UNIVERSITÀ DEGLI STUDI DI TORINO

Laurea Honoris Causa

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LECTIO MAGISTRALIS
A Journey Through the Universe

Aula Magna Rettorato
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NOTE: UPPER CASE TEXT DESCRIBES SLIDE SHOWN

Thank you very much for the exquisite introduction. It is an extraordinary honor to be part of the story of this great university.

INTRODUCTORY SLIDE: MAPS OF TORINO

Maps are everywhere. I am sure you recognize these two maps of the center of Turin. It is hard to tell exactly when they were made, but we know they capture a story of the past. One is from 1674; the other is recent.

These maps show us the past because they were made in the past. In contrast, observations of the distant universe tell us about the past because the light that travels to us from very distant objects takes hundreds of millions or even billions of years to reach us. We thus see objects as they were when the light left them hundreds of millions or billions of years ago. Mapping the history of the universe is very different from mapping the history of Turin.

Nearly the entire history of our fourteen billion year old universe is there for us to observe. We can see how galaxies like our own Milky Way form and evolve by observing more and more distant, younger and younger objects. By looking out in space, we look back in time.

By looking to large distances in the universe, we can also map the way that galaxies like our own trace patterns in the universe. By observing the younger more distant universe, we can observe the evolution of these patterns directly. The age of mapping the universe began in earnest in the twentieth century and it continues vigorously today.

My career has been part of the story of mapping the universe. The maps I have made chart voyages you can make only in your imagination. This afternoon I invite you to join me on the journey we take when we map the universe. I will introduce you to some of the tools we use and I will show you some of the progress we have made. I will highlight some of the mysteries that remain in studying the grandest environment we know, our universe.

Most of you have a smart phone or some other computer with you. If you want to take a picture of something, you just take out your device and click, there it is.

MAP OF ARIZONA

Our journey through the universe begins with pictures of the sky. To take a picture of part of the distant universe, you have to go to the camera. Our camera is mounted on a telescope called the MMT, located on Mt. Hopkins, Arizona, just north of the Mexican border near Nogales.

ROAD UP MT. HOPKINS

Here you can see the long, steep, winding road to the summit of Mount Hopkins. It takes about 45 minutes to drive up the mountain to the telescope.

MMT BUILDING

When you get there, you see this strange looking building. Most people think that a telescope should be inside a rounded dome. Domes of telescopes used to be huge because the telescope had to move around inside the dome to track objects across the sky. By the time the MMT was built in 1978, computer control made it possible to have a telescope inside a compact building that moved with it as the telescope tracks the sky. The small building improves the image quality.

MMT IN THE WINTER

The motion of the building caused some problems. Here you can see why. The telescope is right near a ridge. Telescopes are often built this way because the flow of air up the ridge is laminar. In other words, the atmosphere is more stable and the image quality is higher.

There's a big sign on the MMT building that says "Do Not Park Here." In the early days of the MMT, someone didn't read and they parked their rented car next to the building. They went into the building and did whatever they had to do. When they came out, the car was gone. A crane pulled it up and the damage wasn't too bad. The car was driveable. You can imagine the expression on the face of the rental car clerk when the scientist brought back the car and said, "A building hit my car."

MMT SHOWING THE PRIMARY MIRROR AT NIGHT

The MMT is now a 6.5 meter reflecting telescope. Here is the primary mirror. Light arrives from the distant universe. It is reflected from the primary to the secondary mirror that hangs up in the air here. The secondary is a 2-1/2 meter mirror and it reflects the light through a hole in the primary. Behind the primary are the instruments like cameras and spectrographs that record the scientific images or the spectra.

This beautiful image shows you some of the romance of the night sky when you're at a dark place like Mt. Hopkins. Of course, when you go observing, you're not in the best shape to appreciate the romance of astronomy. For one thing, you're tired. For another, you have a lot to worry about. What are you going to observe? Is it going to be clear? Is the instrument working? Have you done everything you need to do? Every once in awhile you sit there and look up at the sky and think how amazing it is that photons, particles of light, travel through the universe for hundreds of millions, even billions of years. The universe is remarkably empty so they don't hit anything along their journey. When these ancient photons do end their journey in our detectors, they tell us the story of the universe.

