Building for giants: challenges and rewards

Inaugural lecture by

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on the acceptance of his position of professor of

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Universiteit Leiden

TU Delft

Mijneheren de Rectores Magnifici, leden van het College van Bestuur, collegae hoogleraren en andere leden van de universitaire gemeenschap. Beste familie en vrienden, zeer gewaardeerde toehoorders. Dames en heren,

De titel van mijn rede vandaag is "Building for giants: challenges and rewards". Ik zal deze rede dan ook verder in het Engels houden. Dat heeft te maken met het feit dat de voertaal in de Sterrenkunde Engels is, ik geen vloeiend Nederlands spreek, en dat vandaag veel internationale toehoorders - zowel studenten als collega's - mijn oratie bijwonen.

Figure 1 The Hubble Ultra Deep Field (HUDF).[1]

Galaxies of all shapes

A deep look at the universe
The Hubble Space Telescope has given us amazing images of the deep Universe. Almost all objects that are visible in this image (fig. 1) are galaxies. If this image would be as large as the area on the sky covered by the full moon, we would see over one million of these galaxies. And each of them contains billions of stars.

As we look at fainter and fainter galaxies, which are typically at larger and larger distances, we also look further and further back in time. Toward the faintest objects in the image, we look back more than 13 billion years (*dat zijn dertien miljarden jaren*) into the past. That also means that we see them in their youngest phases, just a few hundred million years after the Big Bang, when the Universe was only three percent of its current age.

But it is not only the look back in time which makes these images so fascinating. It is also the *variety* of objects that we see: their wide range in sizes, luminosities, colors, and shapes. Let us zoom in now on a few galaxies for illustration (fig. 2).

Galaxies and star formation

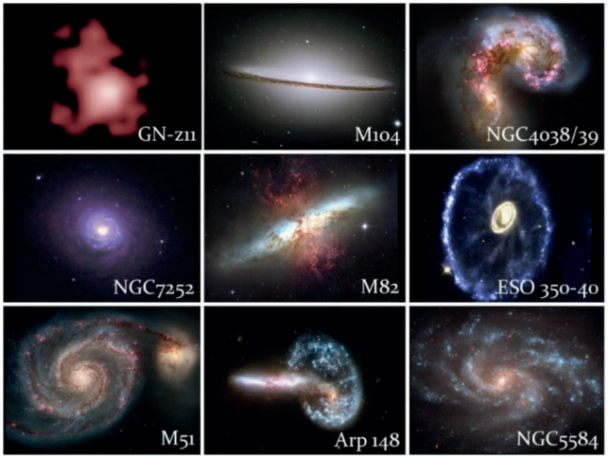

Figure 2 Composite of nine morphologically interesting galaxies as seen with the Hubble Space Telescope.[2]

By our standards on Earth, space is mostly empty - even in galaxies. But sometimes, somehow, a galaxy manages to accumulate gas and dust in certain regions. That may happen because the galaxy accretes gas from the surrounding intergalactic medium, or because it collides with another galaxy, or due to some internal galactic dynamics. We do not need to know here *why* this happens, but we need to look at the consequences: if the density gets high enough, the cloud of gas will collapse under its own weight, and, eventually, stars will form.

In most galaxies this happens continuously, albeit at a low rate. Our galaxy, the Milky Way, forms about one star like our Sun per year, on average. If the Milky Way would continue at that pace for a billion years, we would obviously have formed one billion stars. *Wow!* But then consider that the Milky Way already contains a few hundred billion stars, so that is "peanuts". If some "Extraterrestrians" in a distant galaxy would watch the Milky Way, much of that star forming activity would likely go unnoticed.

However, some galaxies are much more active in that regard. There are galaxies which form stars at rates of dozens or even hundreds of solar masses per year. These spectacular events light up the galaxy, and are often referred to as '*starbursts*'. In such 'starbursts', stars are not formed in isolation, but in clusters of hundreds or thousands of stars. And some of those stars can be very massive and extremely luminous, outshining our Sun by a million times. Because these massive star clusters are so luminous, and because there are often many of them forming together in a starburst, they shape the appearance of a galaxy, and they play a key role in the evolution of their host galaxy.

Regions of massive star formation

The regions where the massive stars are being born are essentially invisible at optical wavelengths, and the Hubble Space Telescope would not be able to spot them. This is simply due to the large amounts of gas and dust, which are still surrounding the newborn stars, and which absorb most of the radiation from the stars. Unfortunately, dust is quite efficient in absorbing visible light, which is also the reason why we have to clean our windows at home from time to time.

While the dust is absorbing the radiation from the newborn stars it will heat up – not yet enough to shine at optical wavelengths, but warm enough to be seen at the longer mid- and far-infrared wavelengths. Eventually, the region clears up, the gas and dust clouds dissipate, and the young stars become visible. Let us take a closer look at the 30 Doradus region in the Large Magellanic Cloud for illustration (fig. 3).

