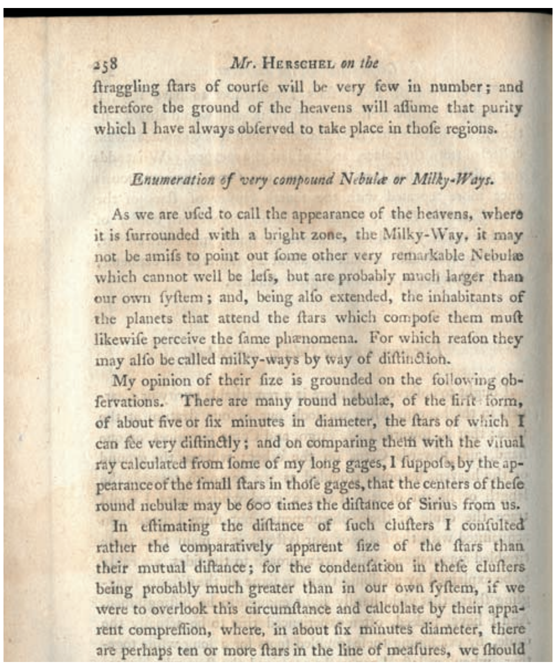
A Galactic Universe

• Fr. José Gabriel FUNES s.j. •

***"I see myself as a child
playing on the seaside
and sometimes having fun
discovering a small rock or a shell
that is more beautiful than normal,
while in front of me,
the huge ocean of truth
extends unexplored."***

Isaac Newton


258 Mr. Herschel on the

ſtraggling ſtars of courſe will be very few in number; and therefore the ground of the heavens will aſſume that purity which I have always obſerved to take place in thoſe regions.

Enumeration of very compound Nebulæ or Milky-Ways.

As we are uſed to call the appearance of the heavens, where it is ſurrounded with a bright zone, the Milky-Way, it may not be amiſs to point out ſome other very remarkable Nebulæ which cannot well be leſs, but are probably much larger than our own ſyſtem; and, being alſo extended, the inhabitants of the planets that attend the ſtars which compoſe them muſt likewiſe perceive the ſame phænomena. For which reaſon they may alſo be called milky-ways by way of diſtinction.

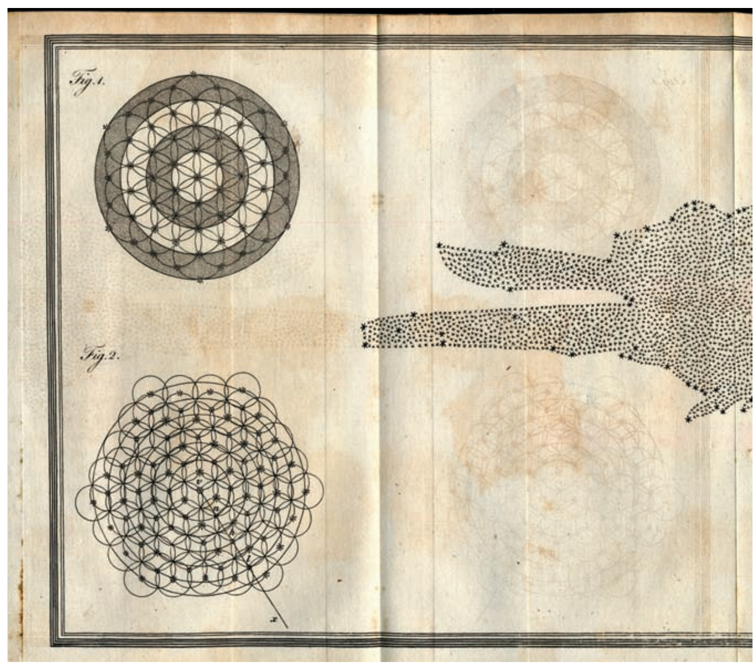
My opinion of their ſize is grounded on the following obſervations. There are many round nebulæ, of the firſt form, of about five or ſix minutes in diameter, the ſtars of which I can ſee very diſtinctly; and on comparing them with the viſual ray calculated from ſome of my long gages, I ſuppoſe, by the appearance of the ſmall ſtars in thoſe gages, that the centers of theſe round nebulæ may be 600 times the diſtance of Sirius from us.