MEGACAM WITH SCIENTISTS

Taking pictures of distant faint objects is not easy. This camera is called Megacam. The black rectangles are CCDs. There are 36 of them. The camera is a 340 megapixel camera. Just about every one of you has a CCD, a charge coupled device, with you in your smart phone or computer. Your CCDs differ from astronomical CCDs. First of all, the CCD in your smart phone is about the size of your fingernail. These astronomical CCDs are a few centimeters on a side.

The CCDs for astronomy are much more sensitive than the CCDs in your smart phone. They detect 90% of the light incident on them.

MMT CARRIAGE

Megacam weighs as much as a Toyota Camry. Every instrument for a telescope has its own specially designed carriage that protects it as it's moved from its storage bay to the telescope. Here you see technicians moving Megacam to the telescope.

MEGACAM HOIST

A special hoist mounts the camera on the telescope.

CAMERA ON THE TELESCOPE

Here you can see the camera mounted on the telescope.

To the side, you can also see part of the drive mechanism that enables the telescope to move around and point at objects on the sky.

NIGHT SKY AT THE MMT

If the telescope did not track the sky, images would be spread in arcs just as the stars are in this photograph. You have to point the telescope accurately and you have to make it compensate for the rotation of the earth. If you take a picture with a camera and you have a telephoto lens, you have to point it to about an arc minute or so. That's about a 30th of the diameter of the moon. This telescope is a 50-ton telephoto lens. You have to point the telescope to 1/2000 of the diameter of the moon and you have to keep it fixed in position to 1/20000 of the diameter of the moon. That's a demanding task.

The telescope tracks the sky in the same way that navigators have for centuries. We pick bright stars with known fixed positions on the sky. A computer makes sure that the telescope always moves so that the positions of those stars are fixed in the focal plane of the telescope. The programming for this tracking is a very sophisticated art.

The exposures to photograph distant galaxies are an hour or two. You can't take the exposure all at once because your images would be completely filled with the trails of cosmic rays. You can only expose for 10 minutes or so at a time. On a computer we later combine several 10-minute exposures to make a deep image.

CLUSTER OF GALAXIES

If you want a color image like this image of a distant cluster of galaxies, things are even more complicated. You have to expose through several different filters. You have a several hour long exposure in a green color, a several hour long exposure in a red color and maybe an even a longer exposure in an ultraviolet color. In your handheld camera there is a tiny filter in front of every pixel. People have very cleverly figured out how to put just the right relative numbers of the different tiny filters to mock up the response of the human eye. Then the software in your camera puts the picture together.

For an astronomical image, you make an image in each filter and you put them together later to make the ultimate color image. CCDs changed astronomy in an amazing way just as they've changed our everyday lives. In fact, CCDs were in wide use in astronomy long before digital cameras were commercially available. For example, Hubble Space Telescope was launched in 1990 with a CCD camera. Commercially available cameras weren't around much until 2000. A young engineer at Kodak, Steve Sasson, patented the digital camera in 1974, but Kodak was a film company. It was not in Kodak's interest to promote the development of digital cameras. That's why it took so long for CCDs to become commercially available.

Once you have done all of the data processing of an astronomical image, you have something really spectacular. The light that made this image of a distant cluster of galaxies traveled through the universe for 4 billion years or so without hitting anything until it was finally captured by our CCD detectors. We see these galaxies as they were 4 billion years ago. It's awe-inspiring.

A 2D image like this one is the first step in mapping the universe. From this image you can find the latitude and longitude, the positions on the sky of the fuzzy objects that are distant galaxies. These gold and red objects are the galaxies that live in the densest regions of the universe. These galaxies are piles of old stars; they are red and dead because they are no longer forming stars. These galaxies are very massive. They're a trillion or even sometimes 10 trillion times the mass of the sun. These galaxies are probably all at the same distance. That's a guess but it is a pretty good guess.

Here is another kind of galaxy; they are blue and they have disks. These galaxies are similar to our own Milky Way. In our own galaxy stars are still forming in the disk. Galaxies like these, spiral galaxies, are generally not in the densest region as you can see here. It's been known for a long time that the properties of galaxies are related to where they live in the universe.