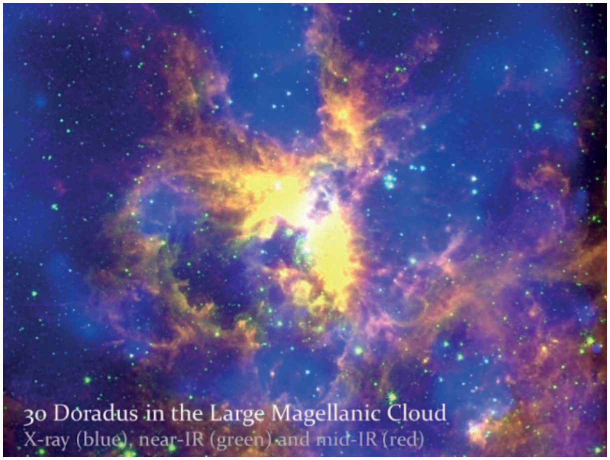

Figure 3 The 30 Doradus region in the Large Magellanic Cloud.[3]

The most recent 'starburst' event here lies just a few million years in the past. We can already *see* many of the stars. But what we also can see here is the impact they have on the surrounding interstellar medium. Unthankfully, these massive stars blow away the stuff from which they were born and shape the remaining gas and dust - often triggering the formation of new stars in their neighborhood.

The most massive stars already end their lives after just a few million years in spectacular supernova explosions. These explosions enrich the interstellar medium with heavier elements which have been built up by nuclear reactions in the star or during the explosion. These heavier elements are the basis for more complex molecules and dust grains, that form in the aftermath of the supernova explosion. Without these processes we would not be here today, standing on the solid surface of a rocky planet.

How do we know all this?
You may wonder "*How do we know all this?*" Well, astronomy is physics! But our laboratory is very remote, and nature has already set up the experiment for us. The remoteness of our lab, however, creates a big challenge to watch and analyze the data from our experiment. We need observations that, firstly, allow us to see the *faintest objects*, and these require very high sensitivity. Secondly, we need to see these objects sharply to understand what we are looking at, and that requires high spatial resolution. (There is a third aspect, namely to obtain comprehensive information over a wide range of the electromagnetic spectrum. But today, I will focus on the optical/infrared wavelength regime, because this is the area for which I have been building astronomical instrumentation).

Our main tool has been - for more than 400 years and in the foreseeable future - the *astronomical telescope*. Because of its importance, I will now give "A brief history of the telescope".[4]

A brief history of the telescope

How it all began
By the early 17th century, lens makers across Europe had developed lens-grinding and polishing techniques. Since these lenses were used as spectacles, the area which had to be accurately figured was small, typically just a bit larger than the pupil of the human eye. At that time, Italian glass-making techniques were practiced in Middelburg, the capital of the province of Zeeland. It was the spectacle maker Hans Lipperhey who experimented with the size of the illuminated area on the objective lens. He discovered that, by reducing its diameter from about 3 to 1 centimeter, the magnified images became much sharper.

On September 25th, 1608 - so, just yesterday, 408 years ago - Hans Lipperhey went to The Hague to present his "spyglass" to Prince Maurice of Nassau, in order to receive a patent for his invention. However, while the usefulness of his invention was immediately recognized, it was also evident that it could be too easily copied, once the principle has been recorded - and therefore the patent was denied.

Not surprisingly, Lipperhey's findings could not be kept secret for long and started to "leak out". Eventually, a newsletter was sent from The Hague to the major European cities in diplomatic pouches. One of them reached Galileo Galilei in November 1608, and he started immediately working on an instrument that magnified 20 times with good optical quality (fig. 4).

Figure 4 Galileo and the Venetian Senate.[5]

In early 1609 Galileo started his observations of the Heavens with the first *astronomical* telescope, which led to his discoveries of the satellites of Jupiter, the mountains on the Moon, and two bodies around Saturn. However, despite the fundamental importance of these discoveries, and the great attention they received, the discovery space was largely exhausted by 1611 - only two years later. Why was that?

Let us consider that the telescope pupil was 1.5 centimeters in diameter, about twice as large as the dark-adapted pupil of the human eye, yielding a four-fold increase in light collection. That was not much by astronomical standards, and further discoveries had to wait for better and bigger telescopes.

Size growth over time

Over the centuries, brilliant scientists like Sir Isaac Newton, Christian Huygens, Johannes Kepler, and William Herschel, have made fundamental improvements to the telescope optics and telescope mounts. As a result, telescopes kept on growing for the last four centuries.[6] In retrospective, we can see on this graph (fig. 5), that the light collecting area, or aperture size, of the biggest telescopes of their times doubled approximately every 20 years. But the path did not immediate lead to the giant telescopes we know or anticipate today.