In eſtimating the diſtance of ſuch cluſters I conſulted rather the comparatively apparent ſize of the ſtars than their mutual diſtance; for the condenſation in theſe cluſters being probably much greater than in our own ſyſtem, if we were to overlook this circumſtance and calculate by their apparent compreſſion, where, in about ſix minutes diameter, there are perhaps ten or more ſtars in the line of meaſures, we ſhould

***Above** In 1785, writing the the* Transactions of the Philosophical Society *of London, Herschel described his "construction of the heavens." Based on his estimation of the number and distance of the stars around our Sun he deduced that we inhabited a finite disk-shaped cloud of stars. And he proposed that other nebulae visible in his telescope were their own "milky-ways."*

A Galactic History: Island Universes

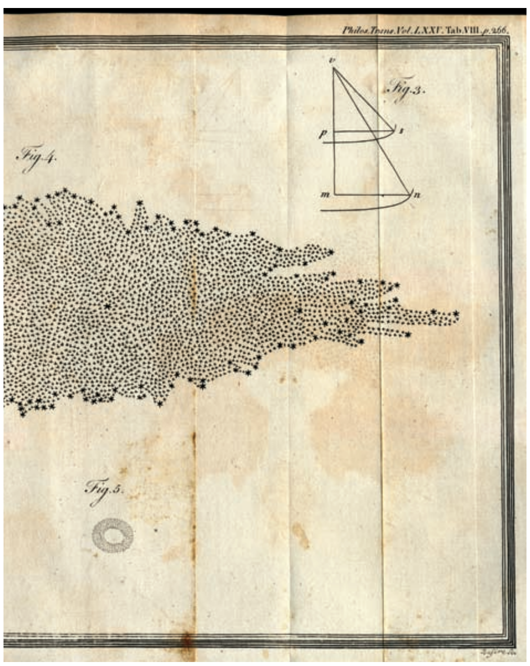
It was not until the twentieth century that we confirmed that we live in a galaxy or "island-universe" according to Immanuel Kant's hypothesis. The German philosopher was the first in 1775 to propose that spiral nebulae were analogies of our own galaxy, the Milky Way. Ten years later, Sir Edmund Herschel backed up this idea with his estimate of the size and shape of the Milky Way, suggesting that "other very remarkable Nebuale… are probably much larger than our own system; and, being also extended, the inhabitants of the planets that attend the stars which compose them must likewise perceive the same phenomenon. For which reason they may also be called milky-ways…" Indeed, our modern term *galaxy* is based on the Greek word for milk.



In the early 20th century, however, the nature of the spiral nebulae (galaxies) and the size of the universe were the subject of considerable controversy. At the time nobody was certain whether the spiral nebulae were merely clouds of gas within our own galaxy. "The Great Debate" between Harlow Shapley and Herber D. Curtis was held in 1920 at the National Academy of Sciences in Washington, DC. Shapley proposed a model for our galaxy in which the position of the Sun was exocentric, overestimating the size of the Milky Way, practically identifying the Galaxy with the universe. In this model, the spiral nebulae were not "island-universes" but nebulae within the Milky Way. On the opposite side, Curtis believed the Sun was at the center of the Milky Way and maintained that spiral nebulae were systems with similar dimensions to our galaxy. Both astronomers knew that the key to solve the dispute was the measurement of the distance to the spiral nebulae.

In 1924 Edwin Hubble proved that the Andromeda nebula was a galaxy similar to ours. Using Cepheid stars, a type of pulsating stars, as standard candles, Hubble was able to measure the distance to Andromeda. The Milky Way and Andromeda have a diameter of about 100,000 light-years and the distance between the two galaxies is about 2.5 million light-years.

In those years, Bertil Linblad and Jan H. Oort discovered that the stars of the Milky Way rotate around a center that was not the Suns's position. The distance from the Sun to the galactic center is about 25,000 light-years. They also found out that the stars in the Milky Way are distributed in a disk and a bulge, both components immersed in a spheroidal halo. Thus it was confirmed that the Milky Way had a structure similar to that of other external galaxies.



