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by Kurt Winkler

The study of astronomy greatly accelerated in the twentieth century. Aided by many advances in technology that improved observations, there has been an explosion of information about the cosmos, and scientists have had to review and overturn many long-held beliefs and assumptions about the universe. Among the most perplexing and enduring questions has been the nature of a mysterious substance known as dark matter.[1]

This paper will discuss the life of the Swiss native, Fritz Zwicky, and this article will present information in a linear fashion, starting with some attention-grabbing information about Zwicky's knowledge of dark matter and then lead to a discussion of his youth and some decisions he made at that time, especially dealing with his education. This essay will then describe some of Zwicky's personal relationships and how his sometimes commanding and abrasive personality affected them. The bulk of this article will deal with how Zwicky was ahead of his time in the areas of astrophysics and the theory of dark matter.

In 1933 a young, brilliant, Swiss-American astronomer, Fritz Zwicky, demonstrated that there must be a huge mass of some unseen material in the universe that has had a great impact on the formation and structure of galaxies. This discovery set in motion the quest to understand the nature of the substance and the search to identify it. In a remarkable career, Zwicky made many other valuable scientific contributions, and he was one of the most important astronomers of the twen-

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[1] Recent studies on dark matter include: Richard Panek, *The 4% Universe: Dark Matter, Dark Energy and the Race to Discover the Rest of Reality* (New York: Houghton Mifflin, 2011); Robert H. Sanders, *The Dark Matter Problem: a Historical Persepctive* (Cambridge: Cambridge U., 2010); *Particle Dark Matter: Observations, Models and Searches* Gianfranco Bertone, ed. (New York: Cambridge, 2010); and Iain Nicolson, *Dark Side of the Universe: Dark Matter, Dark Energy, and the Fate of the Cosmos* (Baltimore: Johns Hopkins, 2007).

tieth century. Despite his contributions, he is often called, "the most unrecognized genius of twentieth century astronomy."[2]

Fritz Zwicky was born in Varna, Bulgaria, on February 14, 1898. His father, Fridolin (1868-1944), was a Swiss national who was a successful businessman in that city. Fritz's mother was the former Franziska Wrcek (1871-1927), and she had Czech ancestry. The boy's parents wanted their son to have a Swiss upbringing, so they sent Fritz to live with his paternal grandparents in Glarus at age six. Even though Zwicky lived for most of his life in the United States, and his first wife was an American, he always thought of himself as Swiss. However, he also admitted that his family had international connections because his one brother, Rudolf, married an Austrian, and his one sister, Leonie, married a Bulgarian.[3]

Initially, Zwicky did not apply himself well as a student in secondary schools. "I must admit I did not try very hard at school, but I still gained the best grades."[4] His friend and classmate, Jakob Stähli, confirmed that Zwicky did well, "Fritz Zwicky was the most intelligent and knew more than any of us. He excelled in every subject. . . . He was fascinated by physics, a subject to which he was to dedicated his whole life." Stähli further admitted that, "Zwicky simply excelled without even trying. He was well liked by all his fellow pupils." Another school friend, Hans Hefti, also had a high opinion of Zwicky, "He was excellent, very clever. He helped others who were not as gifted as himself, for example in maths, physics and even languages. He did not just put himself first. He was always ready to help anyone who had any sort of difficulties. He was a great friend, could not be better."[5]

At age fifteen, Zwicky took the entrance examinations for the Zurich technical college (*Industrieschule*), and he excelled in most subjects, but he had to retake the English test to get a better score.[6] The

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[2] The most comprehensive biography of Zwicky is Roland Müller, *Fritz Zwicky: Leben und Werk des grossen Schweizer Astrophysikers, Raketenforschers und Morphologen (1898-1974)* (Glarus: Baeschlin, 1986). A shorter version of this book in English is Alfred Stöckli and Roland Müller, *Fritz Zwicky: an extraordinary Astrophysicist* (Cambridge: Cambridge Scientific, 2011). Hereafter cited as Stöckli. See also, Tricia Close, "Lunatic on a Mountain: Fritz Zwicky and the Early History of Dark Matter" (master's thesis, Saint Mary's University, 2001).

[3] Zwicky as cited in Stöckli, *Zwicky*, p. 4.

[4] Ibid.

[5] Stähli and Hefti as cited in Stöckli, pp. 7-9; and Müller, Zwicky, pp. 24-26.

[6] Stöckli, pp. 12-13, and Müller, p. 30.