By taking pictures like this, we have a two-dimensional map of the universe. Galaxies don't come with tags on them telling us how far away they are. Looking at this picture you might think that, for example, the galaxies that appear larger are closer to us than the apparently smaller ones. But maybe these apparently smaller galaxies are intrinsically smaller objects at the same distance as these bigger ones. You don't know until you measure how far away they are. Now let me tell you how we measure the distances to the galaxies to make a three-dimensional map of the universe.

GRAY SCALE CLUSTER IMAGE AND MAP OF THE SKY WITH BLACK POINTS FOR GALAXIES

CCD images like this one for large regions of the sky have only really been available in astronomy in the last 15 to 20 years. When I started out in astrophysics, most images were from plates. In fact, all astronomical images initially were from photographic plates. Photographic plates detected only a few percent at best of the light incident on them. The image on the upper left here is an image of a nearby cluster. It's about a tenth the distance to the cluster I just showed you, and it also contains red and dead galaxies. From images like this one, a man named Zwicky and his collaborators made a catalog of positions of galaxies on the northern sky. They laboriously measured the positions at much less accuracy than we can do today, and from their positions they made a 2D map.

This plot shows the positions of 20,000 galaxies on the northern sky. Each dot represents a galaxy comparable with the Milky Way. You might ask "Why are there no galaxies here?" The plane of our galaxy covers this region. It is full of dust that absorbs the light from distant galaxies. Where you do see the dots representing galaxies, there are regions which are very black and regions which are not so black. These black regions contain lots of galaxies. They are clusters of galaxies like this one and the one I showed you in the earlier image.

In the early 1980s, my colleague John Huchra and I studied these clusters of galaxies. We studied them to measure the motions of galaxies inside them to try to understand the dark matter that dominates their masses. 85% or more of the matter in the universe is dark. We know a lot about where it is, but we don't have a clue what it is. This problem was first discovered by Zwicky in 1933. He found that there was more matter in clusters than you can explain by the amount of light emitted by the galaxies in them. In every cluster we observed, we found the same result.

As we went along observing clusters of galaxies, I began to wonder whether there wasn't something more we could do with Zwicky's catalog. I wondered whether there were patterns in the universe much more extensive than these clusters of galaxies. Everybody thought they knew the answer to this question, but noone had ever looked. The idea of the time was that clusters of galaxies were more or less randomly distributed with no larger pattern. I began to think about what we could do with our rather small telescope.

The telescope we used to look for larger patterns is a much smaller telescope also on Mt. Hopkins, a 1.5-meter telescope. How could we try to answer this question? I thought about mapping the earth as an analogy. The earth has two very large kinds of structures, continents and oceans.

Let's suppose you arrive from an alien planet and you can map only one part in a hundred thousandth of the earth's surface. That's the fraction of the earth covered by the smallest state in the US, Rhode Island. How do you choose a region to map that will tell you whether the earth has big features, continents and oceans? If you choose a small patch, you fail. Most of the time the patch will just drop in the ocean and you learn nothing. If you take a great circle around the earth in almost any orientation, even if you make it very thin, it will pass through continents and oceans. Success! You learn that the earth has two kinds of features, both big. There are a few great circles that pass through only ocean, but they are pretty rare. If you choose one randomly, the great circles will cut through continents and ocean.

Our map of the universe will be 3 dimensional, not a 2 dimensional map like the surface of the earth. We start with a 2 dimensional map of the sky. We want to make it a 3 dimensional map of a piece of the universe chosen to answer our question. After finding the question, the choice of an effective, efficient strategy is the next most important step in a scientific project. Life is short and the universe is huge. We are limited to observing a small fraction and we want it to be both typical and informative.

We chose to measure the distances to galaxies in a strip across the sky in analogy with the great circle around the earth. I suggested this idea to John Huchra and he agreed that we should try it even though we thought we knew the answer. After all, noone had ever looked for big patterns because they thought they knew they weren't there. A young student, Valerie de Lapparent, was beginning her thesis research with us. We suggested the map of the strip to her as a thesis project.

THE 1.5 METER TELESCOPE

Here is the 1.5 meter telescope we used. It's on a ridge below the MMT and it still operates today. To measure the distances to the galaxies, we use a spectrograph. A spectrograph spreads the light out into its colors.

PRISM AND GRATING

You've all seen light spread into its colors by a prism like this one. You can also use a diffraction grating to do the same thing. A CD with its fine lines acts as a grating as you can see here. In our spectrographs we use a grating.

