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**The Formation of our Galaxy**

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A typical galaxy, like our Milky Way, has one hundred billion solar masses in stars. It is remarkable that one can do back-of-the-envelope estimates that lead to predictions of the characteristic mass of a galaxy. I will describe how galaxies formed. Beginning from infinitesimal fluctuations in the early universe, gravity helped concentrate the matter into clouds that fragmented into stars and assembled into galaxies. With the largest telescopes, one can look back in time and decipher the remote signatures of galactic youth and even birth.

Galaxies are key elements of the universe. They probe cosmology, they control our existence. The broad line of their formation and evolution is clear. From infinitesimal density fluctuations present very near the beginning of the universe, large-scale structure developed to eventually form galaxies over billions of years. The process was slow for two reasons. Firstly, the universe was once so hot that the dominant radiation inhibited matter from condensing for the first ten thousand years. The repulsive pressure of the radiation was much larger than the attractive force of gravity. Secondly, the universe is expanding. Consequently all the matter in the universe, which initially is almost perfectly uniform, is expanding, and this greatly decelerates the growth of fluctuations in the matter density under the attractive force of gravity.

The fluctuations in matter were able to develop in the next phase of the expansion, when the radiation was sub-dominant but still tightly coupled to matter by scattering off of the electrons. Only 380,000 years after the beginning did the universe cool sufficiently so that the matter was almost entirely atomic, and there were very few electrons around to transmit the tendency of the pressure of the radiation to counter gravity. This meant that cold gas clouds could begin to develop.

In fact most, about 85 percent, of the matter is not atomic hydrogen and helium, the stuff that the stars are made of, but weakly interacting particles, the so-called dark matter. This mater does not scatter with radiation, and so boosts the fluctuations’ rate of growth at early times.

The first galaxy halos grew via the pull of gravity, via a process we call gravitational instability, of cold weakly interacting dark matter that enabled massive clouds to assemble and contract. The first clouds weighed in at a million solar masses. Within the clouds, baryons dissipated and cooled, and the gas fragmented into stars. Massive halos such as that of the Milky Way galaxy assemble from a hierarchy of merging clouds or subhalos. Memory remains in massive halos of the substructure forged by gravity: this has been one of the major revelations to come from computer simulations of structure formation in the expanding universe.

A billion years after the beginning, all is in place for the first stars to form. The structure sequence proceeds as follows. We measure the seed fluctuations as tiny hot spots and cold spots on the microwave sky. These angular temperature variations are equivalent to slight over- and under-densities in the matter distribution, when the universe was a thousandth of is present size, or at redshift 1000. We infer that the mass encompassed by these slight over-densities ranges from a million solar mass up to a million billion solar masses. In fact we directly observe the upper end of this range in the cosmic microwave background, but infer the presence of the smaller scales. The limiting small scale of a million solar masses is set by the requirement that gas must be able to have enough gravity to overcome the gas pressure and contract to form what eventually turns into a star-forming cloud.

Here is the remarkable property of these fluctuations, all of which are destined to eventually contract to form stars. From the distribution of the slight over-densities, we learn that those on smaller scales, encompassing lesser masses, have a head start over their larger scale colleagues. Structure forms in a bottom-up fashion. The smaller fluctuations merge together as larger and larger scales condense out of the expanding universe. We call this process hierarchical structure formation. Computer simulations have shown that the dark matter halos retains signs of their primordial substructure, whereas the ordinary matter, or baryonic component, merges together to form a dense stellar system that we recognize as a galaxy. An important prediction is that the merging of cloudy substructure induces compression waves in the gas that are expected to enhance the formation of stars. We should see outbursts of star formation.

There are many ways to test this scenario. As we look back in the universe we expect to see the numbers of smaller galaxies successively increase relative to the largest galaxies. The star formation rate should be progressively enhanced as we look back in time. This is precisely what we see. In the past, galaxies had a much higher gas content, and so formed stars more prolifically. As time proceeded, their gas content, the raw material of star formation, was gradually exhausted. The cosmic star formation rate peaked when the universe was about a third of its present size, about 4 billion years after the Big Bang, or about when the Milky Way formed.

The oldest stars in the Milky Way are about 13 billion years old, but these stars are in the outskirts of the Milky Way, and formed in the substructure precursors of our galaxy. The central bulge of the Milky Way, which contains the bulk of the old stars in our galaxy, formed about ten billion years ago. For comparison, the time elapsed since the beginning is 13.7 billion years, and our Sun along with the solar system formed 4.6 billion years ago.