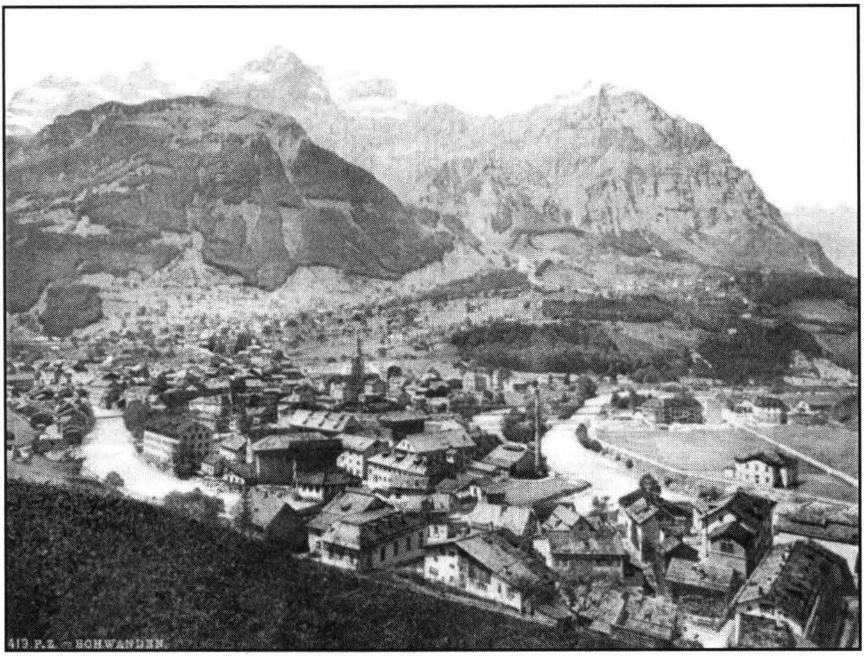

Figure 1. *Glarus about 1900.* Courtesy: Wikicommons.

technical college was the oldest and had the reputation as the toughest middle school (*Mittelschule*) in Switzerland, but Zwicky's accomplishments there were most impressive. At the completion of his studies, he tested in fourteen subjects. He scored 82.5 points out of a possible 84. He was told that in the 150 years of the school's existence, no one had ever come close to that score. This accomplishment miffed Zwicky, "I never could understand where these good grades came from as I made far less effort than my friends." He clearly had mental gifts, and he would show that he was a remarkably innovative and original thinker as well.[7]

Zwicky entered the Swiss Federal Institute of Technology (*Eidgenössische Technische Hochschule Zürich*) in 1916. Also known as the ETH, the Federal Institute of Technology was and still remains one of the most prestigious technical universities in the world. The young scholar took his final examinations in 1920. The highest possible grade was 6, and Zwicky achieved 5.45. In contrast, Albert Einstein took his final examinations at the ETH twenty years earlier and only attained a final grade of 4.91. Passing was believed to be about 5 or close to it.

[7] Stöckli, p. 15, and Müller, p. 36.

Einstein had barely squeaked by, but Zwicky had excelled.[8] Zwicky's dissertation was "On the Theory of Heteropolar Crystals (*Zur Theorie der Heteropolaren Kristalle*), which dealt with unlike polar chemical bonds in crystals. He completed the work in 1922, and he was awarded his Doctor of Science degree (Dr.sc.nat) in the same year.[9]

As an avid mountaineer, Zwicky had a love for climbing. He loved the workout, the view of nature, the escape from daily routine, and the sense of adventure. Early in his life, he climbed in the mountains near Glarus, but he soon looked for greater challenges. Frequently, he would scale a peak taking the most challenging routes, and he would then ski part way down on the glaciers often found on the mountain. He and his associates even pioneered new routes in ascending many challenging peaks. He and his friend, Tadeus Reichstein, who later won a Nobel Prize in Physiology or Medicine, were the first to ascend the north face of the Ruchenglärnish mountain in 1924.[10] Zwicky continued his love of climbing long after he moved to the United States.

During the 1920s, Robert A. Millikan, who later won the Nobel Prize for Physics, was trying to attract an impressive physics faculty at the California Institute of Technology (Caltech) in Pasadena, California. He was aided in this effort by the Rockefeller Foundation that was granting funds for foreign scientists to come to various countries. In all, the foundation offered 135 fellowships, and a third of these scholars came to the United States. This was only the beginning of a flood of 1,800 scientists who came to North America from 1933 to 1938.[11]

Zwicky worked as an assistant in the Physics Institute of the ETH from 1921 to 1925, but he soon came to the United States. When Professor Augustus Trowbridge and Wickliffe Rose of the Rockefeller Foundation came to visit Switzerland, Zwicky served as their guide. They were impressed and soon asked him if he was interested in further studies in America. He jumped at the chance. The visitors asked him where

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[8] For more on Einstein in Switzerland see Kurt Winkler, "Albert Einstein in Switzerland: the Education of the Most Famous Swiss American," *Swiss American Historical Society Review* 48, no. 3 (Nov. 2012): pp. 1-17.

[9] Stöckli, p. 19

[10] Ibid., pp. 19-23, and Müller, pp. 66-70.

[11] Charles Weiner, "A New Site for the Seminar: the Refugees and American Physics in the Thirties," in *The Intellectual Migration: Europe and America, 1930-1960*, Donald Fleming and Bernard Bailyn, eds. (Cambridge: Harvard, 1969), p. 196.

he would like to study, and the Swiss physicist responded, "Where there are mountains" (*Wo es Berge gibt*).[12]

The three men soon agreed that the California Institute of Technology (Caltech) in Pasadena would be the most appropriate place for the young scholar. Reportedly, when Zwicky arrived in Pasadena, he talked with the esteemed American physicist, Robert A. Millikan, who won the Nobel Prize in Physics in 1923, and asked, "Where are the mountains for climbing?" Millikan responded, "Can't you see them?" pointing to Mount Wilson which is over 5,000 feet high. Zwicky was used to the steep, high mountains of Switzerland, and he grunted, "Yes, I can see a few foothills" (*Ja, ich sehe einige Vorgebirge*).[13]