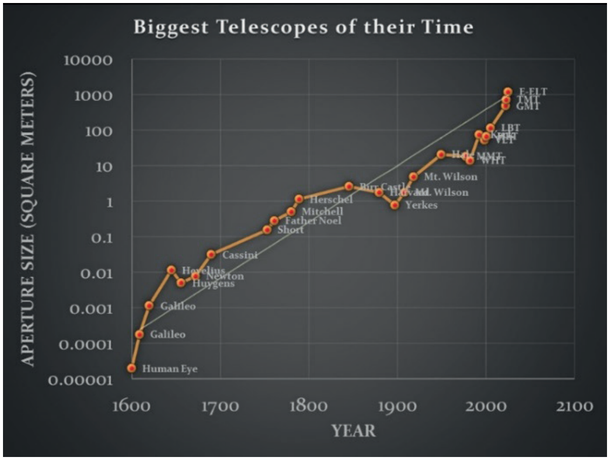

Figure 5 Telescope growth with time.[6]

About hundred years ago, the famous American astronomer and physicist, and director of the Harvard College Observatory, Edward Pickering, argued that telescopes had reached their optimal size - which was approximately one meter at the time - and that there was no advantage in making them any bigger. In an article on the future of astronomy published in 1908, he wrote[7]: "*It is more than doubtful whether a further increase in size is a great advantage*". His opinion was clearly biased by the politics of that time. His competing colleagues on the West Coast of the United States were just about to complete a much bigger telescope: the 1.5 meter telescope on Mount Wilson near Los Angeles - a telescope which would eventually become one of the most productive ones in astronomical history. But Pickering also provided scientific arguments, namely that factors like the atmosphere and the climate had a bigger influence on the quality of astronomical data than the telescope size.

Technological breakthroughs

The path towards the telescope giants of the present and the future was not straight forward and had to await important technological developments. There are at least two fundamental breakthroughs in technology, without which modern observational astronomy would not have become possible.

The first one of these breakthroughs is *fast computers*, which revolutionized several areas: Fast computers enabled *more compact telescope mounts*, they enabled *bigger primary mirrors* by actively aligning and keeping the telescope *mirrors* in shape, and they enabled a technique, called *adaptive optics*, to correct for the atmospheric turbulence, which blurs the image. Active and adaptive optics are nowadays essential on ground-based telescopes to reach their ultimate optical performance, the so-called diffraction-limit.

The second breakthrough technology is *solid-state detectors* - most notably CCDs and infrared array detectors - which superseded photographic plates. With their superior sensitivity of close to 100% quantum efficiency, the detectors were no longer the weakest link of the observations. Furthermore, their extended wavelength response opened new windows of the electromagnetic spectrum, new windows to the Universe.
But now we have to see how bigger telescopes expand the discovery space. This is mainly due to our two before-mentioned requirements, namely sensitivity and spatial resolution.

Sensitivity and resolution
Generally, a bigger telescope collects more photons per hour, and will therefore provide a better sensitivity. Since that gain in sensitivity goes up with the *area* of the telescope mirror, rather than its *diameter*, big telescopes enable observations which have been absolutely impossible before.

And this is absolutely necessary! Consider a typical galaxy (10^{10} L_*) at high redshift ($z = 10$), when the Universe had only 3% of its current age - just like the most distant ones we saw in the Hubble Ultra Deep Field at the beginning of my speech. That galaxy is about 10 billion times fainter than the faintest object we can see with our bare eyes on a dark night. In fact, the pupil of our eye would only receive about *one* photon *per year* from that galaxy, which would make it a rather boring observation. We clearly need a bigger light collecting area. If we had a 6.5 meter Space Telescope - and we will have one soon, as I will explain in a few minutes - we would receive about two photons *per second*! And with very sensitive detectors, which respond to these individual photons, we could now detect and study these "baby galaxies".

Another - but equally important - aspect is the *spatial resolution* which determines the "sharpness" of the image, that is, the amount of small details which can be resolved. Let us consider observing our very distant, young galaxy again. If it is similar to the galaxies we know today, its central region is about 300 light-years across. If we want to resolve that central region, our telescope has to provide an angular resolution of about 20 milli-arcsecond!

It may not be obvious how large an angle of 20 milli-arcseconds is, so let's consider an experiment. This coin here is a regular "one Euro coin". Let's flip it so that we can see it edge-on. Later, I will ask one of my colleagues from the Technical University to take this coin back to Delft - which is about 25 kilometers from here - and hold it up in the air. We can then look from the roof of this Academy building here all the way to Delft, and the angle under which its edge appears is approximately 20 milli-arcseconds!

In our example, the nuclear region of our high redshift galaxy, if observed with our big telescope from Leiden, would then entirely fit behind the edge of that coin held up in Delft. Such an extremely high resolution can indeed be provided by the next generation of telescopes, but it will not be easy!

We need to get rid of the atmospheric turbulence, we need to keep the telescope stable during the long integration time, and we need to record and analyze the light. The latter requires dedicated scientific instruments which process, disperse, and record the light for further analysis.

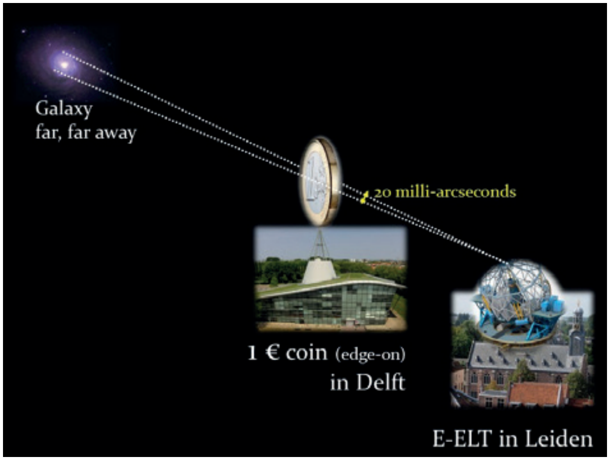

Figure 6 Illustration of the "Euro coin experience" to illustrate the size of an angle of 20 milli-arcseconds.

