WORDS OF MARGARET J. GELLER

Thank you so much for this very special honor. Several years ago my husband and I visited Tarragona and we had the delightful, fascinating experience of exploring the Catalan universe.

This afternoon I would like to take the liberty of combining my experience of Catalonia with a brief tour of the cosmos I have studied in my professional life. Of course, my view of the Catalan universe is the view of a foreigner. And my view of the cosmos…well… in that we are all foreigners taking journeys of the imagination. Often people ask me, ``Don't you feel small studying something so vast as the universe?'' I reply, ``No matter how large a portion of the universe I map, it always fits on an A4 sheet of paper.'' Scientists are masters of abstraction. Whatever we study … the quark, the cell, the earth, the universe … we bring the subject up or down to our own size.

Scientists are not the only ones who play with the universe. Artists do it too. One of the most famous Catalan artists, Joan Miró, was fascinated by the sky. He wrote: "The spectacle of the sky overwhelms me. I am overwhelmed when I see, in an immense sky, the crescent of the moon, or the sun. There, in my pictures, tiny forms in huge empty spaces, empty horizons, empty planes-everything which is bare has always greatly impressed me." During World War II Miró painted a series of 23 constellations. He is a master of space and fills a complex layered space with creatures, planets, moons, and stars. Miró's constellations are visible only in his paintings; he put stars wherever he wanted them to be. Scientists … astronomers … cannot choose where they put stars … or galaxies. But they can discover where they are.

A dark region of the sky (dark to the naked eye … dark with a small telescope), a very small patch of the sky, about 1/1000 the area of the moon, is a perfect place to explore the distant reaches of the universe with Hubble Space Telescope (HST). In this region (known as the Hubble Deep Field) the HST found some 500 distant galaxies. Most are much less massive than our own Milky Way. They are young galaxies in the process of formation. The image reaches deeper into the universe than any other image we have …it takes us within a billion years of the initial big bang. The faintest smudges … galaxies … are more than 12 billion light years from us … we see them as they were twelve billion years ago. The faintest objects are an amazing ten billion times fainter than the faintest object you can see with your naked eye. The image was a measure of the reach of the human mind and imagination. It shows the links between our technology, our curiosity and our drive to understand our place in the universe. Our Galaxy, the Milky Way is hardly unique ... the universe contains billions of galaxies just like it ... and observers in them see the same expanding universe around them. How insignificant our position has become... how undistinguished. And yet we continue to peer out at the universe and ask questions about its nature and evolution ... and even more astounding we can answer many of them.

Only one galaxy is visible with the naked eye from the northern hemisphere of the earth … Andromeda, the massive galaxy nearest to our Milky Way. Like Andromeda, the Milky Way is a large spiral galaxy. The disk is blue because it contains young, hot stars. The sun is located in the suburbs of the Galaxy 25,000 light years from the central massive black hole. If the sun were in Andromeda it would be roughly in the outermost spiral arm …in the suburbs of the galaxy. Galaxies like the Milky Way and Andromeda have masses of 1 or 2 million million times the mass of the sun. They each contain billions of sun-like stars. These enormous systems of stars, gas and dust are held together by gravity, the same force that governs the motion of the planets in the solar system.

We know the masses of galaxies because we can measure the motions of the stars and gas in them. In 1970 Vera Rubin measured the rotation rate of Andromeda. To everyone’s surprise the measurements showed that Andromeda …like the Milky Way and other galaxies … has a dark massive halo. Today, from studies like Vera Rubin’s and from examining the motions of galaxies relative to one another, we know that 85% of the matter in the universe is dark. We know something about where it is … in the haloes of galaxies, for example, but we still don’t know what it is. Vera Rubin has played a special role in my life as a friend and as a mentor. I admire for her warmth and generosity as well as for her scientific prowess. I first met Vera in the 1980s at a meeting in New York City. We wandered around the City together discussing everything from clothes to dark matter in the universe. Since then we have chatted for hours. We have shared joys, the excitement of discovery, and in hard times we have supported each other. Vera has been a special inspiration to me, as she is to many other astrophysicists … female and male.

In the 1980’s I was charting my own course of discovery in the universe. At that time there were no Hubble Space Telescope images. All images are two-dimensional pictures of a vast space. I wanted to see a three-dimensional map. What sort of patterns, I wondered, did these galaxies outline in space? The key to making three dimensional maps is in the colors of galaxies. Looking carefully you can see that the galaxies are different colors. Some are much redder than others. The redder ones are farther away than the blue ones. Why? Because the universe is expanding and with the expansion the wavelength of light stretches to longer, redder wavelength. In 1929 Edwin Hubble discovered this expansion of the universe. Galaxies recede from one another with velocities proportional to their distances. This surprising discovery was actually a prediction of Einstein’s theory of general relativity.

