LUNATIC ON A MOUNTAIN:

FRITZ ZWICKY AND THE EARLY HISTORY OF DARK MATTER

by

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Lunatic on a Mountain: Fritz Zwicky and the Early History of Dark Matter

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Abstract. Fritz Zwicky is identified commonly as the discoverer of dark matter, the unobservable mass that is believed to occupy about 90 percent of the universe. In 1933 Zwicky found a mass discrepancy in the Coma cluster of galaxies, and in 1936 a similar discrepancy was found in the Virgo cluster. The startling news of a mass discrepancy in clusters did not raise many eyebrows. In fact, the astronomical community did not address the problem until the occasion of two conferences held in 1961, and it only gained astronomical prestige at the end of the 1970s, forty years after the initial postulation. Zwicky's role in the history of this most important subject in astronomy is significant in tracing the progression of the understanding of extragalactic dynamics and observations. It also shows that it is not only scientific evidence that defines theories, but that social interactions are also of vital importance.

"What are we to make of such men as Democritus, of the sixth century B.C., who imagined the universe to be populated with an infinity of worlds like our own? Shall we call him a dreamer or a brilliant philosopher? Whatever we claim for Democritus and others like him, we must admit that he was out of touch with his time. If he deserved to be heard because he was interesting, he also deserved to be called irrational. What is the role of such a man in history? These men may have sounded like lunatics on a mountain, but they spoke from the deepest boundaries of their rational selves. They pushed the boundaries of sanity slightly wider and made room for creativity."

Charles Whitney, *1971, 6-7.*

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Photo by James McClanahan/courtesy Caltech Archives

Fritz Zwicky (1898-1974)

Chapter 1
Introduction

> *"Astronomy is a science of matter — for it is matter that heats up, spins madly and darts swiftly throughout the universe, releasing the light waves that enable us to perceive the inner workings of the cosmos."*[1]
>
> Marcia Bartusiak

A. Introduction

Objects in space are observable because they emit radiation. The glowing celestial bodies of the night sky have always been gazed upon and wondered at, providing a rich backdrop for mythical and religious dogma. The rise of science and the invention of the telescope led astronomy into the realm of fact rather than myth, and especially in the past century the increase in telescope power has introduced many new objects to astronomers. Yet despite the ability to observe deep into space in the visual, X-ray, radio, and infrared wavelengths there is much more than is seen. In fact, using the Newtonian law of gravitation has led astronomers to conclude that 90 to 99 percent of the universe is not detectable by present means. That conclusion originates from an inconsistency between luminous and dynamical mass measurements of galaxies. The luminous mass is estimated from the observed flux of radiation emitted.[2] The dynamical mass is calculated from the law of gravitation and the observed motions of the stars in the

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[1]Bartusiak, 1993, p. xiii.

[2]The luminosity L is determined using the inverse square law $F=L/4\pi r^2$, where F is the flux and r is the distance to the galaxy. The luminosity is converted into a mass estimate by multiplying by an assumed mass-to-luminosity ratio. The luminous mass of a galaxy cluster is the sum of the luminous masses of its members.

galaxy. In addition, the dynamical mass of a cluster of galaxies is found using the motions of individual galaxies within it. The two mass measurements are *not* often equal for galaxies or for clusters of galaxies; the dynamical mass exceeds the luminous mass. That is, much of the matter of the universe must be non-luminous; it does not emit or absorb electromagnetic radiation. Such matter, appropriately, is called "dark matter."[3] The only alternative to the presence of dark matter is a revision of the Newtonian law of gravitation. For these reasons, the composition of the universe is one of the great dilemmas of astrophysics today.

Fritz Zwicky (1898-1974) is readily recognized by today's astronomers as the discoverer of the dark matter in clusters of galaxies. Historical outlines in review articles from the past two decades explicitly name Zwicky as the discoverer of dark matter,[4] as does Jeremiah Ostriker, who selected Zwicky's 1937 article (titled "On the masses of nebulae and of clusters of nebulae"[5]) to be part of the *Astrophysical Journal* Centennial Issue in 1999.[6] But the reference to Zwicky in many of the review articles is limited to name-dropping and in some cases to a comment about the four decades that passed before astronomers reached a consensus on the issue.

