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VERA RUBIN AND THE HYPOTHESIS OF DARK MATTER EXISTENCE

Mira-Cristiana Anisiu

Abstract. Our solar system belongs to the Milky Way galaxy. The fact that there exist other galaxies is known since 1920s. They are indeed numerous, and bound together by gravitation to form clusters. In 1930s the existence of dark matter (which interacts gravitationally with normal matter, but does not interact with the electromagnetic force) was predicted to explain the very high speed of galaxies in clusters. Later on, in 1970s the same hypothesis was used by Vera Rubin and her collaborators on the unexpectedly high velocity of stars in galaxies. Vera Rubin achieved remarkable results as an astronomer, and had a complete and successful family life. In addition, she inspired and helped many women to follow their passion and enter the science fields dominated traditionally by men, as astronomy used to be.

Dedicated to all Romanian women in research, who since March 19, 2018 have the legal right to work until the retirement age of men.

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1. INTRODUCTION

The beauty of the universe may be seen on any cloudless night. Looking through a telescope offers a different and complex image, with new objects and structures.

The teachers should take their students at least once to visit an astronomical observatory in order to stimulate their curiosity with respect to our universe. At mathematics and natural sciences classes they should present problems inspired from the reality around us, including some which will arouse students' interest in our place in the solar system, galaxy and universe. They can recommend the students to look at the astronomical images published everyday by NASA at https://apod.nasa.gov/apod/.

In this way the children and young people will understand that research is in progress and it stays in their power to join the scientists who try to know more about our world.

In what follows we present some facts on galaxies and the impressive advances made in the last hundred years in understanding their structure. We insist on the recognized contribution of the American astronomer Vera Rubin, who obtained outstanding progress regarding the structure of galaxies, while being a wife and mother of four children, who all became scientists.

In the process of trying to understand the universe, many new problems appeared, and new means were developed. Still many answers await to be found.

2. OUR GALAXY AND OTHER ONES

A *galaxy* is a gravitationally bound system of stars, stellar remnants, interstellar gas, and dust (Fig. 1). The word galaxy is derived from the Greek "galaxias", meaning "milky". Galaxies range in size from dwarfs with just a few hundred million stars to giants with one hundred trillion stars, each orbiting its galaxy's center of mass.

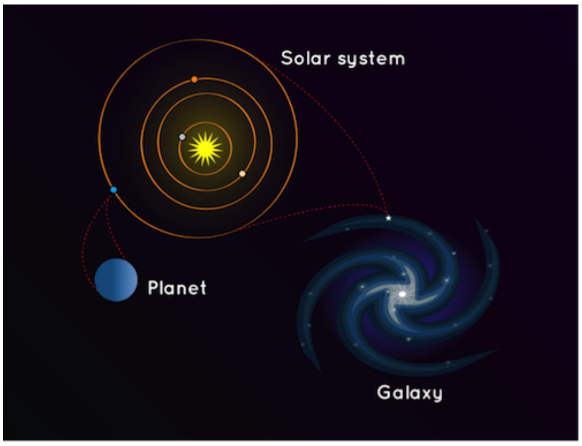

Figure 1. Planets, solar systems, galaxy

The first observed galaxy was the *Milky Way*, which contains our Sun with its planetary system, including the Earth. The descriptive "milky" is derived from the appearance from Earth of the galaxy, as in Fig. 2 (Credit: Bob King) – a band of light seen in the night sky formed of stars that cannot be individually distinguished by the naked eye.

Figure 2. Milky Way

The Milky Way appears as a band because its disk-shaped structure is viewed from within. Galileo Galilei was the first to observe the individual stars by using his telescope in 1609. Until the early 1920s, most astronomers thought that the Milky Way contained all the stars in the Universe. Only after the observations in 1922–1923, with the Hooker Telescope at Mount Wilson, Edwin Powell Hubble (1889 – 1953) concluded that some nebulae, thought to belong to the Milky Way, were much too distant. There exist many galaxies outside our own, and the Milky Way is just one of them. This discovery is considered as important as that of Copernicus, inferring that the Earth is not in the center of the solar system.