During the early part of the twentieth century, one man, Albert Einstein, revolutionized our concept of light and of gravity with his development of the theories of special and general relativity. These two pieces of fundamental physics underlie our ability to explore and understand the universe. The theory of special relativity connects space and time in a natural way. We measure distances in space by recording the time it takes for light to traverse them. The sun is 8 light minutes away. The nearest star, Proxima Centauri is 4.22 light years away, and the center of our galaxy is 25,000 light years from us, and the most distant galaxies are 12 billion light years from us. Nearly all of the information we have about the universe is carried to us by ancient light. We see the sun as it was 8 minutes ago. We see distant galaxies in their youth …as they were 12 billion years ago, not long after they formed. We think we know space and time from our everyday experience. We look at our watches to tell time. We walk around in space and when necessary, we use a GPS to plan or guide our travels. The nature of space is something we just don't think about much. If we leave our bedroom in the morning for breakfast in the kitchen, we expect the space in our bedroom to be exactly the same when we return to it any time later in the day ... or the month ... or the year for that matter. Einstein's theory of general relativity tells us that the space of the universe differs from our local static space. He tells us that massive objects determine the geometry of space --- that gravity is geometry. In the seventeenth century, Isaac Newton, said that gravity is an attractive force between two massive objects. Einstein says that matter determines the geometry of space and the geometry of space tells matter how to move. As matter moves in space, the ripples in space change in response. In Einstein's theory space is dynamic. In Einstein's picture a comet falls into the sun because there is a valley in space around the sun and the comet falls into the valley. Newton says that a comet falls into the sun because of the gravitational force exerted by the sun on the comet.

On the grand scale of the universe, over billions of light years, Einstein's theory of relativity makes the bizarre prediction, confirmed by Hubble’s observations, that the universe is dynamic ... that it expands…the space between the galaxies stretches. When Einstein found this prediction of his theory, he added a term called the cosmological constant to his equations to stop the expansion. Even Einstein, scientific heretic that he was, could not imagine an evolving universe. Observations proved him wrong. In Einstein's theory, galaxies flow away from one another with the expansion of space. They move apart because the space between them stretches. In this stretching space, the wavelength of light also stretches producing the observed redshifts. This effect makes more distant galaxies redder in deep images. By measuring these shifts to the red we can turn a flat image into a three dimensional map.

Galaxies often have friends. Because they are massive, galaxies cluster together in systems ranging from pairs to clusters containing hundreds to thousands of galaxies as massive as the Milky Way. Until the 1980's galaxies and clusters of galaxies were the objects which marked everyone's tapestry of the universe. Most astronomers thought that galaxies were sprinkled pretty uniformly throughout the universe ... and the much rarer clusters were sprinkled uniformly too. This idea was based on a desire for simplicity. There were no complete maps which covered any substantial area of the universe. To make a map of the universe we measure the positions of galaxies on the sky. Then we spread the galaxy light out into its colors to observe the spectrum. From the spectrum we derive a redshift. With the redshifts we can construct a three-dimensional map of the universe.

During the 1970s there was a revolution in the technology we use to detect light and in the way we handle the data. Digital detectors came into use in astronomy. The data from these detectors could be analyzed rapidly with computers. By the 1980s, a 1.5-meter telescope … small even for those days …returned 25 redshifts a night for galaxies hundreds of millions of light years away. My colleague John Huchra and I, along with our student, Valerie de Lapparent, measured redshifts for a thousand galaxies in a strip across the northern sky. I can still remember the day in late 1985 when I first saw the amazing pattern in this first slice of the universe. The striking pattern extends for hundreds of millions of light years. Thousands of galaxies outline vast dark regions hundreds of millions of light years across. It is though the galaxies outlined giant empty bubbles in space. What a thrill it was to see this pattern ... the largest pattern we know in nature.

Over the next seven years, John Huchra and I extended the map. The scientific results were exciting and the public interest in our work spurred me to make it more accessible. In 1993, with the help of Larry Smarr, the director of the National Center for Supercomputing Applications at the University of Illinois, we made a state-of the art journey through the nearby universe. I wanted to make people feel that they were traveling in a space ship through the universe to a space well beyond Andromeda. In making the graphic voyage through the universe, we all learned interesting things about human perception. For example, computer graphics experts like to move through the data forward and backward. When we showed these moves to test audiences they hated it. A cinematographer working with us emphasized that people never fly backwards and that they identify turning and banking with flying. These graphics were the first animated voyage through the universe based on real data. They are part of a 40-minute film called *So Many Galaxies … So Little Time*. As a representation of measurement of the architecture of the universe, they remain unsurpassed.