In searching for lengthier accounts of the early history of the dark matter problem, I found only six discussions, and they were in publications on general cosmological

[3]The possible dark matter candidates are numerous. They include ionized gas (with temperature of 1 keV), brown dwarfs (stars with $M<0.08$ solar masses), black holes, axions, light massive neutrinos, and weakly interacting massive particles (also known as WIMPs). For a review, see Sadoulet, 1999.
[4]For example Bartusiak, 1996; Davis, 1987; Einasto, 1990; Faber, 1987; Kormandy & Knapp, 1987, Krauss, 1986; Lightman, 1991; Ostriker, 1987; Riordan and Schramm, 1991; Rubin, 1983, 1987, and 1999; Sadoulet, 1999; Trimble, 1988 & 1993a.
[5]Until the mid-twentieth century, galaxies were commonly called "nebulae" for their nebulous appearance. Once it had been established that they were extragalactic, the term "galaxy" came into use. When quoting early articles I have kept the author's use of the word nebula. This is not to be confused with present day terminology, in which a nebula is an interstellar gas cloud.
[6]Ostriker, 1999.

topics.[7] Only one was by a historian of science.[8] Until very recently, historical details were essentially limited to short accounts. In his doctoral thesis, Bill Vanderburgh stated that the dark matter problem "has received little or no attention from historians of science" and "almost nothing has been written about the history of dark matter (except a few reviews of the evidence by astronomers)."[9] He included a survey of the early history of the problem in his case study of "evidential reasoning" and "theory choice" in the physical sciences.[10] Sidney van den Bergh has also published recently two very significant, though short, articles dealing specifically with the early history of dark matter and missing mass.[11] However, after reading all of these historical accounts, I did not feel that the reason it took so long for the dark matter problem to reach the spotlight was completely explained.

In this study, I will describe the early history of the dark matter problem, discussing the initial discovery by Zwicky in 1933,[12] the support of his observation by Sinclair Smith (1899-1938) in 1936,[13] and all other evidence for the discrepancy that was published between the 1930s and the 1970s. I hope to clarify the rationale for the forty-year interlude, suggesting that there is a variety of reasons why it took forty years for the dark matter problem to catch on, and Zwicky's relationship with the astronomical community is among those reasons. I will discuss the discovery of the dark matter problem in greater detail than previously, and I will look specifically at Zwicky's role in the discovery. It is also important to illustrate two issues; the use of Newton's law of

[7]Brief discussions of the early history can also be found in Krauss, 1989; Tayler, 1991; Trimble, 1992; Bartusiak, 1993; North, 1994; Rubin, 1997.
[8]North, 1994.
[9]Vanderburgh, 2000, p. 6.
[10]Vanderburgh discusses the use of "evidence" to decide on a theory as a philosophical problem in science.
[11]van den Bergh, 1999 & 2000.
[12]Zwicky, 1933a.

gravitation and the state of astronomy in and around 1930. This chapter will establish those circumstances.

B. Dark Matter and Newton's Law of Gravitation

Historically, dark matter has been discovered by its gravitational influence on visible bodies. The law of gravitation, formulated by Isaac Newton (1642-1727) in 1687, has played a large role in deciphering the motions of stars and galaxies.[14] In 1933, Zwicky found that the law of gravitation implied the existence of a large amount of unobserved mass. At the time the accuracy and completeness of extragalactic observations, and the application of the Virial theorem to those observations, were questioned. However, Newton's law of gravitation was assumed to be the dominant force of interaction between galaxies in clusters of galaxies. The assumption was considered valid despite the fact that no one had been able to test the law of interaction across extragalactic distances. The implication of Zwicky's observations led him to predict the presence of dark matter. However, that was not the first time that unseen matter had been detected.