Hubble also devised the most commonly used system for classifying galaxies, grouping them according to their appearance in photographic images (Fig. 3, https://en.wikipedia.org/wiki/Edwin_Hubble) in Ellipticals (E0 - E7), Lenticular (S0), Spirals (Sa - Sc) and Barr Spirals (SBa - SBc). The Milky Way is a barred spiral galaxy of either SBb or SBc classification on the Hubble Sequence. It has two major arms that branch and twist in local arms.

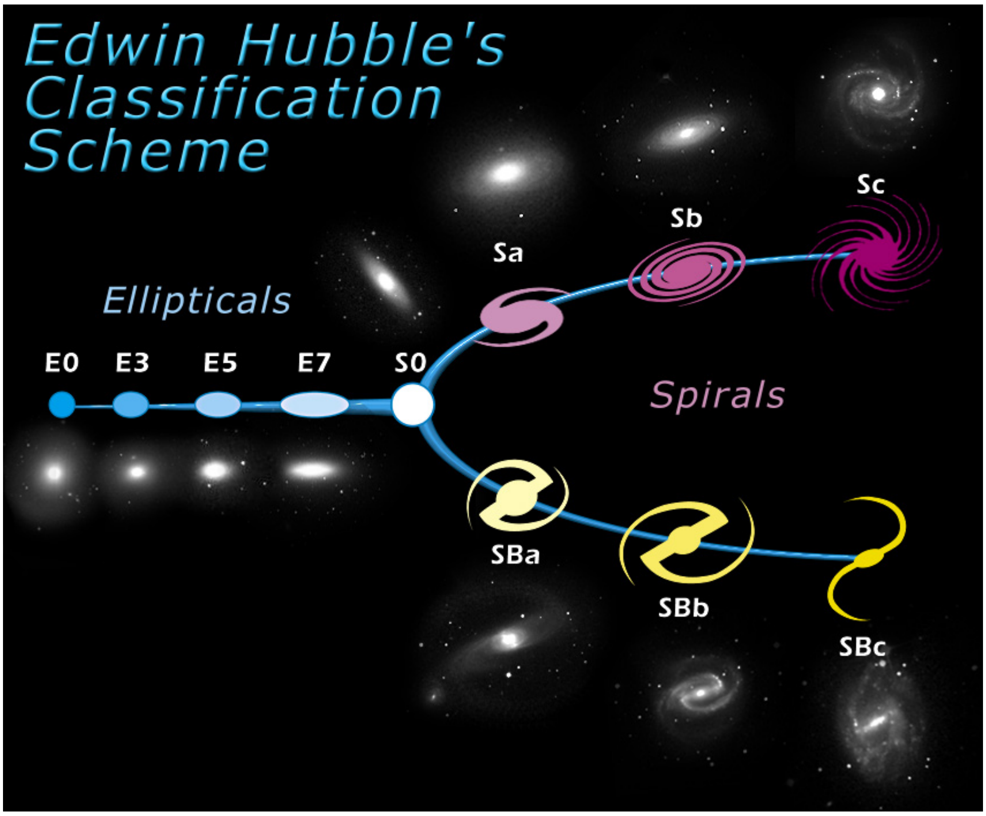

Figure 3. Hubble classification

Further observations added to Hubble classification the irregular ones (Fig. 4), which present no symmetrical structure. Many galaxies are thought to have black holes at their active centers.

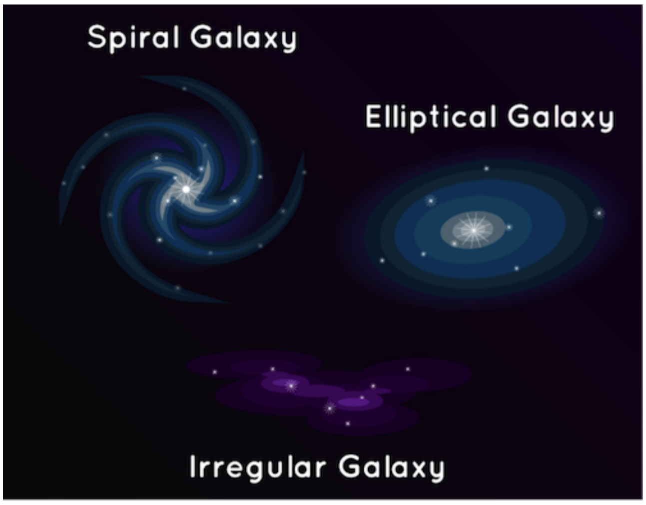

Figure 4. Galaxy types

The Hubble Space Telescope (HST), named after Edwin Hubble, is a space telescope that was launched into low Earth orbit in 1990 and remains in operation, being one of the largest and most versatile. HST's orbit outside the distortion of Earth's atmosphere allows it to take extremely high-resolution images, as the one in Fig. 5.