Today complex instruments on 2-meter to 6-meter telescopes have extended the maps in space and time. For my current research with Michael Kurtz and other members of our group we use the MMT, a 6.5-meter telescope located on Mt. Hopkins near Tucson, Arizona. The instrument we use, called the Hectospec, takes advantage of two technologies you use every day ... CCDs and fiber optics. You have CCDs in your digital cameras and fiber optics carry your e-mail and bring you the world-wide web. CCDs for astronomy are more sensitive than the ones in your digital camera but the principle is the same. Taken together these advances enable the measurement of hundreds of redshifts at one time ... thousands of redshifts per night for galaxies more than 200 times fainter than the ones in our first slice. In the Hectospec two fast robots position 300 optical fibers in the focal plane of the telescope at the carefully measured positions of distant galaxies. In a small region of the sky, 8 times the area covered by the moon, we have mapped out patterns more than 5 billion light years away (that's more than ten times the distance we reached with the first slice) …these maps begin to show us what the universe looked like when it was middle-aged. The patterns are similar. Some day … possibly in the next ten years or so.. we will have a more extended map.

This journey we take through space and time would have fascinated another Catalan artist, Salvador Dali. He was captivated by science and certainly by time. His melting clocks have become iconic images. He did his famous painting, *The Persistence of Memory,*only two years after the discovery of the expansion of the universe. The melting clocks reject the idea of a rigid time. I would not be at all surprised if Dali was influenced by the then recently discovered dynamic stretching space-time of the cosmos. Dali also made an arresting eye of time. It cries for the passage of time, for memories of the past and for an unknown future. In looking at the universe, I think it cries in amazement at what we know and at what we have yet to discover and to understand. Today the eye of the astrophysicist and with her the eyes of all of us can see almost the entire history of the universe. In the early universe there were no stars. It was an essentially featureless sea of matter and radiation. The early universe was so hot that atoms could not form. Electrons, protons, and the nuclei of light elements are charged particles ...the electrons have negative charge and the nuclei positive charge. Charged particles interact strongly with light. In the early universe, photons, particles of light did not travel very far before they were scattered by a charged particle. Because the matter and the radiation were tightly tied together, the very early universe is opaque ... we cannot see though it. The universe becomes transparent as it evolves. It continues its inexorable expansion ... and it cools ... it expands and it cools. When the universe reaches an age of 400,000 years, it is about one thousandth of its current size and cool enough that hydrogen atoms can form. The matter in the universe becomes neutral. Photons are no longer strongly tied to the matter … and the universe becomes transparent Because we can see clearly through the universe from the present (an age of thirteen billion years) back to the young age of 400,000 years, we can reconstruct its history.

We have a picture of the universe when it was 400,000 years old. The cosmic background radiation which fills the universe carries this picture of the 400,000-year-old universe with it. This radiation last interacted with matter ... it was last scattered by the matter ... when the universe was 400,000 years old. If I take a picture of you, I record light ... radiation ... reflected or scattered off your face. In the same way the cosmic background radiation carries this picture of the distribution of matter in the 400,000-year-old universe. When you turn on your television you actually observe this radiation as static ... about 1% of television static is the whisper of the big bang. The picture of the relict cosmic background radiation is from the WMAP satellite. The recently launched European Planck satellite will make an even better map! The map shows a very boring early universe. The lumps and bumps were amazingly small ... about one part in a hundred thousand. If the earth were as smooth ... so uniform ... as the early universe ... it too would be quite boring. There would be no Pyrenees…certainly no Alps. The highest peak would be about 150 meters high … about the highest point in my home state of Massachusetts. Nonetheless, from these small lumps and bumps in the early universe, gravity makes all of the objects we see in the universe today ... galaxies, clusters of galaxies, stars, and planets. The hot big bang model does not tell us how objects form in the universe. The model provides the arena where galaxies and all of the objects in the universe must form and evolve. The basic idea of structure formation in the universe is that gravity likes to make lumps. Gravity amplifies the small lumps and bumps revealed by the cosmic radiation background to make the beautiful objects we observe. It also determines the way they are distributed in space. Gravity can make well-defined objects from small irregularities because it works on the problem for billions of years. Gravity, the weakest and most poorly understood force in nature, fascinates physicist and fascinated the man who defines the look of Barcelona…Antoni Gaudi.

When we visited Barcelona, Scott and I were captivated by the models of Gaudi’s gravity experiments. Many of you have probably seen these odd hanging ropes and weights in the Pedrera. They are models of Gaudi’s gravity experiments. Gaudi used these hanging structures of ropes and weights as an analog computer to design his buildings. Long before computer aided design Gaudi was already doing it! The main rope defines an arch and the weights simulate the load from other parts of the building. It was Gaudi’s genius to understand that these upside down models are perfect simulations of arches in the normal orientation in a building. These catenary arches are characteristic of Gaudi’s buildings and you can see them in the interior o the Padrera. Gaudi used nature to design with nature. His buildings are an exquisite example of the connection between geometry and natural forms … and between geometry and gravity. It is interesting that his appreciation of this connection came at about the same time that Einstein was thinking about the same puzzle on a very different scale. On the grand scale of the universe, gravity determines the patterns we observe in the universe and that I was so fortunate to see for the first time in our slice of the universe.