Every atom in the universe has its own particular fingerprint of bright lines that you can see when you spread the light out into its colors. In many galaxy spectra you can see the lines of hydrogen because it is the most abundant element in the universe.

HYDROGEN SPECTRUM MOVIE

Here is the spectrum of hydrogen as you would see it by looking through a grating at an arc lamp in the laboratory. The red line is the H alpha line at 6563 angstroms and here is H beta at 4861 Angstroms.

When you observe these hydrogen lines in a distant galaxy, something weird happens. The lines are shifted to redder and redder wavelengths the farther and farther away the galaxy is. In 1929, Hubble discovered this telltale signature that we live in an expanding universe. Galaxies appear to recede from us with velocities which are just proportional to the distance. The real reason for the shift to redder, longer wavelength is even more amazing. Einstein tells us that the space in the universe is dynamic. The space between the galaxies is stretching. As the photons travel through that stretching space, the wavelength of the light stretches to longer and longer , redder and redder wavelengths. Here you can see the color of the lines changing as they shift more and more toward the red. Redder and redder spectra correspond to more and more distant galaxies.

We record the spectra of galaxies with CCDs and then we analyze the images of the spectra to measure the redward shift of the lines, the redshift. In the early 1980s, we measured these redshifts one by one. It took twenty-five minutes or more to observe each of the 1000 galaxies in our strip.

MAP OF FIRST SLICE OF THE UNIVERSE

Here is the stunning map. What a gorgeous pattern. Fortunately nature wasn't subtle.

This map is a slice of the universe. We sit here on the earth and we look out into the universe to a depth of 700 million light years or so. In other words, the light from these galaxies at the outer edge of the map took 700 million years to reach us. We see them as they were 700 million years ago.

Each of the 1000 dots in the map represents a galaxy. The blue ones are galaxies like our own Milky Way, and the red ones are elliptical or red and dead objects. The torso of the stick person is elongated because galaxies move relative to one another in the cluster. They move because the cluster is massive.

This cluster shows how Zwicky discovered the dark matter in the universe more than 80 years ago. The galaxies in the cluster move relative to each other at almost 1,500 kilometers per second. 1,500 is a large fraction of the 6,600 km/s flow of the universe at the cluster distance. Thus there is an elongation in this map along the radial direction. By measuring the length of this finger and by measuring the size of the cluster on the sky, Zwicky first discovered the dark matter in the universe. He applied a simple theorem from physics that many of you know, the virial theorem, and he obtained a mass much larger than he could explain from the light emitted by the stars in the galaxies. The problem has been with us since unsolved. It's waiting for some of you, the scientists of the future, to figure out what in the world it is.

In the rest of the map you can see that there are vast empty regions. These regions are a couple of hundred million light years across. There are no galaxies in them. They are surrounded or nearly surrounded by very thin structures. The most extensive of these thin features is as large as it can be and still fit inside the map. There's no question that there are large patterns here. Today this pattern is called the Cosmic Web because it's composed of thin structures and large very empty regions we call voids. This map shows that in our 14 billion year old universe, galaxies like our own trace patterns on very large scales of hundreds of millions of light years. These are the largest patterns we know in nature.

The universe is a time machine. As I told you at the beginning of the talk, light travels essentially unimpeded for hundreds of millions or billions of years through the universe, lands in our detectors, and we study it to learn what the universe looks like and how it came to be. The entire history of the universe back to a very early age is there for us to observe.

MICROWAVE BACKGROUND MAP

Our map was made in 1986, and this map appeared six years later in 1992.

This map shows the young universe observed with a satellite called the Cosmic Background Explorer. It observed the microwave background, a background of radiation that fills the universe. We know that we live in an expanding universe. In an expanding universe, galaxies move farther and farther apart as the universe ages. The universe becomes less and less dense as it ages.

If we turn that statement around, we see that the universe must have been more dense when it was young. Not only that, universe was hot. We know it was hot because today we see the radiation filling the universe at a temperature of 2.7 degrees kelvin. The temperature is almost the same temperature in every direction you look.

In 1992 this map was the very first to show us that there are tiny irregularities in the temperature of the radiation. The red regions are a little bit cooler and the blue regions are a little bit hotter. How different are the temperatures? A part in a hundred thousand. The universe at this early age of about 400,000 years was boring. If the earth were this smooth, there would be no Alps. The initial lumps and bumps in the universe were very tiny. Fourteen billion years later, galaxies trace out huge patterns.