Unseen objects had been detected indirectly before. The first followed William Herschel's (1738-1822) discovery of Uranus in 1781. The observations of Uranus's orbital motion did not correspond to predictions made using the law of gravitation and the properties of the known planets. In 1846 Urbain Jean Joseph Leverrier (1811-1877) and John Couch Adams (1819-1892) independently predicted the position of the planet Neptune, which led to its observation by Johann Gottfried Galle (1812-1910). Some

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[13]Smith, 1936.

astronomers held serious doubts about Newtonian gravity during the 60-year period between observation of the perturbations in Uranus' orbit and the discovery of Neptune.[15,16] In the end, the observation of the eighth planet was a triumph for Newtonian gravity.

Just before Neptune was discovered, Friedrich Wilhelm Bessel (1784-1846) observed perturbations in the proper motions of Sirius (in 1834) and Procyon (in 1840). In 1844 he hypothesized that dim companions caused the variations, and later Alvin G. Clark (1832-1897) observed Sirius B in 1862 and J. M. Schaeberle observed Procyon's white dwarf companion in 1896.[17]

The situations outlined above entail the detection of unseen matter, and since that matter was observed later, each situation was essentially a success for Newtonian gravitational theory. The anomaly with Mercury's precession, however, would not be solved by the observation of a nearby dim object. The precession of the point of perihelion in Mercury's orbit had been observed to be 5600 arcseconds per century, but considerations of the gravitational influence of other planets (notably Venus and Earth because of their proximity and Jupiter because of its mass) predicted a precession of only 5557 arcseconds per century, leaving an excess of 43 arcseconds per century. Leverrier was very much involved with the problem and was convinced that a new planet, called Vulcan, lay between Mercury and the Sun. The idea was accepted by many astronomers

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[14]The law of gravitation states that a force of attraction exists between two masses and it is inversely proportional to the square of the distance between them, i.e., $F = Gm_1m_2/r^2$.

[15]For more information on the discovery of Neptune, see Hanson, 1962; Grosser, 1962; and Smart, 1947.

[16]Smart points out that "it must be remembered that it was only about half a century after the publication of the *Principia* in 1687 that Newtonian theory succeeded in overcoming the almost general hostility of continental scientists, among whom were such redoutable opponents as Huygens, Leibnitz, John Bernoulli, Cassini, and Miraldi." He also says "the discrepancies in the motion of Uranus, unmistakable from 1826 onwards, raised again doubts as to the efficacy of the Newtonian law." Smart 1947, p. 6-7.

and, in fact, many sightings of the Vulcan were reported. The reported observations, however, were proven false and an alternative (improved) theory of gravitation was required to solve the discrepancy.[18] The general theory of relativity predicted that the major axis of an elliptical orbit of a planet rotates in its own plane in the same direction as the orbital motion. For Mercury the speed of the perihelial advance was predicted to be 43 arcseconds per century, in excellent agreement with observation.[19]

A discrepancy between dynamical and luminous mass was also found in the Milky Way. Jan Hendrik Oort (1900-1992) studied the dynamics of stars in the solar neighbourhood.[20] He had begun working on galactic dynamics under Jacobus Cornelius Kapteyn (1851-1922) as a graduate student. He was midway through his thesis research when Kapteyn died, and he inherited Kapteyn's notes and observations. Oort examined the masses and velocities of stars in the Galaxy, and tested for dynamical equilibrium. He published two articles in 1927 and 1932, in which he explained that the total mass of the stars in the solar neighbourhood was not enough to account for their radial velocities.[21] The observations outlined in his 1927 article showed that the velocities of some stars exceeded the escape velocity of the Galaxy. It was the first indication that either the Galaxy was not in dynamical equilibrium or that the mass causing the motion of the stars was 200 times greater than that estimated by direct observation. After Oort's publication in 1932, most astronomers were convinced that there was something amiss. I did not find any evidence that Newton's laws were brought into question then. It was

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[17]For more information on Sirius and Procyon and the discovery of their companions, see Schaeberle, 1896; Israel, 1987; and Aitken, 1964.