Figure 5. Galaxy cluster Abell 2537

Figs. 1, 4 - 5 are taken from https://spaceplace.nasa.gov/galaxy/en/.

In our Northern emisphere, we can see only one galaxy with naked eyes, namely Andromeda galaxy (M31 or NGC 224) which is the closest galaxy to ours. It can be seen between the constellations Cassiopeia and Pegasus (Fig. 6), during moonless nights and far from city lights. The name M31 means the entry number 31 in the catalogue of the French astronomer Charles Messier (1730 – 1817) from 1781, which contains over 100 of galaxies and nebulae. The second name comes from The New General Catalogue of Nebulae and Clusters of Stars (NGC), a catalogue of deep-sky objects compiled by the Danish astronomer John Louis Emil Dreyer (1852 – 1926) in 1888. Now Andromeda is considered, along with The Milky Way, a member of the Local Group of over 20 galaxies.

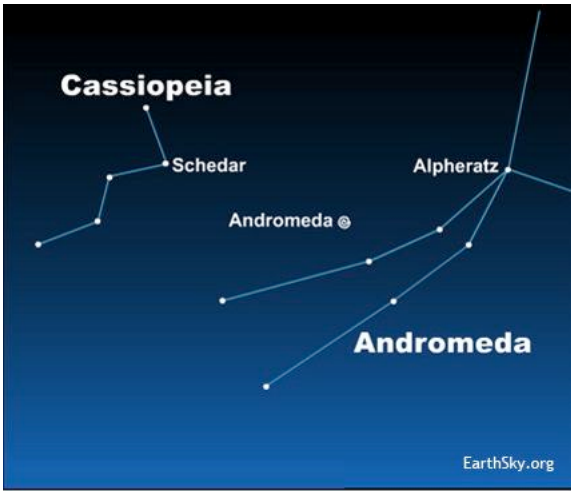

Figure 6. Andromeda galaxy

From southern latitudes, one can see with the naked eye two galaxies, namely the Large and Small Magellanic Clouds. They orbit the center of the Milky Way on eccentric paths and are also members of the Local Group.

A *galaxy cluster* is a structure that consists of 100 to 1,000 galaxies that are bound together by gravitation and has a mass ranging from 10^{14}–10^{15} solar masses. The galaxy clusters can be organized to form *superclusters*.

3. ROTATION CURVES AND DARK MATTER

Fritz Zwicky (1898 – 1974), the Swiss born astronomer, predicted the existence of dark matter in the 1930s, when studying the Coma galaxy cluster. He measured the speeds at which galaxies move in the cluster and noticed that the speeds were so high that the galaxies would fly away, unless there was a large amount of unseen matter binding them to the cluster. He called it in German *dunkle Materie*. Before him, Henri Poincaré (1854 – 1912) wrote in his 1906 work "The Milky Way and Theory of Gases" about *la matière obscure*, but he was skeptical about its existence.

In 1970s, Vera Rubin studied several galaxies and obtained their rotation curves from observations, and postulated the necessity of dark matter at this level too. These and many more interesting facts about our universe can be find in ([2]).

By using Newton's law of gravitation and the centrifugal force one can calculate the rotation speed of a mass in circular motion around another one as a function of the distance to the rotation center.

Newton's law and the centrifugal force can be written as:

$$F_{Grav} = G\frac{Mm}{r^2}, \qquad F_{Centr} = m\frac{V^2}{r}, \tag{1}$$

where G is the gravitational constant, M the mass of the center object, m the mass of the orbiting matter, r the distance between the two and V is the rotation speed. By equating the forces in (1) we get

$$GM\frac{m}{r^2} = m\frac{V^2}{r}, \text{ hence } V = \sqrt{\frac{GM}{r}}. \tag{2}$$

Through these simple calculations it is shown that the rotation speed decreases when the distance grows. When the rotation speeds of planets (or stars) are plotted with respect to the distance from the center of the solar system (or of a galaxy), a *rotation curve* is obtained. The rotation curve for our solar system is found to be precisely in accordance with the theoretical prediction: planets further out have slower orbital velocities (see left-hand side of Fig. 7).