In 1927, after two years at Caltech, the young physicist had planned to return to Switzerland when he heard of his appointment to the position of Assistant Professor in a dramatic fashion. He had attended a graduation ceremony, and he became uncomfortable because he could not hear the speech by the university president, Robert A. Millikan, from where he sat. Zwicky left the ceremony early, and he learned that in his speech Millikan had nominated the Swiss physicist as Assistant Professor only after he had packed his bags to leave. A year later in 1928, Zwicky received an offer of employment from the University of Zurich to assume the position of Associate Professor of Theoretical Physics, a prestigious post held by Albert Einstein from 1909 to 1911. Zwicky did not reject the appointment outright, but he made many demands on the conditions for employment which the university was unwilling to meet.[14]

The decision to remain at Caltech had many advantages for Zwicky. He would have access to some of the most advanced astronomical viewing devices in the world at that institution, including the university-controlled one-hundred-inch Hooker telescope at Mount Wilson which had been in operation since 1917. The timing of Zwicky's decision was also perfect because George Ellery Hale received a grant from the Rockefeller foundation in 1928 for six million dollars for the construction of a two-hundred-inch Hale telescope on Mount Palomar that would also be associated with Caltech. It was completed in 1948. Zwicky and some of his colleagues soon turned from theoretical physics to astronomy and

[12] Stöckli, pp. 23-4, and Müller, p. 74.
[13] Stöckli, p. 24, and Müller, p. 75.
[14] Stöckli, pp. 30-1 and Müller, pp. 88, 91.

astrophysics in order to take advantage of the important opportunities that these devices made available to them.[15]

At the same time, Zwicky's social life was advancing, and he had already kept up a lengthy correspondence with Rösli Streiff, the accomplished Swiss skier, who won two world championships and numerous awards for downhill skiing. The two had much in common. They were both from Glarus, they were very athletic, and they loved skiing. Years later Zwicky even had a ski jump, six meters high, constructed near the observatory on Mount Palomar for his private use.[16] The letters between the astronomer and the skier show a concern for the life and welfare of each other. Then Zwicky met Dorothy Vernon Gates, the wealthy American socialite in October 1931, and they were married in a private ceremony on March 25, 1932. Reportedly, Dorothy's wealth helped fund the construction of the Palomar Observatory during the Great Depression when money was tight. This could have been a factor in Zwicky's attraction for her.

Two weeks after the wedding, the Swiss astronomer wrote an apologetic letter to Streiff which seems to reveal that he still had strong feelings for her and that he had some misgivings about his marriage. He regretted that he would not be able to meet the skier in Switzerland as they had planned. His marriage "caused both my wife and myself to give up many things we enjoy doing; it would seem it's never easy." He indicated that he almost longed for Streiff. "For me it is bitter irony that I did not get to know you earlier, although we both grew up in Glarus. I can only tell you that I have grown very fond of you through your letters. I have always loved hearing from you, and your many successes have made me very proud of you." He asked her not to forget him, "You can still remember me as a good friend and as a good Swiss compatriot."[17]

The newlyweds took their honeymoon in Switzerland where they stayed for three months, and they visited Glarus. One of Zwicky's friends, Betty Vogel, lamented that his wife could not speak German, and she was also no good at climbing mountains. Another friend,

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[15] F. Zwicky, "A Stone's Throw into the Universe: a Memoir," in *Essays on the History of Rocketry and Astronautics* 2 vols. (San Diego: American Astronomical Society, 1986) 2: p. 325.

[16] Stöckli, p. 68.

[17] Zwicky to Streiff on April 12, 1932, as cited in Stöckli, p. 45 and Müller, pp. 119-20.

Jakob Stähli, thought Dorothy was little more than a spoiled American woman. Dorothy could not have children, and as a Christian Scientist, she rejected medical procedures for physical ailments. She refused to undergo an operation to improve her chances of becoming a mother, and the couple remained childless. They divorced in September 1941, but they reportedly stayed on good terms, and Zwicky never said anything negative about her.[18]

After his divorce, Zwicky was free to renew his old friendship with Rösli Streiff, and the two exchanged letters again. He soon changed his form of address when writing to her from the formal "*Sie*" to the informal "*du*." He even closed one letter with the words, "and a kiss for you."[19] At the end of World War II, when Zwicky went to Europe to survey the German advances in rocketry, he also went to Zurich where he met Streiff. Even though their correspondence continued after the meeting, their friendship never fully developed into romance. By this time, Streiff was in her mid forties, and the astronomer had an eye for younger women.

In July 1947, Zwicky was staying at a hotel in Thun, Switzerland, when he met Margarit Zürcher who was working at the hotel. One of the young ladies in the hotel office told her that there was a smart man in the hotel who said we would fly to the moon someday. The idea struck Margarit as ludicrous, and she laughed out loud. She then noticed that Zwicky was sitting in the lobby of the hotel, and she apologized for her recent mirth. He soon invited her to go hiking with him, and their relationship quickly deepened. They had known each other for three months when they were married in October 1947. At the time, she was eighteen, and he was forty-nine. Zwicky wrote to Streiff in December to tell her how happy he was with his young bride. The couple lived in Pasadena, California, and they had three children, all daughters.[20] Fritz was known as a good family man who always had time for his children.

Shortly before Zwicky found long-term employment at Caltech, Edwin Hubble (1889-1953) made a profound discovery, which would later impact the Swiss astronomer's work. Many scientists had long believed that the entire universe was found in the Milky Way galaxy, but some objects remained unexplained. For example, some astronomers

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[18] Stöckli, pp. 50, 74, and Müller, p. 126.

[19] Stöckli, pp. 87-8.

[20] Stöckli, pp. 106-8, 116.