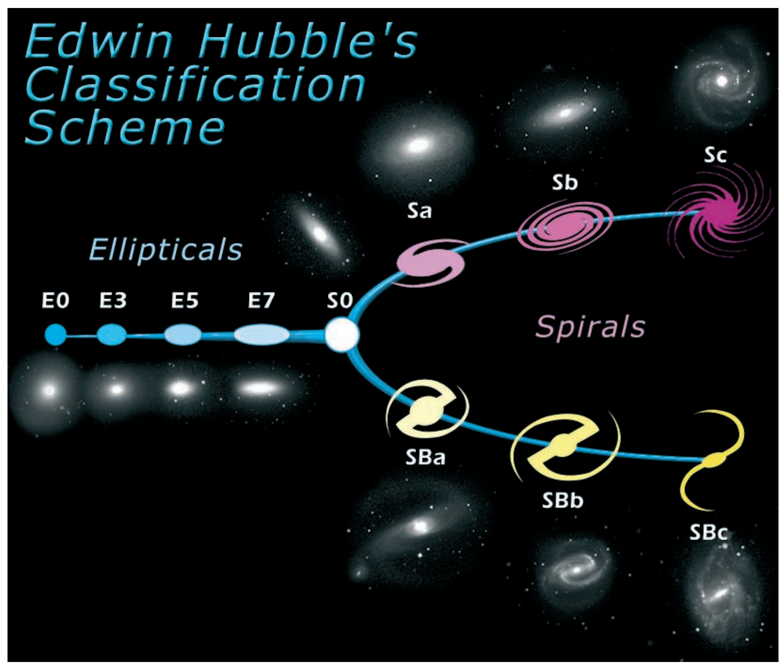
What is a Galaxy Made Of?

Extragalactic astronomers – those astronomers who study galaxies external to our galaxy, the Milky Way – may feel just like children playing in the seaside of a huge ocean. If we think of the universe made of a hundred billion galaxies, it is easy to realize that we are facing a huge ocean. This number is mind-boggling. To render the number more comprehensible, let's think of the population of the world, which is about 6.5 billion. If we divide the number of galaxies in the universe by the number of people in the world, each of us could have 15 galaxies, each galaxy containing between millions and 100 billions of stars.

But are galaxies made only of stars? No, they aren't. Then, what is a galaxy; and what is made of?

A galaxy is a system of stars, gas, dust and dark matter. All this material is gravitationally bound together with a mass ranging from 10 million to 1000 billion times that of the sun. The stellar component is distributed in a spheroidal component (the bulge and the halo) and in a flat component (the disk). Gas and dust are the material between stars and it is called interstellar medium; this is the material from which new stars form. As for "dark matter," we don't know yet its nature; but we have detected and weighed the dark matter and we know as well that it does not emit light. We do know that dark matter is located in the galaxy halos.

These galaxy components (stars, interstellar medium, and dark matter) vary from galaxy to galaxy and define the morphology – the shape – of a galaxy. Galaxies have a disk component and an spheroidal component. Stars in the disk are bluer and "younger" than stars in the spheroidal components. Young, here, means tens of million years!



The famous astronomer Edwin Hubble in 1926 classified galaxies in spirals and ellipticals. His diagram is known as the "Hubble tuning fork." Spiral galaxies are divided in two groups: normal spirals and barred spi-

Above *Galaxy morphologies illustrated. In the foreground is NGC 1427A, an irregular galaxy in Fornax. To its upper left is a background galaxy (which happens to lie in the telescope's line of sight but is some 25 times further away) which is a spiral galaxy somewhat similar to our own Milky Way. At even greater distances, background galaxies of various shapes and colors are scattered across this Hubble image.*

Credit: *NASA, ESA, and The Hubble Heritage Team (STScI/AURA)*
Acknowledgment: *M. Gregg (Univ. Calif.-Davis and Inst. for Geophysics and Planetary Physics, Lawrence Livermore Natl. Lab.)*

rals. Spiral (disk) galaxies are those in which the disk component is predominant. Using a familiar image they look like a fried egg. Our own galaxy, the Milky Way, is a disk galaxy. Elliptical galaxies look like a rugby ball.

Hubble also noticed that there is small fraction of galaxies that can be grouped in a third major type he called irregular galaxies. Galaxies in this class don't seem to have any rotational symmetry as Hubble pointed out (see NGC 1427A).