[18]The theory of general relativity improved Newtonian gravitation by noting that the force of gravity travels at the finite speed of light and that it was not instantaneous.

[19]For more information, see Baum and Sheehan, 1997; Hanson, 1962; and Roseveare, 1982.

[20]Further information on Oort's life and his work can be found in van Woerden, Brouw & van de Hulst, 1980.

perhaps a lesson learned, because it was now assumed that additional matter would be uncovered when observations could be extended to fainter stars.

Newton's law of gravitational interaction was derived from motions in the Solar System. However, it was an open question whether the mathematical form of the law was the same at much larger distances. Whereas the Sun is at a distance of 1 AU, the outskirts of the Solar System extend to about 40 AU, the centre of the Milky Way is 10^9 AU from the Solar System, and the Coma cluster has a linear diameter of 10^{12} AU.[22] In 1937 Zwicky made the first attempt to verify the law of interaction within clusters of galaxies.[23] He acknowledged (in a paper focused on the validity of Newton's law of gravitation) that, although "it would seem obvious" that the forces acting within galaxies and clusters of galaxies are "identical with the gravitational forces operating between the various components of the solar system, little or nothing has been done to prove the strict validity of this assertion."[24]

Zwicky noted that two observations could be useful in testing the law of interaction in clusters of galaxies: (1) the instantaneous spatial distribution of galaxies, and (2) the distribution of the galaxies in radial velocity via the Virial theorem[25] (See Appendix A). However, he claimed that one could not effectively apply the latter because the average galaxy mass was much too uncertain. To test the law of interaction with the Virial theorem, reasonable estimates of mean galaxy mass (e.g. the luminous mass) are compared to the mean galaxy (dynamical) mass calculated with the

[21]Oort, 1927 and 1932.
[22]An AU is a distance measure called an astronomical unit and is the distance from the Earth to the Sun. It is equal to 1.4960×10^{11} metres.
[23]Zwicky, 1937a, p. 234.
[24]Zwicky, 1942e, p. 555.
[25]Zwicky, 1942e, p. 555.

theorem(found by dividing the cluster mass by the number of members). However, mean galaxy mass estimates were not reliable and Zwicky dismissed that test.

Thus, he used the former test. He looked at the spatial distribution of galaxies within a cluster. Whereas a "swarm" of galaxies in a statistically stationary state would be spherically symmetric, the mathematical form of the law of interaction would determine the radial distribution. If the law of interaction *were* Newton's law of gravitation, then this radial distribution would imitate Emden's distribution for a bounded isothermal gas sphere.[26] Zwicky had found that many clusters, e.g., Coma, Hydra, Pegasus, Cancer, Perseus, and Fornax, possessed spherical symmetry and radial distributions identical to those suggested by Emden. Thus, he claimed, gravitation was universal, in the sense that the inverse square law was applicable across extragalactic distances. Although he could not perform the test involving the Virial theorem, Zwicky justified the application of the Virial theorem in his 1933 and 1937 studies of the Coma cluster with the success of the spatial distribution test.[27] That was the only attempt to validate Newton's laws at extragalactic distances until 1963, when Arrigo Finzi proposed that the attraction between bodies at long distances is greater than Newton's law predicts.[28]

Although the general theory of relativity had been introduced in 1916, it appears that Newton's law of gravitation stood on fairly firm ground at the beginning of the twentieth century, if the perturbations of Uranus, Sirius, and Procyon are any example. It would follow that the dark matter revealed when Oort and Zwicky applied standard

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[26]Zwicky, 1942e, p. 556-557 and 1942d, p. 495-496. Robert Emden determined the radial distribution of a statistically stable isothermal gas sphere in which the mean free paths are small compared to the total dimensions of the sphere. Zwicky refers to R. Emden, *Gaskugeln*, Leipzig: Teubner, 1907.
[27]Zwicky, 1937a and 1942e.