JWST and the E-ELT

This brings me now to the two scientific instruments on two new telescopes, which have been the focus of my work for the past ten years, and will continue to be so in the foreseeable future. The first one is MIRI on the James Webb Space

Telescope (the JWST), and the second one is METIS on the European Extremely Large Telescope (the E-ELT) (fig. 7).

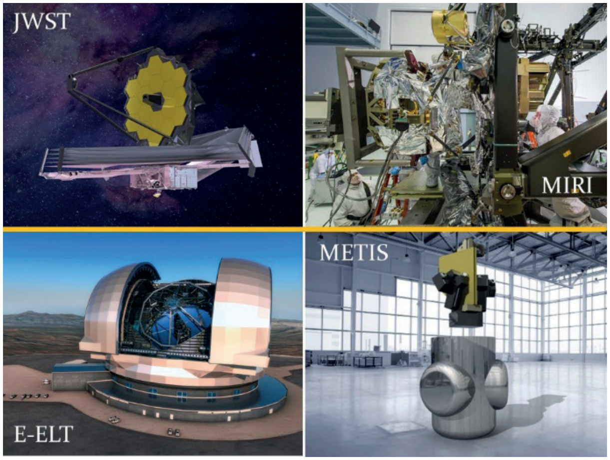

Figure 7 Artist conceptions of the JWST[8] (top left) and the E-ELT[9] (bottom left) with their scientific instruments MIRI[10] (top right) and METIS[11] (bottom right).

JWST-MIRI

The *James Webb Space Telescope*[12] will succeed the Hubble Space Telescope when launched in October 2018. With a primary mirror of 6.5 meters in diameter, it will be the largest optical telescope ever launched into space. To be able to fit within an Ariane-5 rocket the telescope optics, and even its primary mirror, have to be folded up, and will remotely deploy in space. Its 5-layer sunshield has the size of a tennis court – all neatly packed together for the launch. If all goes well, JWST will be the prime facility for frontline research in optical and infrared astronomy for the next decade.

The JWST will be equipped with four scientific instruments; one of them is the *Mid-InfraRed Instrument MIRI*. MIRI[13] was designed and built by a large international consortium of European and US American institutes. It is an imager, *integral field spectrometer* and *coronagraph*, working in the infrared regime from 5 to 28 micrometer wavelength. (By the way, an *integral field spectrometer* simultaneously provides a spectrum for *each* image point within a two-dimensional image. A *coronagraph* rejects the light from a bright star, and thereby enhances the sensitivity in searches for faint objects around the star). One of the key components of MIRI, the ‘Spectrometer Main Optics Module’ has been largely designed, built, and tested by NOVA, the Nederlandse Onderzoekschool voor Astronomie.

E-ELT-METIS

The other project is the *European Extremely Large Telescope*[14], built by the European Southern Observatory (ESO). It will also be a superlative: with a primary mirror of almost forty meters in diameter, it will be the world’s largest optical telescope! In fact, the primary telescope mirror will have the same light collecting area as the eyes of all people in the Netherlands (under the age of 60) taken together. Obviously, this huge primary mirror cannot be made in one piece. It is composed of almost 800 hexagonal mirror segments - all perfectly aligned. Unlike classical telescopes, the E-ELT’s novel optical design already includes an adaptive mirror within the telescope to correct for the atmospheric turbulence. The telescope and its enclosure are also huge! The telescope structure is 14 times more massive than the Statue of Liberty in New York - and clearly not suitable to ever be launched into space! Its construction has just started on Cerro Armazones in northern Chile, and first light is planned for 2024.

The E-ELT will eventually be equipped with a suite of powerful scientific instruments. The ‘Mid-infrared ELT Imager and Spectrograph’, METIS[15], is one of only three scientific “first-light” instruments. METIS will cover the thermal/mid-infrared wavelength regime from 3 to 19 micrometers. It will provide high contrast imaging, slit spectroscopy, and high resolution integral field spectroscopy. METIS is being designed and built by an international consortium of nine partner institutions under the leadership of NOVA, and I feel honored to be the Principal Investigator of this fantastic instrument. METIS is expected to be assembled and tested in Leiden, and installed on the E-ELT in 2025.

Scientific potential of MIRI and METIS
Scientifically, MIRI and METIS complement each other very well: while the superb sensitivity of MIRI in space will allow us to detect the faintest objects, the superb angular resolution of METIS will allow us to explore the tiniest structures. Given their similar observing wavelengths, it is not surprising that both, MIRI and METIS, will generally observe very similar targets, for instance cooler objects - *such as planets* - dusty star forming regions, and distant starburst galaxies.

