MUSE: The Cosmic Time Machine

English Version
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00.24 Roland Bacon
At the base of everything lie the eternal questions of origins. These are questions that priests, philosophers along with us scientists, have all examined. We research extrasolar planets to find the origins of life, and for the origins of the Universe… we try to observe the Universe in its infancy. And that's the main motivation for building bigger and better telescopes and ever more sophisticated instruments.

01.16 Voice-over
Even though light travels at 300 000 kilometres per second, the Universe is so vast that light from celestial objects takes a long time to reach us. The Sun's light takes eight minutes to traverse the 150 million kilometres between the Sun and the Earth, while light from the closest star, Proxima Centauri, takes four years. Our neighbouring galaxy Andromeda, is 2.5 million light-years away, meaning that when we look at the Andromeda Galaxy, we see it as it was more than 2 million years ago.

By attempting to observe even more distant galaxies, nearly 13 billion light-years away, we can go back in time to approach the birth of the Universe.

02.06 Roland Bacon
Astronomers are contemplative. The only thing we can observe is light. Actually, we would rather do experiments like in other sciences… weigh a galaxy for instance, or stop it from turning to see what happens, but of course, we can't do that. Our one and only source of information is light.

Of course, we can take pictures, look at the shape of objects, and see their colours, but because light transmits information about the atoms that emitted it, by using quanta of energy or quantum mechanics we can do much more than that. We can find the signature of those atoms, a sort of unique genetic code, and that's really powerful, as it means we can determine the chemical composition, the physics of the gas, even the movements of the stars, thanks to the Doppler effect. The instruments that enable us to obtain information by analysing light are called spectrographs, and they are absolutely essential to us.

03.23 Voice-over
Since its invention in the 19th century, the spectrograph has been a fundamental tool in astronomy. In the 1990s, a new type of instrument was invented in Europe: the 3D, or integral field spectrograph. For the first time, we could obtain spectra of a wide area of the sky, containing many astronomical objects. The first generation of instruments based on this new concept is now installed on large telescopes around the world.

With its many telescopes in Chile, the European Southern Observatory, or ESO, is the spearhead of European astronomy. Many examples of first generation 3D spectrographs are already in place at the focus of the four Very Large Telescopes, with 8.2-metre diameter mirrors, at the Paranal Observatory.

04.13 Tim de Zeeuw
As technology advances, after say ten years, you can build a much better camera or a much better spectrograph and put it on a telescope and make it more powerful, but it takes five to ten years to do. So early 2000s, planning was going on at ESO — we should have ideas for new, more powerful instruments, called second generation instruments.

04.43 Roland Bacon
ESO’s tender immediately gave us a chance to move up a gear, and to propose something that was based on everything we had learned during all those years, something much more ambitious, which would mean we’d be able to observe the very distant Universe like never before, and so that was the very beginning of the MUSE project.

05.13 Lutz Wisotzki
In the past, we did have instruments that in a way operate like MUSE — integral field spectrographs, they make images and spectra at the same time, they have been around for 20 years, and both in Lyon and also our institute in Potsdam have been very successful in using these types of observations. But what MUSE now really for the first time introduces is to combine this capability with the capability of the survey instrument, meaning really to look at a significant part of the sky, not just at one galaxy, but really at a significant part of the sky and have lots of stuff in there, and everything with this imaging plus spectroscopy capability. That’s a very new approach to do astronomy.

06.00 Voice-over
MUSE, the Multi-Unit Spectroscopic Explorer, is composed of not just one 3D spectrograph, but 24.

When the light of the galaxy captured by the telescope enters the instrument, the first optical element the light encounters is the de-rotator, which compensates for the Earth's rotation.

The stabilised image is then magnified by a pair of mirrors. Next, the beam enters the first field-splitter. The image of the galaxy is split into 24 sections, resulting in 24 separate optical beams. These beams are distributed by a group of mirrors and lenses to the 24 modules.

The light is again split by a second field-splitter, called a slicer — the masterpiece of MUSE. The slicer is composed of two series of 48 spherical mirrors, which split the beam into 48 slices. The light reflected by each small mirror enters the spectrograph, where it is dispersed according to its wavelength.

The detector registers the spectrum of a small part of the galaxy. This process is repeated for each of the 48 beams. The detector is then completely illuminated.

The same thing occurs simultaneously in each of the 24 spectrographs. The resulting 400-million-pixel image holds the spectral information of every part of the galaxy.