Newtonian gravitation to the Solar neighbourhood and to the Coma cluster might be revealed with advances in observing techniques. However, that did not happen. Zwicky's observation of a mass discrepancy on an extragalactic scale was made in an era when the extragalactic universe was not well understood.

C. *Astronomy at the Beginning of the Twentieth Century*

i. *Big Science and Developments in Instrumentation*

Sociological and political movements have direct impact on the approach and direction taken in scientific research. Thus it is important to illustrate some of the events that affected astronomy in the first three decades of the twentieth century. This will establish the context of Zwicky's discovery, and hence clarify the challenges and attitudes that confronted him and his colleagues. The goals of scientific research at that time encompassed both pure and applied demands.[29] The duality of scientific purpose was caused in part by the technological demands of the two world wars. Allegedly, until the beginning of World War II, "astronomy was the purest of sciences, almost devoid of practical application."[30] With the encroachment of international instability all funding, and thus all projects, were contingent on their utility to the war effort. This utilitarian demand stimulated work on numerous projects that made technological contributions not only to the war but also to applied scientific research and to everyday needs.

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[28]Finzi, 1963.
[29]Scientists have long debated the positive and negative effects of the branching of science into pure and applied objectives. As early as 1899 Henry A. Rowland (1848-1901), designer of spectroscopic gratings that allowed the mapping of the solar spectrum in the 1890s, claimed that Americans were confusing mechanical invention with pure science. Mendelsohn, 1966, p. 580.
[30]Struve and Zebergs, 1962, p. 17.

The practical purposes of physical science had been highlighted in many popular science magazines.[31] Otto Struve (1897-1963) and Velta Zebergs have attributed the building of the great observatories to the rise of capitalism and personal wealth in the Western world.[32] One of the great astronomers of the era was the eloquent George Ellery Hale (1868-1938), whose compelling words and actions procured private funds for the construction of three great telescopes.[33] Hale used the duality of research goals to help him obtain private funding for pure science. That is, the appeal to the public with hopes of an improved future aided his search for funding for the large telescopes he would build. In a 1928 publication appealing to the readership of *Harper's Monthly Magazine*, he quoted John Carty, who summed up the link between the pure and the humanitarian:

> "The pure scientists are the advance guard of civilization. By their discoveries, they furnish to the engineer and industrial chemist and other applied scientists the raw material to be elaborated into manifold agencies for the amelioration of the conditions of mankind."[34]

Effectively, the connection between pure and applied science was used to achieve leaps in astronomical instrumentation and observing capabilities.

The state of astronomy is dependent on the capabilities of observation. In 1897 the 40-inch refractor at Yerkes Observatory in Wisconsin defined the limit of telescope-building technology. It was the world's largest refracting telescope, and it was built while Hale was director of Yerkes Observatory. Astronomers of the twentieth century brought the reflecting telescope fully into use, in order to reach beyond the limit of

[31]See Showalter, 1925 and Colton, 1939.
[32]Struve and Zebergs, 1962, p. 19 - 23.
[33]Hale, 1928a and 1928b.
[34]Hale, 1928a, p. 243.

telescope size defined by the 40-inch refractor. Hale's fundraising and organizational abilities made possible the construction of the first great reflecting telescopes in the United States at Mount Wilson (formed in 1904 as a solar observatory) and Palomar (1936) Observatories. The great reflectors included the 100-inch Hooker telescope, which was in use at Mount Wilson Observatory in 1919, and the 200-inch Hale telescope, which was dedicated in 1948.