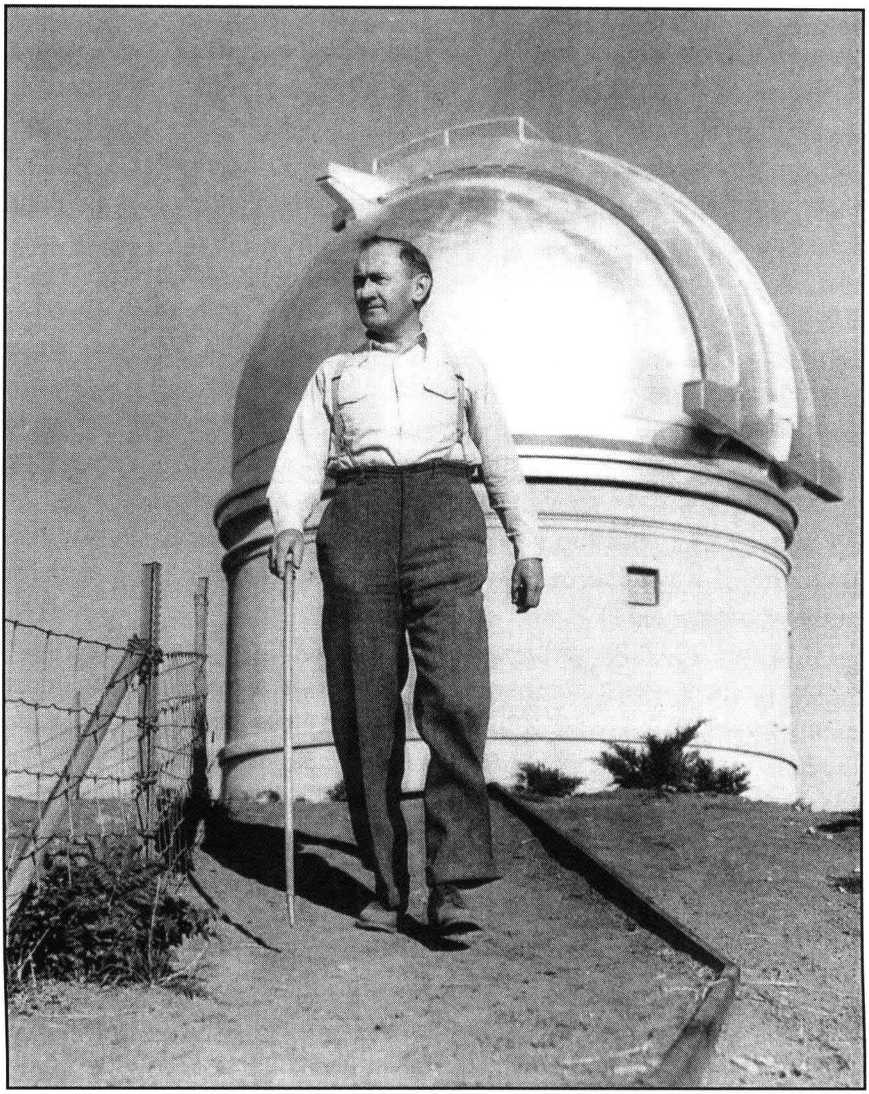

Figure 2. *Fritz Zwicky in 1937 at the dome of the Schmidt Telescope Mount Palomar.* Courtesy: *Baltimore Sun*.

thought that faint objects, many of which had a swirling shape, were simply a kind of nebulae or clouds of matter within our galaxy. They had little idea of the actual nature of these celestial bodies, and they had a limited knowledge of their distance from the earth. Using the Hooker telescope, Hubble demonstrated that the nebulae in question were in fact composed of thousands of stars. He also measured the absolute luminosity of some of these stars which proved that they were located far outside the Milky Way. In fact, Hubble argued, "for both nebulae [he examined] the corresponding distance [from us] is about 285,000 parsecs" or 930,000 light years. This placed them far outside the Milky Way's galactic plain, and thus he had proven that the universe was much larger than our galaxy.[21] Even though many astronomers still referred to them as nebula for decades, these objects were in fact huge galaxies in their own right. This knowledge of the nature of the "nebulae" was an essential feature in Zwicky's quest to understand them better.

The famous Swiss-American astronomer had started on one of the most impressive careers in modern astrophysics. His interests were wide, and he made many important contributions and discoveries. He worked at Caltech for forty-one years, and he was an exacting lecturer who demanded the best from his students. One of his graduate students, Wolfgang Panofsky, gave a negative opinion of Zwicky whom he called "the terror of all graduate students." Panofsky added that "He was a terrible teacher, because he was so extremely orthodox and non-interacting."[22] At times Zwicky had little patience with his students, and he had the habit of mumbling to himself when he was writing formulas on the blackboard. His students wondered if he was talking incoherently in his Swiss dialect, and they smuggled a Swiss national into the lecture hall to translate. Zwicky's mumbling included such comments as, "You stupid thickheads [*Dummköpfe*], you'll never understand this anyway."[23]

Working at Caltech with Walter Baade (1893-1960), the German astronomer, Zwicky invented the term "supernova,"[24] and the Swiss astronomer eventually discovered 122 such celestial objects. Zwicky's insights made him foresee the discovery of neutron stars and dwarf galaxies, and he argued that cosmic rays and neutron stars were related to supernovae. He also supported the theories of gravitational lensing and

[21] Edwin P. Hubble, "Cepheids in Spiral Nebulae," *The Observatory* 48 (1925): pp. 39-42. See also, Gale E. Christianson, *Edwin Hubble: Mariner of the Nebulae* (New York: Farrar, 1995), pp. 152-77; and Marcia Bartusiak, *The Day We found the Universe* (New York: Pantheon, 2009), pp. [ix]-xi.

