car. In a sense, stating that our Sun is an average star is akin to saying that someone with an entry in a phonebook is a typical voter. The difference is that the *Literary Digest* should have known better, whereas we currently have no empirical means to determine whether there is anything special about our Solar System.

After I told you all this about the history of science and gave you a few thoughts about the existence of life elsewhere in the Galaxy, you might ask: why is this a topic for an oratie by someone whose specialization is thinking up, designing, and building astronomical instruments? Isn't an instrumentalist someone like a PhD plumber, running a loodgieter's business in the basement? The answer is: yes, instrumentalists spend a lot of time playing with soldering irons, aligning optics, producing project management plans, or sitting on review committees, depending on their seniority. But in the tradition of Huygens, Brahe, and Galileo, most of us are motivated ultimately by the opportunities for discoveries and scientific breakthroughs that our new instruments create, and the search for other planets and for life elsewhere in the Universe is one such endeavor that will benefit from new technologies in the near future.

To illustrate the close connection between present-day astronomical technology and the potential for new discoveries, I would like to tell you a little more about my most important field of interest, which is instrumentation for high angular resolution, that is, in simple terms, inventing tricks that allow us to take very sharp images, and to make very precise measurements of locations and motions of stars and other objects of astronomical interest. I read about one such method, called Very Long Baseline Interferometry, when I was a student of physics at the universities of Bonn and then Heidelberg. The essence of this technique consists of using several radio telescopes scattered around the world; all telescopes in the network look at the same object at the same time, and then the data from the telescopes are compared to each other (by forming the cross-correlation between the data streams from all pairs of telescopes, for those who want to know more precisely). In this way one can obtain images of radio sources that are as sharp as those one would get with a telescope reaching from Europe to the West Coast of the US, which as such would be quite impractical to build [27].

After completing my third year of university studies, I was invited to attend a summer school at the Max-Planck-Institute for Radio Astronomy in Bonn, in which each of the students should be introduced to one line of forefront research under the supervision of one of the staff scientists. Having read about Very Long Baseline Interferometry, I stated in my application that I wanted to work in this field. This turned out to be an extremely lucky choice, because at the introductory meeting, at which the students participating in the summer school were matched one-by-one with the staff members, I heard a voice say: "Herr Quirrenbach will be working with me," and this voice belonged to Arno Witzel.

From Arno Witzel and his diploma and PhD students I learned the foundations of radio interferometry, how to analyze and interpret data, and how to formulate questions and to design experiments that lead to scientific progress. Soon I realized that I had met the first great love of my life: I had fallen in love with the milliarcsecond. A milliarcsecond is a measure for very small angles; this was the resolution that we could achieve in our images obtained with Very Long Baseline Interferometry. To give you an impression of what a milliarcsecond is, I can use this manuscript in front of me. I typed it up nicely, so that I can easily read it without straining my eyes. If I had eyes with milliarcsecond resolution, I could leave the manuscript here, take a flight to Athens, and I could sit down at the place of Plato's famous Academy, and still read the manuscript left behind on the podium in the Academiegebouw.

It was realized many decades ago that very precise measurements of stellar positions can reveal the presence of planets around other stars. The famous former director of Leiden Observatory, Hertzsprung (he is so famous that he is usually called only "H", as in "HR diagram"), wrote in 1933: "One of the most fascinating questions in astronomy is, whether our sun with its planets is an exception from the rule or not. In this connection the fact may be recalled that the mass of the planet Jupiter is about one thousandth part of that of the sun and its distance from the sun about 5 times that of the earth. The displacement of the sun caused by Jupiter has therefore a range of one hundredth of an astronomical unit. The parallax of α Centauri is ".75 and the corresponding range of displacement ".0075. This is of the same order as the mean error of one plate found above. We are therefore not far from the accuracy required to find evidence of planets belonging to other suns, if such planets exist." [28]

You will have noticed the Copernican question at the beginning of the citation; then Hertzsprung explains an important effect that can be used to detect planets indirectly: the position of a star that is orbited by a planet wobbles around slightly due to the gravitational pull of the planet. Hertzsprung was a little too optimistic with his prediction that astronomers in the 1930's were close to detecting planets in this way, but it is a variation of this effect that led to the discovery of the more than 100 planets that we know today. This variation consists of measuring the radial component of the stellar wobble by precise observations of the Doppler Effect, rather than measuring the two components of that motion in the plane of the sky, as envisaged by Hertzsprung.

No one has yet succeeded in detecting a planet in the way originally proposed by Hertzsprung, but that is exactly what our group here in Leiden intends to do in the next few years. By transferring the interferometric technique of combining several telescopes from the radio regime to visible light, we want to improve the precision of stellar position measurements to the point where we will be able to detect and characterize planets around other stars [29]. Our goal is technically extremely challenging, as we need a precision a hundred times smaller than our friend, the milliarcsecond: we intend to perform measurements with errors of only 10 microarcseconds. To give you an impression of what that means, imagine that we would send another astronaut to the Moon, and we would watch him there from here. The astronaut on the Moon would hold up his hand, and wiggle his index finger back and forth: this motion, seen from the roof of the Academiegebouw, has an amplitude of 10 microarcseconds, that is, it would be detectable with the instrument that we intend to build. To be precise, most of the infrastructure for these measurements already exists at the Very Large Telescope Interferometer in Chile; our contribution will be completing the instrument hardware, and developing the observing techniques and data analysis methods that will allow us to make such precise measurements of stellar positions.