Mount Wilson, a research institute not connected with any university but funded by the Carnegie Institution, was considered the "Mecca of astrophysics." The Mount Wilson (Solar) Observatory's 60-inch telescope became the model for a generation of reflecting telescopes used to observe galaxies. The construction of large mirrors proved the "most crucial technical obstacle to the proliferation of very large telescopes."[35] Nonetheless, Hale did not waste any time before pursuing the bigger and better telescopes that would benefit astronomy. Before the 60-inch telescope had been completed in 1912, Hale was collecting funds for a 100-inch telescope. Hale resigned his position as director of Mount Wilson in 1923 (for health reasons), but immediately began organizing the construction of a 200-inch telescope. It was to be built on Mount Palomar, since urban development in Los Angeles had created too much light pollution to consider placing the new telescope on Mount Wilson. The congregation of scientists building and pursuing research at those observatories exemplifies what is called big science: big instruments, big projects, and big groups of researchers in collaboration.[36]

The development of big telescopes was not the only technological advancement to influence the direction of twentieth-century astronomy. Among the new instruments was

[35]van Heldon, 1984, p. 147.
[36]Weinberg, 1961; Price, 1963.

the Schmidt telescope, invented by Bernhard Voldemar Schmidt (1879-1935) in 1930.[37] It has been rated among the most important advances in optics,[38] and was vital to Zwicky's astronomical successes, because it facilitated his observations of clusters of galaxies. The Mount Wilson Observatory shops developed the 18-inch × 26-inch f/2 (1936) and the 48-inch × 72-inch f/2.44 (1948) telescopes that were installed at Palomar Mountain. It was with the former that Zwicky photographed large regions of the northern sky. That telescope had a field of view 9.5 degrees in diameter, and a limiting magnitude of 17.5 was reached in exposures of about forty minutes. Zwicky became a master of the Schmidt telescope, and even claimed that only two people ever knew how to properly use a small telescope — Galileo and himself.[39]

Spectroscopy and photography increased the rate at which data flowed from the telescopes: data that would lead to further knowledge about the structure of stars and of galaxies and galaxy clusters. At the end of the nineteenth century the physical laws came to be applied to all scientific disciplines, giving birth to such sub-disciplines as biophysics, geophysics, and astrophysics. The introduction of physics to astronomy

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[37] Schmidt found that combining the prime features of the refractor and reflector telescope could provide images free of coma and spherical aberration, these being the nemeses of large mirrors in the era of big science and big reflecting telescopes. A parabolic mirror has a limited field of view because of the optical aberration called coma, which is caused by axial symmetry of the mirror. The coma increases in direct proportion to the diameter of the field, limiting field size. A spherical mirror, on the other hand, does not have an axis of symmetry, but suffers from spherical aberration. Thus the Schmidt telescope was developed to minimize these effects by placing a glass corrector plate perpendicular to the optical axis at the centre of curvature of the concave spherical primary mirror. The corrector plate varied in thickness with distance from the optical axis to modify the path of the incoming rays, and thus compensated for spherical aberration. The spherical primary mirror was free of coma and the corrector plate, smaller in diameter than the mirror (both diameters are used in naming the telescope), was curved to reduce spherical aberration. Schmidt showed that aberrations could be kept small over a much larger field than provided by other optical designs. Thus huge areas of sky could be photographed at a time. See Fehrenbach, 1984; Harrington, 1952; King, 1955; Minkowski, 1972; and Schmidt, 1960.

[38] The 1930 version of the Schmidt was modified in later years to further improve the instrument. For example, in 1942 Maksutov and Bouwers independently suggested replacing the corrector plate with a spherically surfaced meniscus lens.

[39] Bartusiak, 1993, p. 193.

permitted an enrichment of the theoretical aspect of the subject.[40] Spectroscopy was important in the development of astrophysics, as it linked observational astronomy with physics, as well as chemistry. William Huggins (1824-1910) and Henry Draper (1837-1882) had developed stellar spectroscopy at the end of the nineteenth century. The first spectra of spiral galaxies were obtained in 1912. Initially, spectra were obtained by passing the light from a star through a prism. Prisms had drawbacks, however; for example, the dispersion was non-linear[41] and short wavelengths were absorbed by the glass. In 1931 Paul Merrill (1887-1961) at Mount Wilson built a grating spectrograph, which was largely free of those drawbacks.[42] By the mid-1940s gratings, rather than prisms, were being used to record astronomical spectra. Spectra were essential for radial velocity measurements; what was actually measured was the Doppler shifting of the spectral lines.[43] Spectra were not easily obtained and the absolute Doppler displacements were small, making measurements difficult. In 1933 spectra of very distant galaxies were only obtained with a minimum of fifty hours of exposure time. However, the improvement of photographic methods and emulsion sensitivity *did* facilitate recording of the spectra and the direct images, which revealed the presence of new celestial objects. The use of photographic plates was vital in understanding the Galaxy and what lay beyond it.