07.30 Roland Bacon
Obviously, no laboratory could take on a project as complex as MUSE alone, no one would have had the strength or capacity for that, so I brought together a group of laboratories in Europe which, together, had the expertise for such a project.

07.43 Voice-over
Five research laboratories joined the Astrophysical Research Centre of Lyon to develop MUSE, along with ESO. The process began in 2004 with the conceptualisation, design, and construction involving experts in optics, mechanics, electronics and software. The different phases took 9 years and involved a hundred researchers, technicians and engineers to overcome the many challenges, particularly in the development of the slicer, the key component of MUSE.

08.24 Roland Bacon
So you have to understand, that in the beginning, when we launched the project, as is often the case, we didn't actually know how to create this slicer. We'd made a small prototype, but that's all, and so as the project went on, we had to demonstrate that we could in fact do it. So we launched a whole load of tests, made a whole load of things in metal, with different technologies, in the optical field, with a variety of manufacturers, in Europe, and in the USA… and each time, it didn't function. Each time there was something that didn't work, and so at one point, we really thought that the project would have to stop there — no slicers, no MUSE. And then suddenly, a French manufacturer came up with a technology that meant we could finally create the slicer, and of course there wasn't just one, but 24 to be made! We were saved.

09.26 Voice-over
The assembly of MUSE began in Lyon in 2010. Thousands of components arrived from all over Europe. It took three years to assemble, calibrate, align and test the instrument.

In September 2013, after final tests, MUSE was disassembled, carefully packed, and shipped to Chile.

11.00 Joël Vernet
MUSE arrived in dozens and dozens of boxes. Several lorry loads arrived in Paranal, and our first concern was: had everything arrived in one piece? Because you see, they are unique pieces, and if one part had been broken, there wouldn't have been time to make another one quickly enough, so that was already very stressful. But everything was fine, and so once all the crates with all the pieces had been unpacked at Paranal, and we saw that everything was alright, it had to be assembled, tested and aligned; and for MUSE, which is one of the biggest instruments to install on the VLT — *the* biggest, in fact — that phase took a long time. But the really stressful part of this marathon was respecting the deadlines. The nights that had been allotted to us for the commissioning on the sky had been fixed a long time in advance, and we absolutely could not miss them.

11.58 Harald Nicklas
That was a new experience for us, because in earlier projects, we had disassembled instruments, put them into single pieces and reassembled them again, on the telescope on the platform, but for MUSE it turned out it's not feasible, because MUSE was too complicated to do all this assembly and especially these alignments inside of the telescope dome.

It was decided that we will lift the instrument as a total in the single lift into the dome, and there is only one way to enter the dome with a big-sized instrument, and that is the slit for observation.

12.43 Patrick Caillier
Imagine our state of mind beforehand… We knew that it was the crucial part of the operation and that the weather would play a key role in it being successful, since we were going to unpack the instrument and leave it outside before installing it in the telescope. But of course, just as we were about to do this, there was a high wind and risk of rain. So we slowed down a bit, and waited, and then we had a meeting and looked at the weather forecast, and made the decision to go ahead.

13.41 Patrick Caillier

One of the biggest risks was, of course, damage to the instrument. But there was also another parameter: the alignment. This had taken more than two months to do in the integration hall, and if it had become misaligned, we would have had no choice but to take it back down again.

14.06 Harald Nicklas
And then it was lifted up to the fifteen metres elevation above our heads, but to be honest at that moment, I thought I would be totally excited and fear that the instrument could fall down…

14.29 Jean-Louis Lizon
Another critical element was that the telescope has mirrors, and we would have had a big problem with the mirrors if the Sun shone on them, so we started lifting at around 5-5:30 am, and when we had finished, we only had about ten minutes before the Sun arrived on the main mirror, which was the moment when we absolutely had to close the shutter. So not only was it a very delicate technical operation, but one that had to be done in a very limited space of time.

15.34 Roland Bacon
It was the first time that a light, other than ambient light or from a calibration lamp, would reach the instrument… the light of a star or of a galaxy, for example. I wanted to symbolise that moment by choosing a special object that was hidden and secret, so I chose the Captain star. I chose it because it's 13 light years away, which means that the light left this star in 2001, at the same time that we made the bid for ESO's tender. For 13 years, the light had travelled across deep space at 300 000 kilometres per second, and arrived 13 years later in MUSE's channel number 6. It was really amazingly symbolic. I shared this with the team when they asked me, and I also told them that it was because the light from the star had gone straight ahead, whereas for us it had been a bit less straightforward.

