Teresa Jiménez*

Julieta Fierro Unravels the Cosmic Web

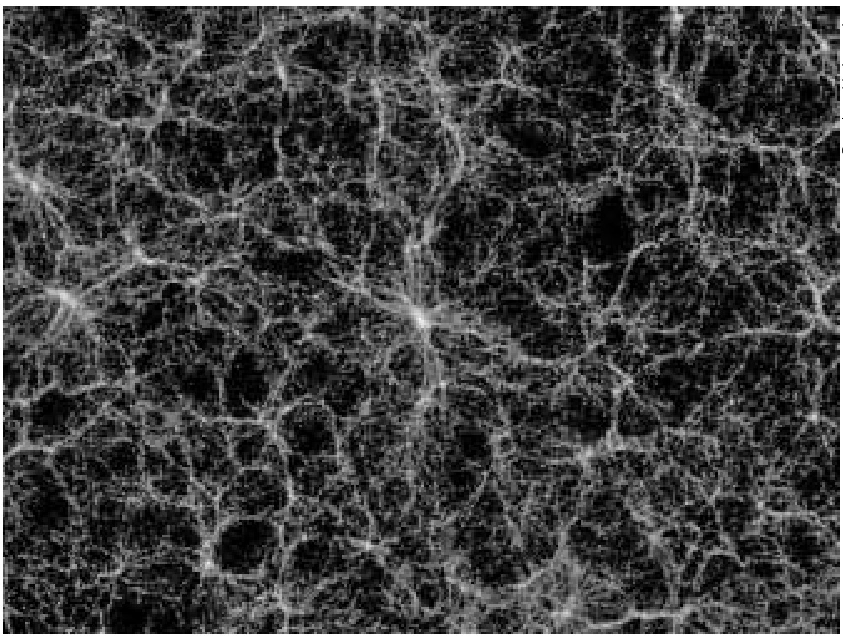
Astrophysicist Julieta Fierro is a full-time researcher at the UNAM Institute of Astronomy; she has also been the head of outreach and a professor at the UNAM School of Sciences. She has dedicated her career to disseminating science, making big contributions, and has held posts such as the presidency of the International Astronomical Union Education Commission, of the Mexican Academy of Professors of the Natural Sciences, and of the Mexican Association of Science and Technology Museums. She is a full member of the Mexican Academy of Language.

In this conversation, Professor Fierro explains the universe on the grand scale: how it forms a web, how matter is woven together, why the stars shine, why they stop shining, and how we know that something invisible exists, among other wonders of the universe.[1]

Voices of Mexico (VM): How do you define the University's web?

Julieta Fierro (**JF**): If we could look at the universe as a whole, what we would see is a distribution known as the "cosmic web." The bright objects we know, the galaxies, are arranged on enormous filaments, long conglomerates of galactic clusters. The spaces between the filaments are mostly empty: that's where the name cosmic web comes from. To know how this kind of web was formed, we have to go back to the origin of the universe. But, how do we know it had an origin? It turns out that the universe is expanding; it is dilating faster and faster. By measuring its velocity, we can calculate when it began expanding: 13.8 billion years ago. In fact, no star is more than 13 billion years old.

* Editor-in-chief of *Voices of Mexico*; tejian@unam.mx.



The cosmic web. Each bright point is a cluster of galaxies.

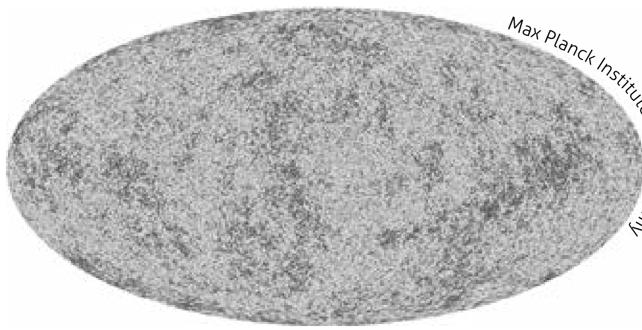
VM: What is the thread that ties the web together?

JF: Energy and matter. Due to vacuum research during the last century, it was discovered that energy is fluctuating everywhere. Let's use as an example a box where it would be possible to remove absolutely all matter —this is impossible because the walls of a box evaporate. But let's just suppose it were possible—, even so, there would still be energy fluctuating inside the box. These fluctuations of the vacuum, called a false vacuum, can generate one or several universes. Invisible fields exist in a vacuum, such as the gravitational field, the magnetic field, the quantum field, the field that generates the Higgs particle, all of which fluctuate and permeate the universe, even where there is no matter. (By the way, the Higgs particle is responsible for giving particles mass.) Thirteen billion, eight hundred million years ago, energy was liberated from vacuum and cosmic expansion began. Two kinds of matter were created: so-called dark matter and common, everyday matter. We should remember Einstein's equation $E=mc^2$, which means that if energy exists, matter can be generated.