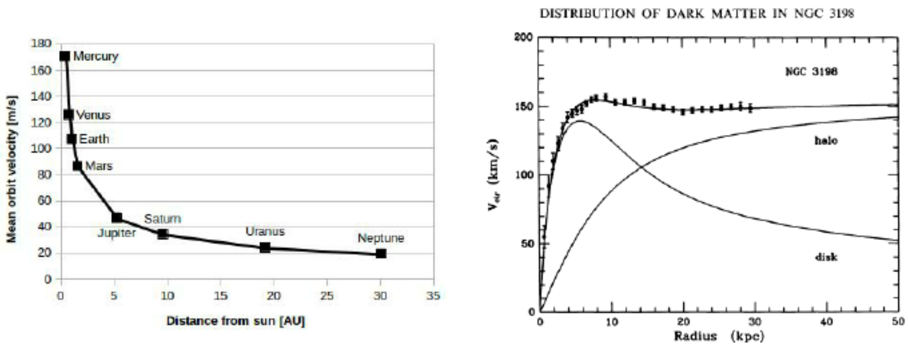

Figure 7. Rotation curves for the solar system and for the galaxy NGC 3198

The velocity of the stars in galaxies is determined using the Doppler effect. Being so distant, the change in their position on the sky is too slight to be measured. The *Doppler effect* (or the *Doppler shift*) is the change in frequency or wavelength of a wave emitted by a moving source. It is named after the Austrian physicist Christian Doppler (1803 – 1853), who described the phenomenon in relation with the coloured light of stars. For acoustic waves, the Doppler effect is obvious when hearing the high pitch of the siren of an approaching ambulance, and notice that its pitch drops when the ambulance passes by. If we refer to light, the observed wavelength of electromagnetic radiation is longer (called a *red shift*) than that emitted by the source when the source moves away from the observer; the wavelength is shorter (called a *blue shift*) when the source moves toward the observer.

Light consists of electromagnetic waves and, for visible light, different wavelengths correspond to different colours. When a beam of white light passes through a prism, on the other side we see a continuum of colours, ranging from red to violet. Light emitted from a hot gas that is incident on a prism displays an emission line spectrum as a pattern of bright lines with particular wavelengths on a black background. When a beam of white light is passed through cool gas before it gets to the prism, the gas absorbs waves having some specific wavelengths, and a pattern of black lines, called absorption lines, appears in the spectrum. Both emission and absorption lines depends on the composition of the gas.

Light that emanates from the hot inner parts of a star develops absorption lines as it passes through the cooler stellar atmosphere. Astronomers measure the spectra of stars, and by comparing with the absorption lines of gases measured in the laboratory, they can find which elements (hydrogen, helium, carbon, etc.) are present in the star. For a moving star, the entire spectrum gets blue- or redshifted, due to the Doppler effect – including the black absorption lines. Astronomers identify line patterns of different elements and find their wavelength λ; they measure the wavelength λ_0 of a gas sample at rest in the laboratory.

On this basis, the velocity V of a star is determined by

$$V = c\,\frac{\lambda - \lambda_0}{\lambda_0}, \tag{3}$$

where c denotes the speed of light, λ is the observed wavelength of a particular spectral line and λ_0 is the rest frame wavelength of the line. This is the velocity along the line of sight from the Earth, and it can be measured for stars in a galaxy oriented so that its plane is sharply tilted with respect to the line of sight. Vera Rubin, using the spectrograph of her colleague Kent Ford, traced the rotation curves for Andromeda galaxy ([4]), and then for hundreds other galaxies ([5]). They obtained curves as that on the right-hand side of Fig. 7, showing that, as moving from the center of the galaxy, the rotation velocity grows, which is natural since the orbit includes more matter. But, getting to the visible edge of the galaxy, one might expect the rotation curves to decrease, as they do for the Solar System. Instead, in many cases the rotation velocity remains the same, or even increases, to distances well beyond the visible edge. In Fig. 7, right-hand side, experimental data can be seen from the galaxy NGC3198 ([1]) with a fitted curve which does not decrease with the distance but is instead constant. This is the discrepancy which can be solved by postulating the existence of *dark matter*. This matter should be situated as a halo around the galaxy.