"*It is difficult to make predictions, especially about the future*", as they say. Our scientific knowledge and goals evolve in parallel to the design and construction of these instruments. The discoveries in ten years from now may be in areas that are very different from our current expectations. For instance, during the conceptual design study of METIS in 2008, the study of exoplanets was still a scientific niche. This has changed dramatically. Just one month ago, ESO announced the discovery[16] of a planet of about 1.3 Earth masses, which orbits in approximately 11 days around Proxima Centauri. This discovery received a lot of attention, because at about four light-years distance, Proxima Centauri is the *nearest* star to our Sun. Its planet orbits in the habitable zone and has a surface temperature which allows the presence of *liquid* water, a necessary ingredient for the evolution of life as we know it (fig. 8).

Figure 8 Artist conception of the surface of the closest exoplanet Proxima Centauri b.[17]

Although it is of utmost interest to know *if* there is a habitable planet in our neighborhood - and possibly even some form of life - the current observing facilities are not capable enough to give us that information. We have not even *seen* Proxima Centauri b yet - we only inferred its presence indirectly from the wobble of its host star. The necessary observations are extremely challenging! Exo-planets can be even fainter than the most distant galaxies, mentioned in the beginning, and would already be difficult to detect as isolated objects. But exoplanets are extremely close to their host stars, which are millions to billions times brighter than the planets themselves.

METIS on the E-ELT will observe at thermal infrared wavelengths, which makes it much easier to eliminate atmospheric turbulence, and to reach the best optical performance of the E-ELT. At an angular separation of 35 milli-arcseconds, METIS will just be able to image the planet Proxima Centauri b, spatially separated from its star. At these long wavelengths, there are also several important biomarkers to probe the existence of a planetary atmosphere. The high resolution spectrograph of METIS could then be used to search for important atmospheric features, such as carbon-monoxide (CO), carbon-dioxide (CO_2) and water (H_2O). In about ten nights of observations, we will know more about Proxima Centauri b's atmosphere - a discovery that might well secure a place for METIS in the history books of mankind. And by building the instrument ourselves, *we* may have the best chances to make these observations.

TU Delft / Faculty of Aerospace Engineering

The immediate neighborhood of our Sun is also of great interest to the faculty of Aerospace Engineering of the Technical University in Delft. With close to 3000 students, it is the largest Aerospace Engineering faculty in Europe, covering many different areas, including space research of our planetary system and nearby exoplanets. Astronomers and Aerospace Engineers have many common interests, not only with regard to planetary and exoplanetary research, but also concerning aspects of spacecraft technology, remote sensing, and data analysis.

Many students of Aerospace Engineering also have a genuine interest in the physics of our Universe. It is evident that the Sterrewacht Leiden and the faculty of Aerospace Engineering in Delft are not only close in terms of geographical distance (we already know from our "Euro experiment" that they are only 25 km apart), but also close in terms of scientific interests. I am therefore extremely pleased to have a *part-time position at the Technical University in Delft*, faculty of Aerospace Engineering, since September 2015.

Challenges for astronomical instrumentation

We are lucky to live and work in the "Golden Age" of astronomical instrumentation. Many of us have witnessed how computers and photo-conductors have changed the way we do astronomy. And many of us will witness the dawn of the extremely large telescopes. At the recent meeting on "Astronomical Telescopes and Instrumentation" organized by the "International Society for Optics and Photonics", SPIE, *2600 papers* on existing and planned facilities and instruments were presented[18] - and many interesting, and sometimes crazy, ideas, as well. Astronomical instrumentation is clearly a very lively field, apparently with "no showstoppers" in sight. But does this mean that there will ever be bigger and bigger telescopes and instruments?

In 1965, Gordon Moore, the co-founder of 'Intel and Fairchild Semiconductor', predicted that the number of transistors per chip doubles every two years - an exponential growth process that we now know as 'Moore's law'. This is very similar to the before-mentioned doubling of the telescope aperture every 20 years. However, just like Moore's law appears to reach saturation now, telescopes cannot continue growing forever. Such a saturation is even more likely since astronomy, unlike semiconductors, is not a billion-dollar industry where the demands of the market keep pushing further developments. Before I make some predictions for the future of this field, I will summarize what I consider to *be the three biggest challenges* for modern telescopes and instruments in general.

Budget Limitations

The first, and arguably biggest, challenge is the enormous costs of the next generation of telescopes or space missions. Even the JWST - NASA's flagship mission with enormous public support - went through rough times when the cost estimates continued to grow with time[19] - as can be seen in this diagram (fig. 9).

Our colleagues from high energy physics very well remember the fate of the *Superconducting Super Collider* (SSC), a particle accelerator under construction in Texas. In 1987, the American Congress was told that the project could be completed for 4.4 billion US dollars, but the cost estimates eventually reached 12 billion dollars. After 2 billion dollars had been spent, the US Congress canceled the project in October 1993.[20] Looking at this graph, we can be lucky that a similar fate did not happen to the JWST - most likely because of the enormous popularity of astronomy. Many people, who are not scientists, *love* the images from the Hubble Space Telescope, but have much less grasp on the importance of an 87 kilometer long, underground particle accelerator. We should always keep that advantage in mind, and never underestimate the value of public outreach.

Figure 9 The cost increase of the JWST mission with time.