[22] Wolfgang K. H. Panofsky, "Interview at Stanford Linear Accelerator Center," May 15, 1973 www.aip.org/history/ohilist/4994_1html. Accessed January 15, 2014.

[23] Stöckli, 73-4.

[24] Walter Baade and F. Zwicky, "On Super-novae," *Publications of the National Academy of Science* 20 (1934): pp. 254-9.

the existence of black holes. At that time, he disagreed with the use of the terms "black holes" because he thought they were not holes at all but "objects of greatest compactness," which he called "objects Hades."[25] Overall, he published 562 academic articles, 10 books, and 2 star catalogs, and he held 50 patents. In several instances, he was so advanced for his time that the veracity of his contributions has often only been recognized after his death.[26]

Among Zwicky's most profound insights is the existence of dark matter, an issue that is still unexplained and intrigues astronomers to this day. In his first academic article published in 1928, Zwicky was already thinking in terms of unseen or dark materials that help create thermodynamic equilibrium among the stars, meaning that some indistinct substances must cause forces to be in balance. He argues that "the existence of dust particles can be treated as an evaporation equilibrium," and he poses the question in parentheses that "(dark clouds [of dust might be located] in interstellar space?)."[27] He soon expanded his arguments dramatically on the existence of unseen materials in space, when he argued that a considerable amount of unobserved mass must be present to account for the gravitational equilibrium in galaxy clusters.

These measurements had to be consistent with an understanding of how gravity functions in the universe. Isaac Newton formulated the universal law of gravity in 1687 in his masterpiece *Principia Mathematica* in which he argues that all objects attract each other in relationship to their mass and the distance between them.[28] Gravity, which is associated with all objects containing mass in the universe, has long been used by astronomers to explain and account for the movement of celestial bodies. The perceived discrepancies in the paths of stars and planets have even led to the discovery of new previously unseen objects.

After William Herschel discovered Uranus in 1781, astronomers noted that the orbit of the planet was not as expected according to the accepted laws of gravity. Specifically, the radius of the orbit of Uranus

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[25] F. Zwicky, *Catalogue of Selected Compact Galaxies and of Post-Eruptive Galaxies* (Zürich: Speich, 1971), p. [14].

[26] Close, "Lunatic on a Mountain," p. 37.

[27] F. Zwicky, "On the Thermodynamic Equilibrium in the Universe," *Publications of the National Academy of Science of the United States of America* 14, no. 7 (July 15, 1928): p. 596.

[28] For a translation into English see, Isaac Newton, *Principia*, Andrew Motte, trans. (Amherst, N.Y.: Promethius, 1995).

seemed to be distorted. Another planet pulling on Uranus could account for the discrepancy, and several scientists predicted the new planet's location. This allowed Johann Gottfried Galle to look in the right place, and he first observed Neptune in 1846.[29] In a similar fashion, the motions of the stars Sirius and Procyon were long unexplained because they appeared to wobble in their positions. Scientists realized that small, dim companion stars they had not yet seen could account for the perturbations of the locations of the much larger stars. These theories were confirmed when astronomers discovered Sirius B in 1862 and Procyon's small companion in 1896.[30] These were theories that were proven by direct observation. Zwicky's ideas were much more challenging because they were based on unseen and perhaps unseeable materials, and no observations could verify their existence.

The Dutch astronomer, Jan Herndrik Oort, published an article in 1927 in which he stated that the velocity of some stars in the galaxy is sufficient for them to escape the gravitational forces of the galaxy and to fly off into space, implying that something unknown must be holding them.[31] In 1932, Oort expanded the ideas of unseen interstellar dust to which Zwicky had referred in 1928. Oort examined the motion of stars above the plane of the Milky Way Galaxy, and he stated that the galaxy should not be in equilibrium. To account for the stability of the Milky Way, there must be about fifty percent more mass in the galaxy disk than could be seen through the brightness of stars or illuminated matter. He had no immediate explanation for this unseen material, and he called the missing mass, "dark matter."[32]

In his seminal paper on dark matter published in 1933, Zwicky expanded Oort's arguments beyond the stars of the Milky Way to include

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[29] Tom Standage, The Neptune File: the Story of Astronomical Rivalry and the Pioneers of Planet Hunting (New York: Walker, 2000).

[30] Robert Grant Aitkin, The Binary Stars (New York: np, 1918) and Werner Israel, "Dark Stars: the Evolution of an Idea," in Three Hundred Years of Gravitation S.W. Hawking and W. Israel, eds. (New York: Cambridge, 1987): 205-6 and 210-11.

[31] J. H. Oort, "Observational Evidence Confirming Lindbald's Hypothesis of the Galactic System," Bulletin of the Astronomical Institute of the Netherlands 3 (1927): 275-82.

[32] J. H. Oort, "The Force Exerted by the Stellar System in the Direction of Perpendicular to the Galactic Plane and some related Problems," Bulletin of the Astronomical Institutes of the Netherlands 6, no. 238 (1932): 249-87. See also Oort and the Universe: a Sketch of Oort's Research and Person, Hugo van Woerden and Willem N. Brouw, eds. (Boston: Reidel, 1980).