We expect that the Milky Way is surrounded by an immense halo of dark matter. This can actually be traced by astronomers who are able to measure the rotation of the galaxy. If the mass were concentrated where we see the visible light, the orbital velocities of stars and gas clouds should decrease with distance. The decrease of the gravitational force with distance was predicted by Newton’s theory of gravity, and was shown by Kepler to account for the motions of the planets around the sun.

Modern observations measured the velocities first of massive stars surrounded by bright ionized nebulae in the outskirts of the Milky Way, and then peered even further out into the dimmest regions where there are few if any visible stars by targeting clouds of atomic gas. One pioneer was Vera Rubin, one of the first modern female astronomers, who observed in the 1950s at the Mount Wilson Observatory in Pasadena when there were no facilities for females on the mountain top. She targeted emission from optical nebulae excited by massive stars around the Andromeda galaxy, our nearest galactic neighbour that is a Milky Way twin. Her work was soon followed by radio astronomer Morton Roberts who used the 21cm emission line from atomic hydrogen to probe orbital velocities in the Andromeda galaxy at even greater distances.

Here is what they discovered. The nebulae and clouds were orbiting Andromeda in nearly circular orbits. However as one looked further and further away from the bright galaxy, the velocities did not decrease. They stayed constant! This could only mean that invisible or dark matter was present in order to provide the extra gravitational force needed to explain their velocities. The amount of dark matter needed amounted to 10 times the mass in luminous matter and extended to 10 times the radius of the luminous matter from the centre of the galaxy. To this day, we have no idea of the nature of the dark matter, just that it is a source of gravity.

Following the mapping of the Andromeda galaxy by Rubin and Ford, it was not long before dark matter was found everywhere and in particular in our Milky Way galaxy. Although closer than Andromeda, our galaxy is more difficult to survey as a 3-dimensional map has to be constructed taking account of our non-central location. Modern techniques use precision velocity measurements made with interstellar hydrogen masers, and demonstrate that the rotation curve of our own galaxy stays flat out to a distance of two hundred thousand light years.

The dark matter that surrounds our galaxy forms a giant halo. For many years, astronomers assumed that the halo was a huge monolithic blob of dark matter. The density of the dark matter is very low and completely transparent, and hence very difficult to measure directly.

The big advance in our understanding of the distribution of dark matter came from an unexpected direction, that of computer simulations. The discovery was the following. Dark matter is the dominant constituent of matter. It provided the giant clouds, controlled by their own gravity, within which ordinary matter, mostly hydrogen and helium that we collectively refer to as baryonic matter, condensed into stars. Initially a disk was formed as we see in the Milky Way, along with a central spheroidal bulge of stars.

The surrounding halo, within which the disk and bulge are embedded, was found in the simulations not to be a gigantic amorphous blob, but to be teeming with dark matter substructure. It is as though there is a memory of the assembly of the halo, which formed by the merging of many smaller dark structures.

In fact, in the simulations we see thousands of dwarf halos orbiting within the parent halo. We observe far fewer dwarf galaxies around the Milky Way or Andromeda, at most fifty or so. The difference might be due to the fact that dwarf galaxies are extraordinarily inefficient at forming stars.

It just takes the explosion of the first supernova in one of these tiny galaxies to blast out all of the residual interstellar gas. There is no subsequent star formation, until more cold gas can be accreted. This is rather unlikely as the dwarfs are orbiting their parent galaxy at high velocity, and there is little cold gas remaining in the halo after the Milky Way formed. The result is that there are thousands of dark dwarfs around the Milky Way. Because dwarfs have low escape velocities, they are easily disrupted when predominantly gaseous, whether by passage through the disk of the Milky Way or by the violent deaths of their first generation of massive stars. Many of these early dwarfs should still have a few surviving stars from their initial formation phase, and would be exceedingly faint but in principle detectable.

Searching for ultra-faint dwarf galaxies around the Milky Way has had some success by searching for incredibly faint ghostly relics of galaxies. Some dozens of candidates have been reported, seen essentially as star piles that are discovered by counting faint stars and looking for slight excesses over the background. These are believed to be the relic survivors from when our galaxy formed, some ten billion years ago.

The relics also satisfy the expected property of being chemically primitive, that is with very low abundances of heavier elements such as metals. The heavy elements are produced by successive generations of stars, and one requires a more massive galaxy to retain the stellar debris and systematically form more enriched stars.

Chemical evolution is studied in the Milky Way where one finds that the inner regions of our galaxy are progressively more enriched than the outer regions. The enriched debris from the first generations of stars are captured in the central regions of the galaxy and dispersed into interstellar clouds that form new generations of stars. The Sun was formed about half way through this process, some 4.9 billion years ago.

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