However, in a world of global warming, terror attacks, and instable financial markets, governments and our societies will only support science projects up to a certain maximum. It appears that there is a virtual limit around 10 billion dollars. And this is for high profile space projects … For ground-based observatories it is certainly much less, maybe 1 to 2 billions. Both JWST and the E-ELT have already come close to these virtual limits. The next generation of observing facilities beyond JWST and E-ELT, which is hopefully ten times more powerful, must not be ten times more expensive!

Technological Risks

The second challenge is the technological risks. Telescopes and instruments have become incredibly complex systems, comprised of hundreds or thousands active and passive components. In order to reach their science goals, astronomical telescopes and instruments manipulate the detected light in various ways:

- they use *active optics* to correct for slowly varying misalignment,
- they use *adaptive optics* to correct for the quickly varying atmospheric turbulence,
- they use *slowly moving optics* to adjust and rotate the image orientation,
- and they use *quickly moving optics* for calibration (chopping).

All these devices need sophisticated mechanisms, sensors, and control. And all these control loops have to work together perfectly, in order to provide the best possible image. Optimizing the overall performance of complex instruments has become a serious challenge for Systems Engineering.

Organizational Structure

The third challenge is the complexity of the organizational structure of a project. Building an instrument for modern, state-of-the-art telescopes involves teams of 50 to 100 people, from science to engineering, and from physics to management. The large costs of these projects, and the political pressure to serve a large community, generally require international collaborations. That brings many different "working cultures" together. On one hand, it can be very rewarding to be able to work with talented people of different cultures. On the other hand, the management of people, interfaces, and the proper flow of information, have become a serious challenge that must not be underestimated.

In 1999, NASA lost the Climate Orbiter, a 125 million dollar Mars mission, because NASA used the metric system for spacecraft operation, while a subcontractor used English units instead. When the Climate Orbiter fired its engine to push itself into the orbit around Mars, the wrong units caused it to come too close to Mars - and fail! Quoting Tom Gavin, the JPL chief administrator at the time[21]: "*This is an end-to-end process problem. (…) Something went wrong in our system (…)*".

One part of this problem are the project durations, which get longer and longer. The first proposal for JWST was written in 1989[22], even before the Hubble Space Telescope was launched (1990). The JWST will be launched 29 years after that first proposal!

The METIS instrument is a much smaller project than JWST, but we finished the first conceptual study - back then still for a 100m “Overwhelmingly Large Telescope” (OWL) - in 2005. With an anticipated “first-light” in 2025, METIS also stretches over 20 years for design, construction, and testing. This is almost one “career lifetime”! It is therefore difficult to keep all individuals within the team, and preserve their expertise - even more so in the academic environment, in which young researchers only get 5-year contracts, and have to leave before they can enjoy the fruits of their hard work.

Specific challenges for METIS
High costs, technological risks, and organizational complexity are fundamental challenges that apply to almost all big, modern instruments. On top of them, most instruments have their own, specific challenges - and METIS is no exception. Here I would just like to list a few.

In order to provide the *high imaging contrast*, which is necessary to detect faint exoplanets near bright stars, METIS must have almost perfect optics without stray-light, and must provide excellent control of the telescope’s deformable mirror to eliminate atmospheric turbulence.

Due to the huge *thermal background* from sky and telescope at longer wavelengths, infrared astronomy at 10 micrometers is like attempting optical astronomy during day-time. Sophisticated calibration methods have to be developed to reduce the thermal background from the warm telescope and atmosphere.

METIS is unique! Its *combination* of very high spectral resolution (R~100,000), with very high angular resolution (provided by the integral field spectrograph), at thermal-infrared wavelengths is “a first” for night-time astronomy. This novel combination opens up new discovery space, but it also creates new challenges for the operation and calibration of METIS.

The Future of Astronomical Instrumentation…!?

What challenges and opportunities will the future bring for astronomical instrumentation? It seems clear that we cannot follow the “bigger, better, and more expensive” approach, and we need to find ways to break the cost curve. In the past, progress in astronomy benefited strongly from developments in other fields, which have bigger revenues.

Example: detectors
A good example is detectors. At *optical wavelengths*, the consumers of PC- and pocket-cameras, surveillance systems and smartphones, created a world market with a revenue of more than six billion dollars, annually. This enormous economic value ensures the continuous improvement of *CCDs and CMOS detectors*, leading to detectors with larger formats and better performance at lower prices. Astronomy benefits tremendously from these developments - if not directly in terms of catalog items, then at least indirectly by getting access to the technologies to make affordable customized devices.

At *infrared wavelengths*, the situation is somewhat different. Since the cold war, the development of suitable detector concepts, manufacturing techniques, and material selection was driven by the military with generous governmental funding. After classified information eventually became accessible, and export restrictions were partially lifted, infrared astronomy made an enormous progress based on these developments. However, about a decade ago, the gap between the requirements of military applications and astronomical observations became bigger and bigger. It is easy to see why:

A portable, cryogenically cooled, mid-infrared camera can detect a human body at about 3 kilometers distance. An uncooled detector can only reach about half that distance. While its performance is obviously reduced, its handling becomes much easier, and it is always operational. Astronomers, on the other hand, want to detect single photons from the most distant galaxies; operational aspects such as temperature, weight, and size, are only of secondary importance.