The microwave background map and our map of the first slice of the redshift survey opened the modern age of mapping the universe. They challenged us to understand the evolution from this very smooth early epoch to the current time. We have an early picture of the universe and a picture now. We would like to fill in all of the missing frames of the movie of the history of patterns in the universe. We want to know how patterns grow in this universe full of dark matter. We want to understand the way galaxies we see trace the dark matter.

MONTAGE OF FOUR MAPS

Since 1992, our ability to map the universe has increased phenomenally as has our ability to model it. The lower panel shows another map of the cosmic microwave background from the recent Planck satellite. The difference in the pixel size from the first map to this map is a factor of 100. The new map shows far more detail.

The lower right is an image from the Sloan redshift survey. This survey reaches to about three times the depth of our first slice. It contains not 1,000 redshifts but more than a million. Here too the patterns in the survey cross the entire region. They appear to be as big as they can be and still be included in the survey. This feature, for example, is a cut through a wall-like structure called the Great Wall that spans the northern sky. Here is another wall three times the size. These are the largest structures we know in the universe.

These maps show that we live in an extremely strange universe. 85% or more of the matter in the universe is dark. We have no idea what it is. 70% of the energy density in the universe is something called dark energy which accelerates the expansion of the universe. We don't really know what that is either, but we have measurements of these parameters along with a measurement of the expansion rate of the universe. We can use these to simulate a universe with the physics we know and ask whether it looks like the universe we observe.

Gravity likes to make lumps. In an expanding universe gravity will make lumps grow. It's somewhat less obvious that gravity also makes holes grow. Low density regions in the universe act like universes that are even lower density than the average. They want to expand faster than the universe around them and they drive structure into these thin walls.

SEQUENCE OF FOUR SLIDES SHOWING COMPUTER SIMULATION

This computer simulation follows 10 billion dark matter particles. It was made by Volker Springel in Germany. We know from observation that at least on very large scales of tens to hundreds of millions of light years, galaxies trace the distribution of this dark material quite well.

Here you can see what the structure of the universe looks like at an age of 200 million years. The bar shows a scale of about 400 million light years. There are regions that are dense and there are regions that are little holes. As the universe ages, the denser region gets denser and the holes get bigger and bigger until you arrive at more or less the current age of the universe. The pattern here looks very similar to what we observe in our slice of the universe.

In principle, we can observe this evolution. We now have very good three-dimensional maps of the nearby universe with its age of 14 billion years and we have a very good map of the universe when it had an age of 400,000 years. We don't have extensive maps at intermediate ages. Let me show you how we begin to make those maps so that we can ultimately make a movie of the history of the universe.

FIBER POSITIONER

Telescopes like the MMT can help us take some steps toward our goal. The instrument we use is another marvel of modern technology. This spectrograph gets mounted on the MMT. This part of the instrument is a fiber positioner. It places 300 optical fibers in the focal plane of the telescope. The fibers inside these metal sleeves are very much like the ones that carry some of your Internet service. The fiber is attached to a little prism that enables the fiber to look up at the sky. Each of these probes is placed at the accurately measured position of a distant galaxy we want to observe.

With this instrument, we can measure redshifts of 250 galaxies at once. The two robots place these fibers in five minutes and then we observe for about an hour. When we were mapping the first slice of the redshift survey with the 1.5-meter telescope we observed galaxies out to distances of about 700 million light years from us in a half hour. Instead of measuring 25 redshifts a night, we now measure 2,000 at more than 10 times the distance. The change in our ability to map the universe just during my scientific career is a remarkable measure of our curiosity and ingenuity.

Our mapping project is an international collaboration called HectoMAP. It includes Antonaldo Diaferio and his group here.

Our goal is to map the universe when it has an age of 7-10 billion years. In other words we plan to map the middle-aged and older universe.

TWO TELESCOPES

Two big telescopes are involved: the MMT maps the distribution of the galaxies we see and the Japanese 8-meter telescope Subaru on Mauna Kea maps the dark matter.