In the preface of his famous book *The Realm of the Nebulae*, published in 1936, Edwin Hubble wrote that "the book is believed to furnish an authentic picture of a typical case of scientific research in the process of development." That statement is still true in 2009... and the Vatican Observatory has contributed and contributes to the progress in this field. Two international conferences on the formation and evolution of disk galaxies were organized by the Vatican Observatory in 2000 and in 2007.

Galaxy Formation

One of the major questions in astrophysics regards the formation and evolution of galaxies. As was pointed out by Sandy Faber (University of California) in the Conference Summary of the first of these Vatican meetings, galaxies are the crossroads of astronomy because they look up to cosmology and they look down to the interstellar medium and star formation. The study of galaxies is crucial when trying to connect our knowledge of the universe as a whole with the formation of stars and planets.

And so, concerning the question of how galaxies form and evolve, we begin by asking: What makes galaxies to look different?

Our best models for galaxy formation assume that in the first million years of the universe matter originally filled all of space "almost" uniformly. The distribution of matter was not completely uniform. There were regions that were slightly denser than the surroundings. In these "little" cosmological perturbations, gravity pulled in surrounding matter. Cold dark matter caused matter to fall towards dense regions and made rarefied regions more rarefied. Denser regions contracted, forming protogalactic clouds. Hydrogen and helium gases in these clouds formed the first stars. The first primordial stars began within a billion years after the Big Bang as tiny seeds (with a mass 1% of that of the Sun) that grew rapidly into stars one hundred times the mass of our own Sun. The supernova explosions from first stars heated the surrounding gas slowing the collapse of the protogolactic cloud and the star formation rate. The leftover gas settled into rotating disk. This simple picture explains the existence of a bulge and a disk in spiral galaxies. The spheroidal component was formed during the collapse of the protogalactic cloud while the disk component was formed when galaxy's rotation became organized.

Models of galaxy formation suggest that galaxies look different because the conditions of the galactic clouds were slightly different or because they are the result of the interactions with other galaxies. In other words, galaxies are also the result of a trans-formation.

In the first case, the initial conditions of the protogalactic cloud that could explain the existence of elliptical and spiral galaxies are spin and density. If the protogalactic cloud had a considerable rotation, the cloud would end up in a spiral galaxy. If the cloud rotated very slowly, the final result would be an elliptical galaxy.

Density is the other physical property that rules the evolution of the protogalactic cloud. Higher density causes a faster cooling, allowing more rapid star formation. If the star formation were fast enough during the collapse, most of the gas would form stars leaving very little gas to settle in a rotating disk. The final result would be an elliptical galaxy. If the cloud has a lower density, it would end up as a spiral galaxy.

Things are a bit more complicated, however. Galaxies are not exactly island universes, in the sense that they don't evolve in isolation; they interact with other galaxies.

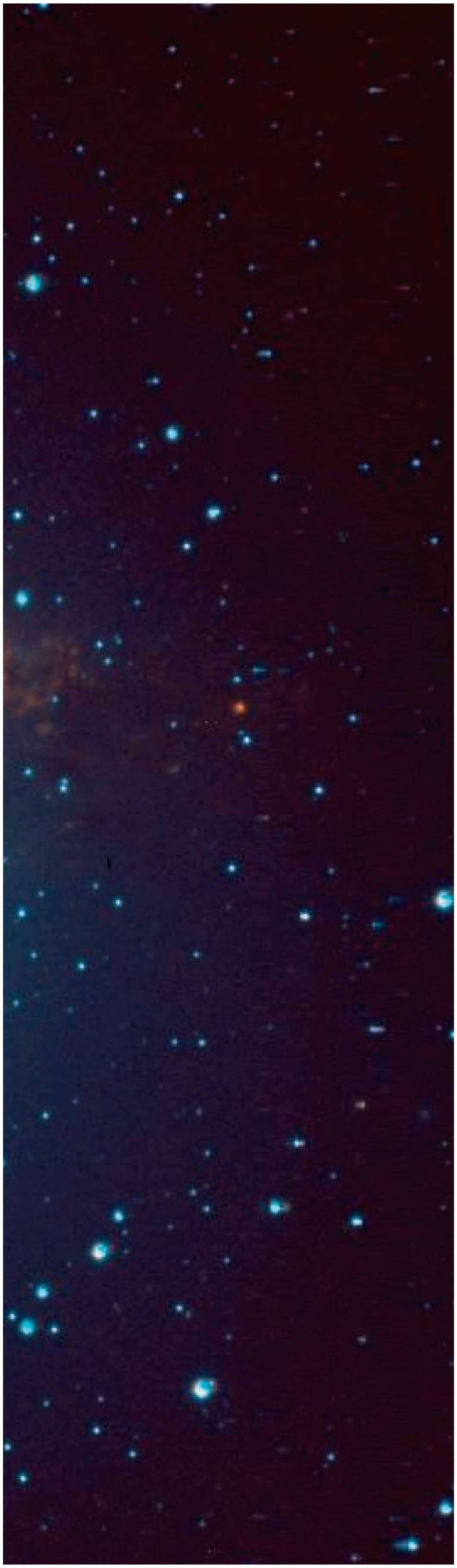
Spiral galaxies tend to collect into groups of galaxies, which contain up to several dozen galaxies. Elliptical galaxies are more common in clusters of galaxies, which contain hundreds to thousands of galaxies, all bound together by gravity.