Figure 3. *Coma Cluster.* Courtesy: NASA.

measurements in intergalactic space. The Swiss astronomer turned his attention to the Coma Cluster, which contains hundreds of galaxies and is about three hundred light-years away, and he found every measurement he could on the motion of the galaxies in the cluster. He concentrated his effort on eight galaxies and noticed that the their velocities should make the cluster fly apart unless something unseen was holding it together, and Zwicky came up with some unexpected conclusions. The observable material or illuminated matter (*leuchtende Materie*) of these galaxies was insufficient to account for the cluster's equilibrium. Therefore, some material that could not be observed must be keeping the cluster stable. "In case these [measurements] prove to be true, then the surprising result must follow that dark matter [dunkle Materie] is present in much greater density than illuminated matter."[33]

[33] F. Zwicky, "Die Rotverschiebung von extragalaktischen Nebeln," *Helvetica Physica Acta* 6 (1933) 2: p. 123. "*Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.*"

Zwicky concluded that the mass of the cluster would have to be four hundred times greater than what the luminous matter or star light indicated. Other astronomers later calculated that the mass of the dark matter would only need to be fifty times larger than what could be directly observed to hold the cluster together. Even at this reduced proportion, the amount of unseen matter still had to be very large.[34] In 1936 Sinclair Smith, who also worked at Caltech, published the first follow-up article to Zwicky's initial observation. This time Smith examined the Virgo cluster of galaxies and measured their gravitation mass. He referred to the Swiss astronomer's research and presented similar findings to the earlier study. Smith stated, "the view that the cluster possesses a powerful gravitational field is strongly supported by the mean peculiar velocity of cluster nebulae."[35]

The validity of Zwicky's conclusions relating to unseen mass in the Coma cluster clearly rested with the accuracy of his observations. Fortunately for his continued investigations, the eighteen-inch Schmidt telescope, often called "Little Eye," was installed at Mount Palomar in 1936, and Zwicky was given control of the instrument. Rated as one of the most important advances in optics, the Schmidt telescope was a technical advancement that greatly aided the Swiss astronomer. Zwicky soon mastered the use of the device, and he employed it extensively to gather data for his further inquiries. He once bragged that only two people in the history of science knew how to use a small telescope properly, Galileo and himself.[36] In highly painstaking operations, he was often able to make images of some very faint galaxies by using photographic exposures from 30 to 60 minutes long.[37] In the attempt to answer additional questions and to clarify earlier theories, the Swiss astronomer expanded his observations to include examinations of additional galactic clusters.

In 1937, Zwicky explored the question of how the actual masses of galaxies in clusters could be measured best. In his general theory of relativity, Albert Einstein had stated that mass bends light, or more cor-

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[34] Panek, *The 4% Universe*, p. 48.

[35] Sinclair Smith, "The Mass of the Virgo Cluster," *Astrophysical Journal* 83 (1936) 1: p. 29.

[36] Marcia Bartusiak, *Through the Universe Darkly: a Cosmic Tale of Ancient Ethers, Dark Matter, and the Fate of the Universe* (New York: Harper Collins, 1993), p. 193.

[37] F. Zwicky, "On the Masses of Nebulae and of Clusters of Nebulae," *The Astrophysical Journal* vol. 86 (October 1937) 3: p. 241.

rectly, mass creates a warp in space-time which causes the light passing through it to change its direction. In one of the great discoveries in cosmology, this effect was demonstrated in the 1919 solar eclipse when measurements proved that the sun bent light from distant stars. In a short article published in 1936, Einstein postulated that light bending around stars could create a gravitational lens effect in which the more distant object could be observed. But he stated, "Of course, there is no hope of observing this phenomenon directly."[38]

Zwicky greatly expanded this theory in the following year to include a discussion of distant galaxies. The Swiss astronomer argued that the gravitational lens effect should be observable in galaxies, and this effect could be used as a means of measuring mass. "The observation of such gravitational lens effects promises to furnish us with the simplest and most accurate determination of nebular [galactic] masses."[39] In 1979 this effect was confirmed by the observation of light from a galaxy that bent around a nearer galaxy.

One of the most perplexing questions relating the movement of galaxies and the existence of dark matter relates to physical laws and how they operate at such distances and on such a huge scale. Principally, the question of how gravity functions in galactic clusters needed to be understood to make sure that any measurement of the effects of dark matter was correct. In this effort, Zwicky had to question the validity of Isaac Newton's law of universal gravitation. The Swiss astronomer states the problem succinctly, "Newton's law of the gravitational interactions of celestial bodies was originally derived from observations of the motions of the moon and of the planets." He argues that clusters of galaxies should obey the "forces identical with the gravitational forces operating between the various components of the solar system." But he is quick to add, "little or nothing has been done to prove the strict validity of this assertion." Through a careful examination of the location of galaxies clusters and their radial velocity, spherical symmetry, and spacial distribution, Zwicky demonstrated that they were indeed following Newton's law of universal gravitation.[40]

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[38] Albert Einstein, "Lens-like Action of a Star by the Deviation of Light in the Gravitational Field," *Science*, New Series 84 (Dec. 4, 1936) 2188: p. 506.

[39] Zwicky, "On the Masses of Nebulae," p. 238.

[40] F. Zwicky, "On the Clustering of Nebulae I," *Astrophysical Journal* 95 (1942): pp. 555-64.