The costs of developing and procuring infrared detectors, however, exceed the budget of almost every astronomical instrument today. Cost and availability of focal plane detectors have become a serious challenge to infrared instruments. A new - potentially very large - market for infrared detectors is currently developing in the *automotive industry*, which we need to follow carefully, namely infrared cameras for driverless vehicles. At any rate, detectors are just one of many examples of linking our needs to promising technology developments in other fields.

Example: space

In space, the size and mass of the facility is limited by the available launch vehicles. The 6.5m JWST is already folded in many ways to make it fit within an Ariane-5 launcher. It seems impossible to follow the same approach for a space telescope of 30 meters, or even bigger. If we cannot launch one big piece, we need to launch many smaller pieces. These pieces then have to be either robotically assembled in space, or configured for formation flying of many smaller, phased telescopes.

Both approaches require tremendous efforts and financial investments in the development of the necessary technologies - too much to be carried by astronomy alone. However, apart from military applications and future communication networks in Space, many of these technologies will be needed in the context of a manned mission to Mars. If the big space agencies pursue this goal, we have to carefully watch their technology roadmaps. Astronomers may be happy to provide a "pathfinder experiment"!

The future: photonics

So what do astronomical instruments need for the future? I believe that the most important technical area is 'Photonics'. Here I refer to '*Photonics*' in the wider sense[23], including all active and passive components, which give control over the optical beam, as well as integrated photonics, which enables much more compact optical systems.

In December of last year, researchers from UC Berkeley, the MIT, and the University of Colorado built the first *fully integrated photonic chip*. The device, consisting of two processor cores with more than 70 million transistors and 850 photonic components (including I/O's), has a bandwidth density of 300 Gigabytes per second *per square millimeter*. That is about 10-50 times higher than in purely electrical microprocessor chips available today.[24] While these chips will be used for digital computations, the development of the techniques, which are necessary to produce accurate and cost-efficient devices, should be of great interest to modern optics as well.

Some examples of photonics devices - which are, or will become of interest to astronomical instrumentation - are planar waveguides, photonic lanterns, laser frequency combs, various types of coronagraphs, polarimeters, active and adaptive mirrors, novel types of diffraction gratings (such as immersed gratings, volume-phase holographic gratings, or Bragg fiber gratings), and so on (fig. 10).

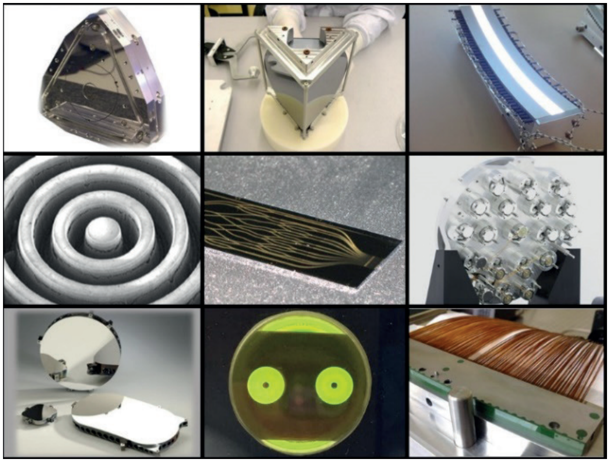

Figure 10 Examples of photonics devices used in astronomical instrumentation. From left to right, top to bottom: (1) cryogenic beam chopper for METIS [JPE], (2) immersed high resolution grating for METIS [SRON], (3) flatfielding unit for WEAVE [R.Stuik], (4) coronagraphic annular groove phase mask [U.Liege], (5) near-infrared beam combiner for GRAVITY [IPAG/CEA-Leti], (6) cryogenic active set-and-forget mirror [JPE], (7) nickel-plated metal precision mirrors [Fraunhofer] (8) vAPP coronagraphic mask for the LBT [F.Snik] (9) fibres for the Subaru prime focus spectrograph [LNA].

Let me just illustrate the need for novel solutions with another example: For seeing-limited spectrographs of a given spectral resolution, the size of the instrument is proportional to the diameter of the telescope aperture - and that can become a real challenge on extremely large telescopes. The proposed optical spectrometer (WFOS, operating at 0.3 - 1.0μm, 40 arcmin^2 field of view, seeing-limited) for the American Thirty Meter Telescope (TMT) is 8 meters in diameter and 10 meters in height. That instrument would not fit in this room!

Clearly, novel optical approaches are needed to cope with the needs of instruments for the next generation of telescopes. Ideas and concepts exist, but many photonics devices cannot cope with the vacuum conditions or cryogenic temperatures, launch vibrations, radiation hardness, or do only work over a small range in optical wavelengths.

Unfortunately, such technology developments - unless directly connected to a specific, big project - often have difficulty to secure funding. On the European scale, a dedicated OPTICON Horizon 2020 proposal has just passed the evaluation stage three weeks ago. However, neither the 'Nederlandse Organisatie voor Weten-schappelijk Onderzoek' (NWO), nor the NOVA program have a dedicated budget for project-independent technology developments. These developments are risky, their applications are often "one-of-a-kind" within astronomy, and there is no sufficient "business case" to get support via NWO's 'Technologiestichting STW'. On the other hand, the criteria for funding through NWO's 'Exacte Wetenschappen' give preference to projects which promise a *direct* scientific return. This is the right approach to maximize the immediate science return, but may lead to problems in the long term.