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[40]Meadows, 1984.

[41]That is, a constant increment in millimetres along the spectrogram corresponds to a variable change in the wavelength of the recorded light.

[42]Bowen, 1962, p. 58. The grating spectrograph had been invented in 1899 by Henry Rowland.

[43]Johann Christian Doppler (1803-1853) first observed the Doppler-effect in 1842. The relationship between the spectral displacement and radial velocity is, $\Delta\lambda / \lambda_{rest} = v_r / c$, where $\Delta\lambda$ is the difference between observed and rest wavelengths λ_{rest}, v_r is the radial velocity, and c is the speed of light.

ii. Extragalactic Astronomy

Prior to 1924 many astronomers considered all celestial bodies to lie within the reaches of our Galaxy. The notion of other galaxies like the Milky Way was somewhat whimsical, perhaps comparable to the notion of extra-terrestrial life. Immanuel Kant (1724-1804) speculated in 1755 that a variety of diffuse objects (collectively called "nebulae" by early astronomers) were island universes. The same objects, often mistaken for comets until it was revealed that they did not move among the stars, were observed and catalogued by Charles Messier (1730-1817). William Herschel and his son John Herschel (1792-1871) postulated that nebulae were clusters of stars. Although the objects were commonly recognized in the night sky, their distances could only be crudely estimated and many believed that they lay within the Milky Way system.

The first method of accurately determining distances to galaxies, through the use of the period-luminosity relation for Cepheid variable stars, was established by Henrietta Leavitt (1868-1921) in 1912. It was the observation of Cepheid variables with the 100-inch telescope on Mount Wilson that allowed Edwin Powell Hubble (1889-1953) to prove that at least some nebulae were extragalactic systems. At the American Astronomical Society meeting of 1924, Hubble announced that M31, M33, and NGC 6822 lay at distances that clearly placed them outside the Milky Way.[44]

The intrinsic brightness of Cepheids limited their observation to galaxies at distances less than several million light years. Other distance indicators were necessary to map more remote objects. They eventually included redshifts, the statistics of the brightest stars in galaxies, novae, and irregular variables. But in the first years of

[44]His results were published in numerous articles including, Hubble, 1925.

extragalactic observations, the distance indicators listed here were yet to be refined, and in 1933 approximate distances of only about 60 galaxies were known.

iii. Galaxy Masses

Distances were not the only fundamental problem to trouble extragalactic astronomers in the early twentieth century; mass determination caused difficulties as well. Four methods were used to determine galaxy masses. The internal rotational motions of a galaxy could be used for the purpose; Ernst Julius Oepik (1893-1985) first attempted it in 1922 and found the mass of M31 to be 4.5×10^9 solar masses.[45] A second method involved determining the mass implied from a "suitable" mass-luminosity ratio, as Hubble demonstrated in 1934.[46] Hubble looked at M31, M33, and NGC 4594, and assigned them mass-to-luminosity ratios ranging from 5 to 15. He found a mean galaxy mass of 6×10^8 solar masses, which he rounded up to 10^9 solar masses.[47] Thirdly, mass could be determined from the orbital motions of binary galaxies. The method was first proposed and used by Erik Holmberg in 1937.[48] Lastly, by analyzing the velocities of galaxies in clusters of galaxies using the Virial theorem, the mass of a cluster could be found. Dividing the result by the estimated number of galaxies in the cluster yielded an average (dynamical) galaxy mass.