In a deep slice of the universe we have now used the MMT to measure 100,000 redshifts. With these data we will use classical physics to map where the matter is. With Subaru we will image these 53 square degrees of the sky. With the Subaru images we will use Einstein's theory of relativity and a phenomenon called gravitational lensing to map where the matter is. About 40% of the imaging is complete and we will soon be able to compare these two complementary maps.

The Subaru data are not yet analyzed. I'll show you the map we have made with the MMT.

YELLOW TEST PROBE ON BLACK

Here is the first test probe we made to see how we could use the MMT to map the middle-aged universe. The blue points show you the depth of our first slice of the universe. At the limit of this slice we look back 700 million years. The yellow points show the MMT probe looking back nearly half the age of the universe to a time when it was 7 billion years old. The photons that we recorded traveled for more than 7 billion years. They didn't hit anything until they struck our detectors and enabled us to make this map. We see the most distant objects as they were more than 7 billion years ago.

Even in this small probe, the kind of structure that you saw in the first slice is obvious. There are very empty regions and very thin structures. But you might ask "What's here?" outside the probe? I'll show you.

SLICE MOVIE

This slice contains 100,000 galaxies. We sit here on the earth. At the outer limit of the map we see galaxies as they were 6 billion years ago. Each yellow point represents a galaxy more or less comparable with the Milky Way. As the image rotates, you can see patterns in this image that are similar to what we saw in our first tiny slice of the universe. Zooming back 4 billion years we see that dense regions marked by galaxies cross the entire slice, There are also many very empty regions.

COMPARISON OF DATA WITH SIMULATIONS SHOWING LOGOS

To interpret the data, we need very large simulations. The largest simulations in the world are run at the Korean Institute for Advanced Study. Here is a comparison of our data with the simulations.

We ask whether the model we use to make the simulations explains the data. Do they agree or not? A piece of the observed map is on the left and the simulated map is on the right. We also show the logos of the participating institutions. The University of Turin logo represents the theoretical support Antonaldo Diaferio and his group provide.

The data and the simulation are very similar. Both your eye and careful analysis tell us they are similar. However, there is actually a subtle difference. The patterns are slightly sharper in the data than they are in the simulation. The empty regions are slightly larger and emptier in the data than they are in the simulation.

Now we have a difficult question. The simulations follow the mysterious dark matter. We observe light emitting stuff, galaxies. How do the light emitting galaxies trace the dark matter? On scales of hundreds of millions of light years, the size of the empty regions, we think that the galaxies are good tracers of the distribution of dark matter. However, there are many uncertainties in making the connection between the two. The answer should come from the deep Subaru imaging. We will then compare two different kinds of observations to explore the way the galaxies trace the dark matter with two different observations.

SUBARU CAMERA MOVIE

The Subaru camera we use is the largest camera in the world. It is an 870 megapixel camera. The camera is 3 meters high. Here you can see the robot mounting the camera at the prime focus of the telescope. It takes a day to mount the camera.

SUBARU IMAGES

Here is a Subaru image of one of the most massive clusters in the HectoMAP region. If you look carefully at this image you can see blue arcs. The massive cluster acts as a gravitational lens. It magnifies and distorts distant galaxies behind the cluster; we see these distant lensed galaxies as blue arcs. From these arcs we can measure the total mass of the cluster even when most of the cluster material does not emit any light. By studying lensing objects like this cluster we will know better where the dark matter is but we still won't know what it is.

One of the wonderful things about science is that others will solve the problems that you fail to solve. As a working scientist, it is rewarding to train people who will come after you. They in turn will train people who look at these problems with fresh eyes. Perhaps one of you will discover what the dark matter is, what the dark energy is, or even what might be wrong with the theory of gravity we have.

HECTOMAP MOVIE A SECOND TIME

Let me share the HectoMAP movie with you once again, partly because I like to see it. I never tire of looking at this. That's fortunate because it has taken 7 years of observations years to make this map.

During my career, astronomy has changed from a field where there were essentially no data to a field that is data rich. We have many spectacular images like this Subaru image. These images are a measure of the reach of our imagination. Our maps of the universe make us grand because they show how we wonder.

When the ancient photons that have traveled through the universe for billions of years end their journey in our detectors, we use them to understand how objects in the universe form and how the universe evolved. We come to understand our place in the universe and to see ourselves in a different light.

It's amazing that we are compelled to ask questions about the universe. It's even more amazing that we can answer some of them.