In this regard, not much seems to have changed since 1608, when Lipperhey was denied the patent for his telescope by the authorities. Although it may not have been apparent at the time, the telescope, as we know now, developed into a good business case *and* one of the biggest discovery tools of our times.

Students

Let me now come to the last part of my speech: the next generation of instrument builders, our students. Designing instruments for big telescopes requires an interesting combination of physics, astronomy, optical-, mechanical- and electrical engineering, material sciences, project management, and a bit of art. There is a lot to learn for students!
For the best training, we now offer a specialized masters (MSc) program on '*Astronomy & Instrumentation*' at the Sterrewacht Leiden, supplemented by several elective courses at the TU Delft. But there are also some challenges. Students are

scientists in training. They need and deserve our support, and the training aspect must have the highest priority, even when some tasks take significantly longer than anticipated. This is unfortunately incompatible with the boundary conditions of large instrumentation projects, which follow a tight schedule with pre-defined milestones - at least during the construction of an instrument. However, preparatory studies in the early phases, as well as testing and commissioning of the instrument at the later phases of a project, generally provide ample opportunities for PhD projects.

Instrumentation projects are sometimes considered by astronomers as "*too technical, with too little science*". Here, the students from the Technical University in Delft fill a gap. At Aerospace Engineering, the development of *technical* solutions is highly valued as an intellectual achievement per se.

After all, building astronomical instruments is not just important work and a good preparation for the job market, but also *a lot of fun*! We work at the forefront of science and technology. Designing and building "your own" instrument, pointing it to the sky, and discovering and exploring objects - from planets to distant galaxies - is still as exciting as it was in Galileo's time, 407 years ago.

Special Acknowledgements

Well, even American presidents hold inaugural speeches. In 1841, President William Henry Harrison gave the longest inaugural address in American history, which lasted for nearly two hours! His oratie took place outside, on a very cold day, and he was not wearing a winter coat. He developed a cold, which became pneumonia, and he died one month after his speech.[25] Obviously, inaugural lectures should not last for two hours, and I should come to an end now. But before I finish, I would like to thank several individuals and organizations. Most of my work on the projects discussed today would not have been possible without their strong support.

Over much of the 20th century, observational astronomy from the ground was dominated by scientists in the United States. As we know, observational astronomy is technology driven, and the Americans had the best telescopes. But with *ESO*'s Very Large Telescope (VLT) this has started to change in the 90ies, and the E-ELT will establish a European lead role in ground based astronomy. In fact, the idea for the European Southern Observatory was born in Leiden, here in this building, in 1954. ESO is an excellent example of how European countries can work together to everyone's benefit.

In 2009, we received a generous grant from the *Ministerie van Onderwijs, Cultuur en Wetenschappen* (OCW) to develop instrumentation for the E-ELT (in the context of the European Strategy Forum on Research Infrastructures, ESFRI). This grant, managed by *NWO*, has been significantly enlarged with funds from the *NOVA* instrumentation program. Together it will not only pay for the design and construction of METIS, but it did already put us in an excellent position when the instruments for the E-ELT were selected by ESO. Without this money, there would be no METIS!

Generally, it is impossible to fit our work into the nominal 38 hours per week. We do what needs to be done, because we enjoy it. However, that is only possible within the right working environment. Throughout my career I have been lucky to be surrounded by, and work with, scientifically inspiring and personally very friendly and helpful *colleagues*. Many thanks go to my colleagues and friends at Leiden University, at the TU Delft, and to all those who contributed to my appointment. Specifically, I would like to thank three individuals who played a key role in my career:

Prof. Reinhard Genzel - Max-Planck institute director, with an honorary doctorate from Leiden University. He was my PhD promotor, who made an astronomer out of me, *Prof. Jim Houck*, my supervisor and mentor at Cornell University, who taught me about the beauty of simple solutions, and introduced me to the world of NASA, and

Prof. Ewine van Dishoeck, who provided great support for my roles in MIRI and METIS, and introduced me to the wonders of Dutch research politics.

A project like METIS shapes a quarter of your lifetime, and it better be good! I would like to thank the members of the "*METIS family*" for their good and friendly team spirit, and the *NOVA directorate* for their pragmatic and helpful attitude in many instances.

Our *students* are an important pillar of modern research: they do a lot of the work, and they keep us young by asking the right questions that keep us thinking. You should always keep in mind - I am addressing this to our students - that most of the observing facilities we are building or planning now, are for your use in the future!

Last but not least, I want to thank my family for their continuous support. My *parents* - who unfortunately cannot be here today but will be watching the video later - have been supporting my interests in science for many years, and made it possible for me to study physics. My wife *Elke*, my son *Philipp*, and my daughter *Katharina* have moved with me around the globe to settle in the Netherlands. Now they hear about many exotic places mainly in my Skype calls from conferences. I would like to thank them wholeheartedly for their understanding and great support.

Dames en heren, ik dank u voor uw aanwezigheid en aandacht. Ik heb gezegd.

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