According to cold dark matter models, or hierarchical models, dark matter halos form from the clustering and merging of "small" dark matter halos.

Galaxy Trans-Formation

Galaxies evolve due to internal changes (for example changes in color, brigthness, chemical composition basically due to the star formation history) and due to the interaction with other galaxies.

Collisions are also a factor that



shapes galaxies. Of course we cannot live long enough to see how galaxies merge. It would take several billion years!

So how can we check these ideas with observations? Astronomers are like detectives, following clues. Which signs can we find in galaxies that can lead us to think that there is or there was a merger? These are some:

Images of pairs of galaxies may reveal tails and bridges of stars and gas that are sign of interactions.

Counter-rotation. In some galaxies that otherwise look pretty "normal", there is evidence that one of the components is counter-rotating or rotating orthogonally to the other component. For example, in a stellar disk, the inner disk could be rotating in the opposite direction of the outer disk, or the spheroidal component opposite to the disk component.

Structural details in elliptical galaxies. For instance, elliptical galaxies with dust lanes have undergone a major event at some point in their evolution. The younger population of stars in these galaxies could have formed at a later stage of the evolution of the galaxy through either a merger event or a secondary in situ star-formation burst by the acquisition of gas from the environment. NGC 5128 (also known as Centaurus A) is a prototype of this class of galaxies, for more information see "NGC 5128: A Merger Tale."

Observations show that collisions trigger bursts of star formation. Computer simulations of such collisions confirm that the merger of two spiral galaxies can form an elliptical galaxy.

NGC 5128:
A Merger Tale

One of the gems of the southern sky is, without a doubt, the galaxy NGC 5128 (also known as Centaurus A). This galaxy has inspired about a thousand scientific papers and still poses several questions.
There are many reasons that have made this elliptical galaxy particularly interesting to study.
NGC 5128 is the nearest giant elliptical galaxy to us; its distance is only 12 millions light-years away.
It is also the nearest active galactic nucleus, hosting both a supermassive black hole of 100 million solar masses and a powerful radio source.
Furthermore, NGC 5128 is the nearest galaxy with shells; it contains a central dust lane, and boasts a bimodal populous system of 1700 globular clusters and a hundred active star forming regions along its dust lane.
NGC528 is part of a group of 25 galaxies, and there is indirect evidence to believe that it is the result of a merger of an elliptical galaxy and small spiral galaxy. The "signs" of past major event occurred in the past are the following:
- A warped disk of dust, gas, and young stars
- Shell structures
- Bimodality of the globular cluster system.

The image was taken by Jose Funes S.J. at Cerro Tololo Inter-American Observatory in Chile and processed by Sanae Akiyama. The stellar body of the galaxy is shown in blue and emission of the ionized gas in red.

Fr. José FUNES S.J. *(Argentina), the director of the Vatican Observatory, specializes in the comparison of galaxy morphology, and he has organized two international meetings on galaxy morphology and evolution at the Vatican. This chapter was written specially for the book.*