The discovery of the mass discrepancy in the Coma cluster was at odds with Edwin Hubble's measurements because there had to be more mass in the galaxies than he had argued. The difference should have been addressed more carefully, but Hubble was in control of the one-hundred-inch telescope on Mount Wilson, the most advanced astronomical instrument at the time, and he barred Zwicky from using it. The reason for this oversight remains unclear. The Swiss astronomer long believed that prejudice was involved, and that the American cosmologist held some kind of grudge against him.[41] As astronomer, Freeman Dyson, stated, "Fritz Zwicky's radical ideas and pugnacious personality brought him into frequent conflict with his colleagues at Caltech. They considered him crazy and he considered them stupid."[42]

The Swiss astronomer had personality quirks and eccentricities that tended to alienate people and make enemies. To demonstrate that he was physically superior to the other professors at Caltech, he often dropped to the floor of the cafeteria to do one-armed push ups, and he challenged everyone else to outdo him. He would often intimidate graduate students who walked by his office by calling to them, "who the hell are you?"[43]

Zwicky even turned on Walter Baade, his former collaborator, and started to call him "the Nazi." This was cruel and most unfair. Even though the German astronomer was slow to apply for citizenship, he had left his homeland before the Nazis came to power, and he had never even served in the German Army. Ironically, Zwicky never became an American citizen even though he worked in the United States over forty years. The Swiss astronomer was often insulting to his colleagues, including Baade. Zwicky called them "spherical bastards," because "they are bastards every way you look at them." The German astronomer was a sensitive man who walked with a limp and spoke with a stutter, and Zwicky's prodding made him fearful that the Swiss would become completely deranged and kill him.[44]

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[41] Close, p. 47.

[42] Freeman Dyson, "Dynamic Universe: the First Person to carry out a Modern Survey of the Night Sky, Fritz Zwicky's Astronomical Observations led to a New Picture of a Turbulent Universe that is Punctuated by Violent Events," *Nature* 435 (June 23, 2005): p. 2033.

[43] Richard Preston, *First Light: the Search for the Edge of the Universe* (New York: Random House, 1996), pp. 117-20.

[44] Ibid.

Zwicky lashed out at his enemies in print. Clarendon Press even refused to publish an early draft of his book *Morphological Astronomy* explaining that "your attacks on other astronomers cannot be tolerated."[45] The Swiss astronomer later wrote that he was the victim of a conspiracy to keep him from doing adequate research. Even though he had been a professor of physics and astrophysics since 1927, "I myself was allowed to use the 100-inch telescope only in 1948, after I was fifty years of age, and the 200-inch telescope on Palomar Mountain only after I was 54 years old." According to Zwicky, his lack of access to the most advanced observational instruments allowed other astronomers to control information and to make serious errors. "E. P. Hubble, W. Baade, and the sycophants among their young assistants were thus in a position to doctor their observation data, to hide their shortcomings and to make the majority of astronomers accept and believe in some of their most prejudicial and erroneous presentations and interpretations of facts." Furthermore, Hubble and Baade had reached, "glaringly incorrect conclusions."[46] Zwicky published these accusations in 1971 long after Hubble and Baade were dead, and when they could not respond to his claims.

The use of an inferior telescope did not inhibit the Swiss astronomer from working on theories relating to the missing mass in the galactic clusters. He speculated that dark matter [might be] "incorporated in nebulae in the form of cool and cold stars, macroscopic and microscopic solid bodies, and gases." He added further, "we should expect a considerable number of stars, as well as matter in dispersed form from disrupted nebulae, to be scattered through the internebular spaces within clusters. Sufficiently large amounts of internebular matter in clusters might seriously change our estimates of the average value of nebular masses."[47] Decades before the question of dark matter became a topic of extensive scientific research and discussion, Zwicky had already set the parameters of much of the debate.

When the larger 48-inch telescope, also known as the Schmidt telescope, was completed on Mount Palomar in 1948, Zwicky was able to make more precise observations on intergalactic materials. Yet the

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[45] Stöckli, p. 147.

[46] F. Zwicky, *Catalogue of Selected Compact Galaxies and of Post-Eruptive Galaxies* (Zuerich: Speich, 1971), pp. vi-vii.

[47] Zwicky, "Masses of Nebulae," pp. 218, 237.