Dark matter has gravitational interaction, but no electromagnetic interaction, so it cannot be seen.

The evidence of Rubin's observations made the astrophysicists to admit the existence of dark matter in the Newtonian frame. There exist theories which propose modified attraction laws in order to explain the rotation curves for galaxies. The researchers who admit the dark matter hypothesis are trying to determine from what particles is it made, but until now none of the models consisting of known particles seems to be right.

So, we can only think at Vera Rubin's words: "We have peered into a new world, and have seen that it is more mysterious and more complex than we had imagined. Still, more mysteries of the universe remain hidden. Their discovery awaits the adventurous scientists of the future. I like it this way."

4. BIOGRAPHY OF VERA RUBIN

It is easy to learn about the life and work of Vera Rubin, from the autobiographical paper [7], several interviews, and her own writings collected in the book [6].

She was born Vera Florence Cooper on July 23, 1928, in Philadelphia.

Her father, Philip Cooper (1897 – 1989), was born in Vilna, Latvia, as Pesach Kobchefski, being the second of four children. He immigrated to the United States when he was seven, together with his mother and brothers, to join his father who had come earlier in Gloversville, NewYork. Cooper studied engineering at the University of Pennsylvania in Philadelphia and he took a job with Bell Telephone Company.

Her mother, Rose Anna Cooper (1901 – 1997), was born in Philadelphia, in Applebaum family, as the second of four children. Rose's mother (Vera's grandmother), Pauline Applebaum – born Schultz – had lived on an apple orchard in Bessarabia, and at age 16 sailed alone to New York. Then she went to Philadelphia, to be near her relatives, and there she married Jacob Applebaum (1875 – 1936), who had come from Austria.

Rose attended the South Philadelphia High School for Girls, and after graduating she worked at the Bell Telephone Company, as Philip did. Rose stopped working following her marriage, and has given birth to two daughters: Ruth, on March 29, 1926, and Vera, on July 23, 1928. Ruth became an Administrative Judge and Division Head in Armed Services Board Contract Appeals and married Max Gunter Breslauer in 1946 (deceased on August 1964), then Maurice Benjamin Burg in 1967. She had four children, two boys and two girls.

Cooper family moved from Philadelphia to Washington when Vera was 10. From the window looking North of her bedroom she used to watch the night sky revolve and asked herself questions about this. Her father helped her build a simple telescope and went with her to amateur astronomers' meetings. She attended Calvin Coolidge High School, graduating in 1944.

In 1945 Vera got a scholarship to the women's college Vassar, and she graduated as the only astronomy major in 1948. There, she had access to a very good library, and to a modern five-inch telescope which was at her disposal. The summers of 1946, 1947, and 1948 were very beneficial to her, studying in

Washington D.C. at the Naval Research Laboratory (NRL) the properties of optical instruments.

She applied to graduate schools, and she could not study at Princeton, where women were not accepted in the astronomy program. In fact, Princeton did not accept women in graduate physics until 1971, in graduate astronomy until 1975, and in graduate mathematics programs until 1976. Vera was accepted at Harvard University, but after marrying Robert Rubin she chose to go to Cornell University, where her husband was a graduate student. At Cornell she studied physics under Philip Morrison and Richard Feynman, and quantum mechanics under Hans Bethe. Vera worked on galactic dynamics with astronomer Martha Stahr Carpenter (1920 – 2013), who had received a Ph.D. degree in astronomy from the University of California – Berkeley.

She married Robert Rubin (born on August 17, 1926) on June 25, 1948. He was 21 and working on his thesis, while she, at 19, had obtained the B.A. degree from Vassar. Robert Rubin got a Ph.D. degree in Chemistry in 1951. He developed elegant mathematical models for complex physical systems while working for 30 years at the old National Bureau of Standards and 10 more years at the National Institutes of Health (NIH). Robert died on January 18, 2008.