16.47 Florence Laurent
It was the First Light and it was the first time that we'd taken a picture of the sky. Personally, I was under a lot of pressure, because we had installed the instrument and then spent a week aligning it correctly with the telescope, so when we took the first image, it was also validation that the instrument was exactly opposite the telescope.

17.15 Edgard Renault
It was the result of 10 years of work and it functioned, we could see our stars! They were clearly defined and we could put them in the right order. We had succeeded, so now we could hand this instrument over to the scientists, and we knew that they were going to have a lot of fun with it.

17.43 Voice-over
MUSE was set up, but before entering service, it had to pass a battery of tests and adjustments. This stage, known as "commissioning", required many nights of data acquisition so that the engineers and researchers could obtain MUSE's optimal performance.

18.02 Gérard Zins
On this screen, we can see the reconstructed image of the area of sky which is being observed. You can see the different objects that we have marked, and for each of the objects, you can see the spectra which gives us the characteristics and tells us what it is… if it's a galaxy, or a quasar or another object of scientific interest.

18.28 Roland Bacon
One of the big challenges of this project was being able to analyse efficiently the enormous amount of data that the instrument provides. You see, it's capable of producing 400 million bytes of data a minute. The volume of information can be considerable, but it's not only the volume, it's also the complexity. The image that arrives on the detector has been cut several times into small pieces by slicers and by field splitters, and so it's extremely complicated and you have to retrace algorithmically what happened on the detector and compare it to what was in the sky.

19.08 Lutz Wisotzki
What MUSE fundamentally creates is a lot of pixel data on some detectors, and if you look at that, you cannot make much head nor tail of it. So it's a very complicated process. We have an expert in the team who wrote what we call the data reduction software, and that basically puts all these pixel data together to make images, spectra, the combined data cube, and so on.

19.37 Voice-over no. 7
In February 2014, during the validation phase, MUSE observed the Orion Nebula to test its ability to analyse a large region of the sky. In less than two hours, MUSE took more than 60 pictures of the nebula — that is, 2 million spectra — 100 times more than available so far. After processing, the data was arranged in a cube composed of a series of 4000 images of different wavelengths.

The analysis of this data reveals a number of distinct chemical elements as well as the physical conditions of the gas in the nebula. Compared to simple images, the data-cube produced by MUSE is so rich in information that researchers will need many months to fully analyse its contents and publish the results.

20.30 Lutz Wisotzki
So the real thing is, what we got with the Orion Nebula was really what we hoped for, even much better; it was so spectacular. Because there's lots of gas, and that gas is in motion, and there are stars — hot stars — that excite this gas, that bring it to radiate in different parts of the electromagnetic spectrum. So you can easily visualise this with very colourful maps, and that's what we've done afterwards. And really, the interesting thing is that this was a showpiece for the capabilities of MUSE but it also contains an incredible richness of scientifically valuable data.

21.20 Voice-over

Every 6 months, the members of the MUSE consortium meet for “busy weeks”. At these times, they report on the status of the observing program and discuss the latest results. Throughout the week, professors, postdocs and students of many nationalities come together with one objective: to extract scientific information from the light analysed and dissected by MUSE. Numerous topics are explored.

21.50 Simon Lilly
In particular, my own interest is on how galaxies, like our own Milky Way Galaxy, how galaxies change with time, how they evolve, how they are formed in the early Universe, how they then develop over time, what controls how they develop, and so on. And we know that a key part of that is the interaction with gas in the Universe, how gas flows from the surrounding Universe onto the Galaxy and that’s then the fuel out of which stars like the Sun are eventually made. And we know that surrounding galaxies, there is gas, it’s the gas left over if you like from the Big Bang. We see that in absorption against background objects, but that always just gives us a sort of one-dimensional probe. It’s literally like a needle through a haystack. With MUSE, we can actually now see where this gas is, in a sort of three dimensional volume. And so what we want to do with MUSE is to understand this process of how gas flows from the surrounding Universe onto galaxies.

I would say holy grails of my own research field has been to detect this web of gas which we think must be there in the early Universe, out of which galaxies are forming. And MUSE really is the best instrument now to really try and see this.

23.43 Joop Schaye
We observe quasars, so-called quasars, and these are some of the brightest sources in the Universe, and what the quasar is, is a supermassive black hole. Gas is spiralling in because of the gravity of the supermassive black hole, and because the gravity is so strong, the gas moves really really fast as it spirals into the black hole. And because it’s moving so fast, there’s a lot of friction between gas layers that are moving at different speeds, and the gas gets really really hot, and as it gets hot, it emits huge amounts of radiation. Now, we were using those quasars as tools, not to study them themselves, but as flashlights. Because it’s so bright you can see them all the way across the Universe, and you see a flashlight, and if you then check what the gas, on its way from the quasar to you — the telescope, the observer — what that gas around a galaxy that’s in between you absorbs, then you can learn about the gas around that galaxy, that you can’t observe in any other way.