Progress in mapping the universe has been rapid. In 1970, when I began as a graduate student in the Princeton physics department, only a few thousand galaxies had measured redshifts. Today there are more than a million. If technology continues to advance as it has since the 1970s, we will have a complete map of the visible universe by the year 2100. The map will be a map of space and time ... We will be able to take a thirteen billion-light year journey sitting comfortably in our chairs.

I may have made it sound as though we have seen ... and know ... almost everything about the universe. But ... I have hidden some very important riddles. The first, and perhaps, most profound problem in our attempts to understand the history of the universe is that we don't know the nature of most of the matter in it. Eighty-five percent of the matter in the universe is dark. We know something about where it is from the motions it causes, but we don't know what it is after seventy years of trying to figure it out. The search for the dark matter is one of several links between the physics of the very large ... cosmology ... and the physics of the very small ... particle physics. Perhaps the dark matter particles will be discovered with the Large Hadron Collider , a particle accelerator with a circumference of 27 kilometers at CERN near Geneva. But the matter is not the whole story. Observations indicate that the expansion rate of the universe is accelerating. 70% of the energy density in the universe is also something we cannot yet explain ... we call it called ``dark energy." In Einstein's theory the evolution of the universe is determined by the amount of energy it contains in each cubic light year. Some of the energy is in the form of matter ... Einstein's theory of special relativity specifies the connection between matter and energy ... the famous $E = mc^2$. The low matter density and the perplexing dark energy tell us that the universe will expand forever and that is infinite in extent.

There are a number of mind-bending things about that ... ours is the only history of this

universe. It began fourteen billion years ago and it will continue to expand forever. Stars will age ...and eventually they will run out of fuel. The end will be cold and dark.
We would have to wait an infinite time to see our infinite universe ... and by then there will be no light to show us anything. At the present time we only see an infinitesimally small fraction of the universe. We assume that what we don't see is like what we do see. Clearly profound puzzles remain for those of us who seek to understand the history of the universe. We don't know what most of the matter is ...and we haven't known for 70 years. To make matters worse, it seems that most of the energy density of the universe is also something mysterious … the dark energy. Of course, most working scientists, myself included, confidently assume that we will solve these problems... that one day we will be able to ask even deeper questions about the universe and about its origin. People often ask me why we should answer these questions. Some would say that in answering these impractical questions we develop techniques which have important practical consequences. The development of CCDs for astronomy contributes to their availability in your digital cameras. Astronomy has taken a lead in the use and processing of digital images and in managing very large datasets. The techniques astronomers use to search and analyze large sets of data are being used in the human genome project to identify some of the anomalous patterns responsible for genetic disease. The argument of practical spin-off is valid, but I must confess ... just in case you haven't already guessed ...that I am a romantic.

I think that asking questions ... curiosity ... the human sense of wonder makes us special. Our sense of wonder compels us to discover the universe and to understand its history. Our sense of wonder is the most precious characteristic we have and one we must nourish in our young people by providing them unstintingly with opportunities for education and by nourishing their creativity regardless of their economic background, ethnicity, or gender. We must also fulfill the promise of that education by providing the opportunity for discovery on an equal footing to all who have the talent to ask and answer fundamental questions about the vast universe we inhabit.The human dream is to make a lot, to understand a lot from a little. Astronomy does just that on the grandest possible scale. It is a measure of the reach of the human mind. We boldly assume that the physical laws we discover in our laboratories on earth apply all over the universe ...everywhere and every when....and it works!

When I finish speaking, you will walk out into the sunshine. Every second, one hundred billion billion optical photons will strike the top of your head. Most of these are from the sun ... a mere billion of these ... one billion photons every second come from other galaxies in the cosmos. These galaxies ... island universes like our own Milky Way ... are hundreds of millions...billions ... even ten billion ... light years away from us. Some of the photons hitting your head are millions ... billions of years old. They have traveled through the universe for all those years without hitting anything until they hit your head! What a waste! When these ancient photons end their journey in a telescope ... especially a big one like the planned 42 meter European Extremely Large Telescope ... we can read the messages they carry about the nature of the universe. They tell us how the universe looks today ... and how it looked yesterday and billions of years ago. With the right instruments, the entire history of the universe is there for us to observe and to understand.

We live in the first age when it is possible to map the universe. It is remarkable that we human beings ask questions about the universe ... it is even more remarkable that we can answer them. Thank you so much for including me in your University family.