Robert and the parents of both of them supported and encouraged Vera to continue studying and working while she raised her four children:

David (born 1950), a geologist with the U.S. Geological Survey;

Judith Young (1952 – 2014), an astronomer at the University of Massachusetts;

Karl (born 1956), a mathematician at the University of California at Irvine;

Allan (born 1960), a geologist at Princeton University.

All of them obtained Ph.D. degrees in their domains.

Vera earned her master's degree from Cornell University in 1951. She then enrolled in Georgetown University, the only university in the area that offered an advanced astronomy programme. She started work with George Gamow, who was nearby at George Washington University, and she got her Ph.D. in 1954. The thesis was published in the *Proceedings of the National Academy of Sciences* ([3]), after being rejected by Chandrasekhar, who was then the *Astrophysical Journal* Editor (awarded the 1983 Nobel Prize for Physics with William A. Fowler). She also studied with Father Francis Heyden, after whom Georgetown's observatory is named.

She worked one year (1954 – 55) as an instructor of Mathematics and Physics at Montgomery County Junior College. Then, Georgetown University offered her a position of research and teaching, namely:

1955 – 65 Research Associate Astronomer, Georgetown University

1959 – 62 Lecturer, Georgetown University

1962 – 65 Assistant Professor of Astronomy, Georgetown University.

She met with the astronaut John Glenn (1921 – 2016, fighter pilot in WWII, first American to orbit the Earth in 1962, and United States senator from

Ohio, 1974 – 1999) when he visited Georgetown University in 1963. By 1964 she recognized that observing was very important to her, so she chose to give up teaching. On April 1, 1965, she was accepted as staff member at the Department of Terrestrial Magnetism (DTM), one of the branches of the Carnegie Institution of Washington, being the first woman there. Vera Rubin (Fig. 8, Credit: Carnegie Institution of Washington) continued her research and mentorship until her death in 2016.

She made herself observations on the rotation of galaxies since 1963 at Kitt Peak National Observatory in Arizona and at the McDonald Observatory in Texas. In December 1965, she was the first woman officially admitted at the Palomar Observatory (she confessed that astronomer Margaret Burbidge did some observations there earlier, but near her husband Geoffrey).

At DTM she met Dr. Kent Ford, who had just returned from the Mount Wilson Observatory, where he had tested his new image tube spectrograph. His electro-optical device decreased observing time by a factor of up to ten compared to the conventional photographic plate. Ford handed her a photographic plate and asked her to measure the stars' velocities. That was the beginning of their long and fruitful collaboration. They used the spectrograph at first in August 1965 at the Lowell Observatory in Flagstaff, then at the Kitt Peak National Observatory in Arizona, and in 1981-82 at the Cerro Tololo Inter-American Observatory and the Carnegie Observatory in Las Campanas, Chile, to determine the orbital velocities of stars and gas as they circle the centers of their galaxies. They were interested in the study of the internal dynamics and distribution of mass in galaxies in relation with their size and form, and they published several papers together with other collaborators.

Figure 8. Vera Rubin in 1974

Vera's seminal accomplishments have been honored by numerous awards, as the U.S. National Medal of Science for Physical Science (1993), the Gold Medal of the Royal Astronomical Society of London (1996), the Gruber Cosmology Prize (2002), the Watson Medal of the National Academy of Sciences (2004). She received several honorary doctorates, including the 2005 one from Princeton University that previously barred her from their graduate programme. She was a member of the National Academy of Sciences (1981), American Philosophical Society (1995), and Pontifical Academy of Sciences (1996).

After her death, the Carnegie Institute has created a postdoctoral research fund in Rubin's honor, and the American Astronomical Society has named its Division of Dynamical Astronomy early career award after Rubin. An area on Mars, Vera Rubin Ridge, and Asteroid 5726, discovered in 1988, bear her name.

When awarded the Gruber Cosmology Prize, the complexity of her life was described as follows ([8]):

"Vera Cooper Rubin's success has expanded outward from the sphere of a warm, brilliant family to the challenge of a cosmos studded with galaxies and laced with mysterious dark matter. Along the way, she has inspired countless students, and especially many women who, before Rubin, were told they had no place in astronomy."

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Tiberiu Popoviciu Institute of Numerical Analysis
Romanian Academy, Cluj-Napoca
e-mail: `mira@math.ubbcluj.ro`