But, to learn how that relates to gas inflow and outflow of the galaxy, you need to know where the galaxy is, and that was the bottleneck. We couldn’t find the galaxies, only the very brightest ones. With MUSE we can go *much* fainter, one to two orders of magnitude fainter, so we can find many more galaxies. In fact, I realised we could find as many galaxies as we could see absorption lines, so we could really start to correlate the gas that we see in absorption with the galaxies detected by MUSE, and in that way, for the first time, learn about the gas inflows and outflows of galaxies that are far away. And these are important because far away in astronomy means further back in time. And with MUSE we can study this process at a time when galaxies were most active in the history of the Universe, and they were forming stars very vigorously, and because of that producing big explosions that blew a lot of gas back into intergalactic space.

25.48 Thierry Contini
They do ice core drilling in Antarctica to go back in climate history, and it's the same when we observe a sky zone very deeply. We go back in time. Now, I'm particularly interested in galaxies, those huge groups of millions of stars, and the millions of galaxies in the Universe. We want to know when they were formed, how they evolved, and so it's like very deep core drilling of the Universe which means we can see galaxies at different ages — when they were infants, adolescents, adults, and so on… and that's how we try and retrace their story. MUSE is really the perfect instrument for doing this. I think it's brilliant, because I used to want to be an archaeologist, and I've rediscovered the love I had for it in my youth. With MUSE I'm doing the archaeology of the Universe!

26.37 Voice-over
In 2014, over the equivalent of four nights, MUSE observed an area of the Hubble Deep Field. This field had previously been imaged in the year 2000 by the Hubble Space Telescope, using very long exposures to obtain colour images of hundreds of galaxies.

The MUSE data-cube of this field is rich in information. As we go through the cube, we advance in wavelength, from blue to infrared. A number of bright points can be seen, which vary in brightness with wavelength. These are mostly galaxies. From the brightness variations we can deduce the physical properties of the galaxies — for example, which types of stars are present there.

We now select a small region of the data-cube; two zones to be precise. The first is the centre of a bright galaxy. The second is empty. On the left, we see a spectrum appear. Near 520 nanometres we encounter a bright emission line. The galaxy shines intensely at this wavelength, showing the presence of hot oxygen in the galaxy. In the red we suddenly see another line in the second part of the cube. There, where nothing was visible before, a galaxy is now revealed thanks to the presence of ionised hydrogen. By measuring the precise wavelength of the emission line, it's possible to deduce the distance to the galaxy. It's a very distant one, 13 billion light-years away, and we have observed it just 1 billion years after the Big Bang.

28.26 Johan Richard
The quality of the Hubble telescope's image allows you to see a galaxy and its form with precision, but what you are essentially seeing is how much light is received at a given moment in that galaxy. With the spectra, you also have the distribution of the energy of this light, all its wavelengths and all its colours, and this provides a lot more information, like the speed at which these galaxies rotate, the movement of gas, chemical elements, and the number of stars of different ages — young and old — that the galaxies are composed of. All this information put together enables us to estimate what stage of development the galaxy has reached. Thanks to

MUSE, we could measure the distances of something like 180 galaxies in the same field of vision, and we have discovered about 30 new very distant galaxies in that same field that couldn’t be seen with Hubble.

29.39 Thierry Contini
We are aware that we have made a very beautiful instrument, which is now considered not only by us, but by the community of those who have really used it, to be the Rolls Royce of astronomy.

After being used for a year, a remarkable number of articles have been published using data from it, mostly by people who were not on the MUSE team. It’s really great to see that people outside of the project can use this instrument easily, get results — and extremely good results — very quickly.

30.30 Roland Bacon
In 2014, I lived through some truly extraordinary moments. It was like a dream come true; it was an idea, a vague plan that became, in reality, a fantastic machine to travel back in time. It was a technical, scientific and human adventure. Throughout it, I met some remarkable people, with remarkable intelligence devoted to the project, and together we made something extraordinary that none of us could have done alone. MUSE will be used by ESO and by us for maybe the next 10, 15 or 20 years, so I think that MUSE will mark its era as an important contributor to scientific discovery.