Dark matter does not emit light, or reflect it, or disperse it, or absorb it: that is, this dark matter is invisible. How do we know it exists? Because it attracts visible objects. If we consider the Earth, it attracts the Moon because of its gravity, or the Sun attracts the planets and that's why the Solar System doesn't disintegrate. Dark matter attracts visible objects. If we add up all the observable matter in any galaxy (stars and gas and dust clouds), the mass of the visible objects is not enough to keep a galaxy from evaporating, for its stars not to leave its gravitational pull. Thus, we can infer that dark matter exists, matter that exerts gravity and is invisible. This means that when the cosmos began to expand, in the first instants of the early universe, the energy freed up from the vacuum produced dark matter and ordinary matter, the kind we're made up of: protons, electrons, neutrons.

The early universe produced the energy responsible for its own expansion, which constitutes 70 percent of what exists. Dark matter, which produces gravity and which we can't see, makes up 26 percent of everything in the universe; and the other 4 percent is ordinary matter, which makes up the stars, the planets, and human beings. How do we know this? By studying radiation: light is 0.005 percent of the content of the universe.

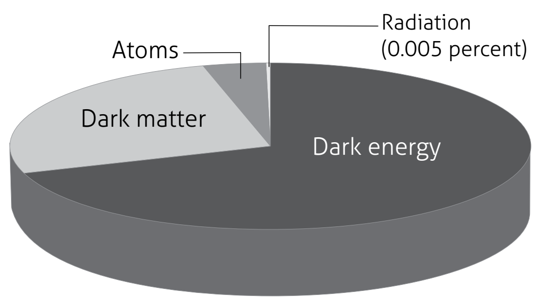
Using telescopes, analyzing the radiation from the stars, and, of course, applying our extraordinary brains, we've come to infer the nature of the cosmos. In addition, we've also observed that the early universe wasn't perfectly homogeneous; it had irregularities, and, as it expanded, matter settled into the cosmic web: galactic clusters, visible and dark matter merged into filaments that surround matter-free spaces.



Max Planck Institute for Astronomy

The cosmos's background radiation shows us the non-homogeneities of the early universe.

The Content of the Universe



The most common thing in the universe is dark energy, which is responsible for its expansion; 26 percent is dark matter; 4 percent, ordinary matter, and only 0.005 percent, radiation.[2]

The region of the cosmic web where our galaxy, the Milky Way, is located is called Laniakea. The name means "open skies" or "immense heaven" in Hawaiian. Some of the world's most powerful telescopes are on Mauna Kea, one of the volcanic islands of the Hawaiian archipelago, which is why that language is used to name some stars.

VM: What does it mean that the universe is a web? What would happen if the galaxies didn't group together?

JF: If there were no fluctuations in density, that is, if the universe were perfectly homogeneous, no stars, or galaxies, or planets would have formed. For stars to form, there must be variations in density. In the densest places is where gases can come together to create stars. If the universe were completely homogeneous, the clouds where new stars, planets, and smaller celestial bodies originate would not have been formed.

In the large scale universe, visible matter is distributed in the cosmic web: 100 billion galaxies with an average of 100 billion stars each. We should note that besides stars, galaxies contain clouds of gas and dust, the interstellar medium, which is where the new stars and planetary systems are born.

VM: What is the cycle of the stars?

JF: When the universe was formed, only two chemical elements existed: hydrogen and helium. We're talking here about the early universe, when it was less than three minutes old.

We can imagine the cosmos as an expanding gas that cools as it expands. As that happened, the universe's temperature dropped more and more until the gas made up of hydrogen and helium was able to conglomerate in clouds, and inside those clouds the first stars were born. They were made up exclusively of hydrogen and helium. Atoms at the stars' nuclei fused and generated new elements such as nitrogen, carbon, and oxygen, the substance of life.

At the end of their evolution, stars expand —this will happen to the Sun in 4.5 billion years— and hurl new elements into space. The biggest stars explode, and when they do, their atoms collide with each other, forming the heaviest chemical elements like iron, gold, or lead, for example. These elements are less abundant than carbon, nitrogen, and oxygen because they are only formed during stars' explosions.