The present ***indirect*** methods of planet detection, in which we do not see the planet itself, but observe the consequences of its presence for the parent star, allow us to determine the planet's mass, but not much else about its physical properties. In the longer run, however, perhaps in the middle of the next decade, we also hope to use interferometry for the ***direct*** detection of Earth-like planets. The ***Darwin*** project is a mission planned by the European Space Agency that will use telescopes on separate satellites flying up to a few hundred meters apart to form an interferometer. It will use an optical trick called “nulling” or “destructive interference” to reduce the glare of stars so that faint planets close to them become observable [30]. By carrying an infrared spectrograph, ***Darwin*** will be able to analyze their atmospheres, and to detect water, carbon dioxide, and ozone on them. If we find water on a planet around another star we will know that it is in principle habitable, and that will be very interesting. Moreover, if we find ozone, we will be able to infer that oxygen must be present, too. This would hint at the possibility of seeing the imprint of photosynthesis, and with suitable additional information regarding temperature and climate, we might actually be able to exclude an abiotic origin of oxygen. ***Darwin*** will thus help us to understand the atmospheres of planets many light years away from Earth, and, if we are lucky, might reveal the presence of life on some of them. Such a discovery would then be the next step towards a true completion of the Copernican Revolution.

We live in a truly exceptional time: we are the first generation that can address age-old questions of the human race, about our origins, our place in the Universe, and our destiny, in a genuinely scientific way. At the same time, our educational system seems to be unable to convey the excitement of modern science to students and to the general public. Superstition is on the rise, and scientific literacy not a high priority in education. What are the reasons? We seem to do something utterly wrong to children at a fairly young age. I would venture to claim that most six-year-olds are extremely curious and eager to learn about science, just as I was excited to see the reasons for day and night, and why there are seasons. A few years later many children have lost this sense of wonder at nature, perhaps because we teach them to be lazy, to consume, not to think. This trend continues; when physics enrollment drops we invent “physics lite” curricula, as if there was anything “light” about physics. I would argue that we should stop thinking that we do children and students a favor by ***not*** challenging them to the utmost extent of their intellectual abilities, we should emphasize again teaching those subjects that are truly useful in life: mathematics, sciences, classical languages, philosophy, in short: the liberal arts. And, most importantly, we should convey to our children that learning and thinking are fun.

Dear students, the University is from its origin Universitas magistrorum et scholarium, gemeenschap van leraren en scholieren. I have always liked the German translation “Gemeinschaft der Lehrenden und der Lernenden”, community of those teaching and those learning, because this leaves room for interpretation about who is teaching and who is learning. Clearly, one hopes that professors keep learning throughout their lives, and it is said that students learn more from each other than from their instructors. I enjoy teaching because every time I explain a subject to students I learn something new myself. Learning can be hard, however, because it means breaking through the present limitation of your mind, opening new perspectives for your imagination, exercising the capabilities of your brain, grasping a piece of truth that was beyond your understanding only a minute ago. Be not mistaken, listening to a professor is not the same as learning; learning means thinking, and there is no other person who could do the thinking for you.

Towards the end of my speech I would like to express my gratitude to all those who have contributed to my appointment as hoogleraar in Leiden. I thank the College van Bestuur for having entrusted me with the tasks of teaching and performing research at this wonderful university.

George Miley, until recently Scientific Director of the Observatory, and now Royal Academy Professor, lured me from sunny Southern California to the cool and damp Netherlands, promising that the collegial warmth and the scientific excellence of the Sterrewacht would more than make up for the slightly less benevolent climate. So far, I have not been disappointed, for which I am very thankful to George, the new Director Tim de Zeeuw, the professors, staff, postdocs, graduate, and undergraduate students at the Sterrewacht.

The Dutch astronomical community has a reputation for close collaboration between the different institutions, and for being able to find a consensus when important decisions have to be made. Although a newcomer to the Netherlands, I have already benefited tremendously from many interactions with colleagues across the country, and I have entered a number of collaborations with ASTRON, SRON, ESTEC, and Dutch industry, which I hope will be lasting and fruitful.

As you can certainly imagine, building advanced and complicated instruments for astronomy is expensive, and requires a dedicated group of people with complementary skills. I am very grateful to the Sterrewacht, NOVA, NWO, and the European Union for providing funding for my research. This has enabled me to attract a number of young co-workers, whom I would like to welcome. In this context I would also like to thank NOVA and especially George Miley for the foresight to establish an expertise center for interferometry, which has done a lot of ground work and given me a nice head start for my own scientific endeavors.

I am deeply indebted to all those who have set me on the track to a career in astronomy. First and foremost I should mention my parents, who always had time to answer curious questions, and always thought that children should be provided with intellectual challenges. I was fortunate to have many good high school teachers and university professors, who over nearly two decades taught me everything from reading and writing to general relativity. I have already mentioned Arno Witzel, whose role in my life is much better described with the German word “Doktorvater” than with the English expression “thesis advisor”. All these, and many other friends, relatives, and colleagues, have in one way or the other contributed to the fact that I have been given the honorable task to speak from this podium today.

My final word of thanks goes to my dear wife. Bettina, you waited three years for me to come back from my first position in the US. Then we got married, and it is not always easy to be married to an astronomer who spends long hours at work, and who travels frequently and far, to exotic places such as Chile and New Mexico, Hawaii, La Palma, Delft and Dwingeloo, always in pursuit of that elusive second love of mine, the milliarcsecond. It may sometimes appear as if astronomy was always on the top of my mind, but rest assured, Bettina, you are first in my heart and my life.

Ik heb gezegd.

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