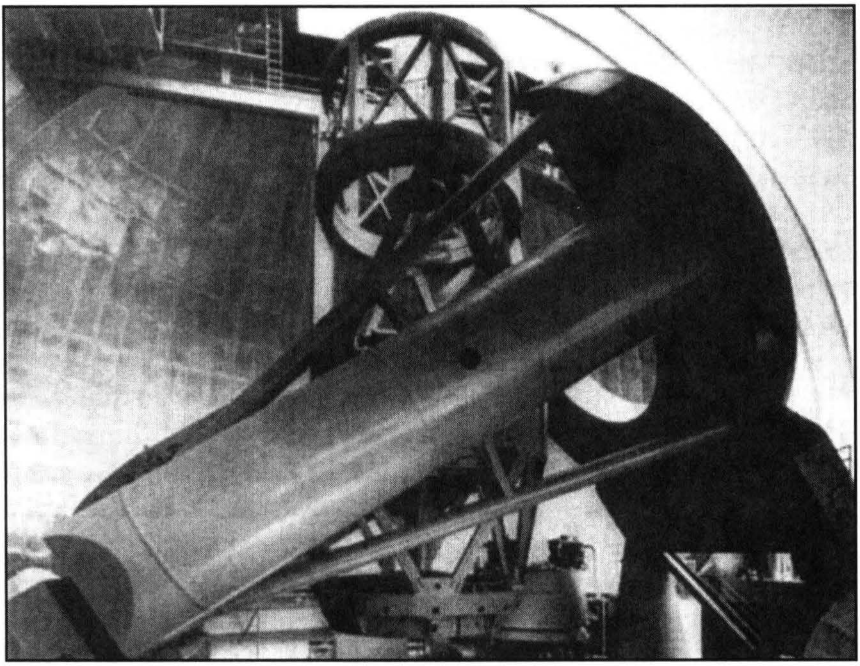

Figure 4. *Hale Telescope Mount Palomar.* Courtesy: NASA.

Swiss astronomer had trouble getting acceptance for his initial findings on matter between galaxies. He stated that "the majority of astronomers still seem to be mislead by Baade's statement that he does not believe that experimental astronomers will accept the existence of intergalactic matter." But the issue went far beyond a difference of opinion, and Zwicky accused his colleagues of blocking the publication of his discoveries. "My first reports in the 1940's, however, had been arbitrarily (and illegally) censored by our observatory committee and withheld from publication in any of the regular American Journals."[48] He then went outside of the United States to publish many of his initial findings on intergalactic matter. These articles first appeared in Swiss newspapers and in the journal *Experientia*, which was published in Basel, Switzerland.[49]

Clearly, much of the evidence that Zwicky was argumentative and accusatory comes from his own statements, but an accurate assessment of his character must include an appraisal of his other activities. Even though Zwicky never took US citizenship and was a national of neutral

[48] Zwicky, "Catalogue," p. ix.

[49] F. Zwicky, "Intergalactic Matter," *Experientia* 6 (1950): pp. 441-5.

Switzerland, he used his scientific knowledge to help the Allied war effort. He contributed to research on the development of jet engines, and he also participated on the development of the atomic bomb. Additionally, he served as a military advisor to the United States, and he wore the uniform of a colonel in the US Army at that time. At the end of the war, he assessed the development of German rocketry, and he also examined the damage done by the atomic bomb on Hiroshima. For his work in aiding the United States during the war, Zwicky was given the prestigious "Commendation for Meritorious Civilian Service."[50]

In 1949, the Swiss was also the first foreigner to be awarded the Presidential Medal of Freedom, which is the highest award that can be given to a civilian. The citation reads in part, "Dr. Zwicky distinguished himself by meritorious service to the United States in the prosecution of the war. . . . He contributed immeasurably to Air Technical Intelligence. His initiative, remarkable linguistic abilities, broad knowledge of physics and chemistry as pertains to the art of rocketry–together with an outstanding ability to exploit foreign technology in rockets, guided missiles and associated equipment for further utilization by the United States, made his services most valuable in our war effort."[51]

The Swiss astronomer had a strong social conscience. Following the Second World War, he created the Committee for Aid to War-Stricken Scientific Libraries, Pasadena. He knew that many scientific publications had been lost due to the ravages of the war in Europe, and he tried to replace them. Zwicky had noticed that a large number of scientific journals were routinely discarded after they had been examined. He contacted companies that often threw these periodicals away, he made appeals to retired scientists, and he even wrote to widows and relatives of deceased academics to see if they had any unwanted materials. Starting in 1947 and for the next ten years, he shipped roughly one hundred tons of books and journals to Europe that were valued at about $700,000. This effort clearly aided the academic recovery of Europe after the war.[52] The Pesalozzi Foundation of America awarded him the Silver Medal (1951) and later the Gold Medal (1953) for his humanitarian work.[53]

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[50] Stöckli, pp. 90-7.

[51] Stöckli, pp. 125-6.

[52] Ibid., pp. 113-4

[53] Ibid., p. 138.

The highest award Zwicky received for his work in astronomy was the Gold Medal from the Royal Astronomical Society, which he received in 1972. The distinguished astronomer, Fred Hoyle, gave an address honoring Zwicky and outlining many of his contributions. In his speech, Hoyle stated that the question of Dark Matter was a very important addition to scientific knowledge. "The dynamic energy of galaxies is too large unless hidden mass is somehow present within the clusters. This difficulty has not gone away with the passage of time. Quite the contrary. Many clusters must be unbound unless hidden mass exists in great quantity in some as yet unrecognized form."[54]

The Swiss astronomer went into the hospital to have a routine hernia operation in February 1974. As his wife Margrit reported succinctly, "My husband underwent a hernia operation. Everything went well. He came home on Thursday, but on Friday morning [Feb. 8] he had a heart attack and died in the evening." Zwicky had died six days shy of his seventy-sixth birthday.[55]

Zwicky lived a full life, and he made many contributions to humanity and to science, but he did not live long enough to see the full impact of his ideas on the academic community. In the case of dark matter, he was too far ahead of his time, and for decades other astronomers were too timid to take his findings seriously. However, he had presented the evidence on the existence of unseen matter convincingly, and he also effectively set the parameters for future investigations on the topic. Cosmologists finally started taking the issue seriously in 1978, and the question of dark matter, first introduced by Zwicky, remains one of the greatest mysteries in astronomy.

- Provo, Utah

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[54] Hoyle as cited in Stöckli, p. 189.

[55] Margrit Zwicky as cited in Stöckli, 197.