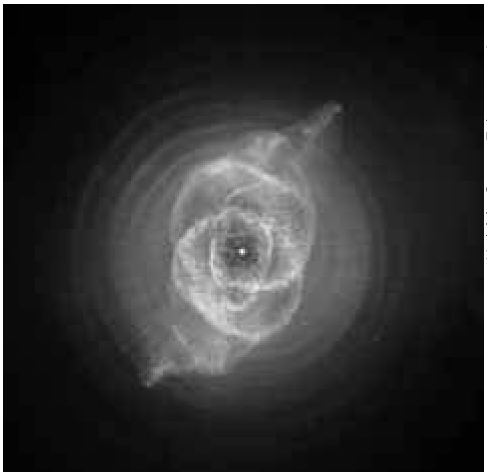
The matter the stars expel mixes with the interstellar medium gas and dust clouds to form new star systems, including planets. These stars in turn will hurl substances into space that will mix with other clouds. In this way, generations of stars follow each other. The most recent ones have a larger number of elements like carbon or oxygen. Millions of generations of stars existed before the Sun did, and thanks to the elements that they processed, planetary systems like our own were formed that require considerable amounts of elements like calcium, silicon, or iron.

The Solar System was formed just like the others, starting with a gas and dust cloud from the interstellar medium about 4.6 billion years ago. The star formed at the center with almost all the matter from the cloud; what was left over formed the planets; and later, life appeared 3.8 billion years ago when the Earth cooled and numerous comets collided with it, bringing water from the outskirts of the solar system where they had formed.

If we looked at our hand or any part of our body with an electronic microscope, we would be surprised to imagine that each carbon, nitrogen, and oxygen atom had been in the nucleus of a star, and when that star died, it hurled all these atoms into space, which finally became part of our body. That is, we come from the stars. In addition, each proton of every one of those atoms has been traveling through the universe for 13.8 billion years: each one entered a star, became part of another element, and when it concluded its evolution, the star sent the new atoms out into space, which gave rise to another star, the creation of new elements, which then ended up expelled into space, mixing with the cloud that gave birth to the Solar System. So, each one of our protons has been going in and out of stars for 13.8 billion years, and have become part of life.

Hubble Space Telescope / NASA

In 4.5 billion years, the Sun will hurl its outer atmosphere into space, which will contain the chemical elements it created through thermonuclear reactions.



Cloud forming a planetary system.

VM: So, is it infinite regeneration?

JF: No, the moment will come when stars stop forming, the interstellar medium gas will be exhausted. The existing ones will burn out. The universe will continue to expand and it will be colder and colder.

For example, when the Sun's life cycle ends, it will expand and lose its outer layers, its nucleus will slowly cool; the Earth will evaporate; all matter on Earth will become part of another cloud; and new planetary systems will certainly be formed. But the stars' energy runs out more and more, and there will be no more gas and dust clouds from which new stars could be born.

One characteristic of physics, and therefore of astrophysics, is that if you know the conditions of a system, you can know what its past was like and you can predict its future. It's difficult to define time; but science measures it based on the increased disorder. For example, in order to live, human beings create disorder: the light of the Sun comes and is absorbed by plants, and then we eat them and obtain energy. Nevertheless the plants cannot use the energy we emit to generate more fruits or vegetables; because not enough of it is useful. All the energy of the universe is degrading, and there are fewer and fewer gas and dust clouds to form new stars. So, in trillions of years all stars will burn out. How can we know how long stars last? The thermonuclear reactions that take place in the stars' nuclei can be calculated; how much matter is transformed into energy. For instance, it's possible to calculate how much energy the Sun is emitting and how much matter is being transformed into energy, using the $E=mc^2$ formula, and infer how long the Sun's evolution will last.

All the ancient galaxies no longer have gas; their stars are burning out and they no longer form stars. It's interesting to imagine how, in a billion years, our galaxy, the Milky Way, will merge with the Andromeda galaxy, and during that integration, many stars will be formed. But after that, the interstellar gas will get used up and there will no longer be any new stars.

In a billion years the Andromeda galaxy will merge with our own.

In addition, since the universe is expanding, it's dilating with the cosmic web. The voids between the filaments are increasing in size.

VM: What analogy would you make with this cosmic web on Earth?

JF: In nature, large groups of objects called emergent phenomena appear spontaneously and unpredictably. For example, if we place an ant on a table, it will begin to walk from one side to the other until it becomes exhausted and dies. If we put ten ants on the table, the same thing happens. But when we have 1000 ants, they begin to organize; some go and look for water; others, for food; others find a place to make a nest. This is an emerging phenomenon. Another example are neurons: a single neuron is pretty stupid, but in our brains, which have 100 billion neurons, we witness emergent phenomena: if there is a stimulus, a group of neurons gets fired up that enables thinking, creating, or communicating. Emergent phenomena occur in the universe. Matter is organized in galaxies, and galaxies, stars, planets, and life are created in the cosmic web. VM

Notes

1 julieta@astro.unam.mx.
2 Chart developed by the author.