In the collection of his lectures titled *The Realm of the Nebulae* published in 1936, Hubble discussed only the determination of galaxy mass from internal rotation, and also from simple mechanics (in which the velocity of escape determined the gravitational

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[45]Oepik, 1922.
[46]Hubble, 1934.
[47]Hubble, 1934, p. 75.
[48]Holmberg, 1937.

field) that Smith had used in his 1936 article on the Virgo cluster.[49] Although, he did not discuss it in his own publication on extragalactic astronomy, Hubble's estimate of 10^9 solar masses for the mean galaxy mass was readily accepted. It was used by the astronomical community despite (or perhaps because of) the preliminary state of galaxy mass measurements — a prime example of the influence that he exerted within the community.

D. Prospectus

Fritz Zwicky postulated the existence of non-luminous matter in the Coma cluster in 1933.[50] That was followed by a study of the Virgo cluster by Sinclair Smith and a second study by Zwicky on the clusters of galaxies in 1937.[51],[52] That much is clear, but the history traced in modern reviews leaves a gap between the initial recognition of the discrepancy and the work of Vera Rubin, Jeremiah Ostriker and James Peebles in the 1970s, which established that "dark matter" *does* exist in the universe. Why was so little published between the three papers of the 1930s and those of the 1970s? Not unlike many scientific problems, the history is convoluted, and one might ask, as I do: what was the *actual* sequence of events? How did Zwicky unveil one of today's leading astronomical mysteries? To examine these questions I will consider who Fritz Zwicky was, how he came to discover the need for "dark matter," and the response to his discovery. Chapter Two will trace the details of Zwicky's life and accomplishments. A comprehensive biography of Fritz Zwicky is lacking, and my aim is to provide an outline

[49]Hubble, 1936a, p. 178-181.
[50]Zwicky, 1933a.
[51]Smith, 1936.
[52]Zwicky, 1937a.

of his life.[53] Zwicky was well known for his eccentric character and so a study of his person is important in understanding why his discovery was not immediately influential in extragalactic astronomy. Chapter Three will look at his discovery. His 1933 and 1937 studies of the Coma cluster will be examined, along with Sinclair Smith's 1936 study of the Virgo cluster.[54] Chapter Four will review the attention given to the problem of extragalactic dynamics in the 1940s, 1950s and 1960s. Chapter Five will provide conclusions concerning Zwicky's role in the early history of the dark matter problem.

[53]Roland Muller has written a biography of Zwicky, but it has never been translated into English. Roland Muller, 1986, *Fritz Zwicky — Leben und Werk des grossen Schweizer Astrophysikers, Faketenforschers und Morphologen*, Glarus: Baeschlin.
[54]Zwicky, 1933a and 1937a; Smith, 1936.

Chapter 2
Fritz Zwicky: Conqueror of High Peaks

> *"The history of science cannot be limited to the development of ideas — to a similar extent it must be concerned with human beings, their peculiarities and talents, and their dependence on the social conditions of their country and time."*[1]
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> *"The life and work of pioneers in science are very important for progress in science and their biographies are a significant part of the history of science."*[1]
>
> Sergei Vavilov

A. Who was Fritz Zwicky? A Short Biography[2]

In 1933 *The New York Times* identified Fritz Zwicky as "a name not yet known by newspaper readers."[3] The statement suggested that one day he would be well known, and in fact, Zwicky *did* become an accomplished scientist and person. I will discuss his life and the circumstances of his more prominent discoveries to demonstrate the role he played in the astronomical community. Zwicky was of eccentric character and several of his theories were very much before their time. His virtuosity had not been readily recognizable. The astronomical community had not been prepared to deal with, or accept his hypotheses because they could not always follow his reasoning. His style of public speech may exemplify how he might not have been understood; it was "full of

[1]Quoted in Sharov and Novikov, 1993, p. xiii.
[2]The biographical information has been compiled primarily from the following sources: Adams, 1947; Arp, 1974; Asimov, 1964; Bartusiak, 1993; Goodstein, 1991; Greenstein, 1974; Hoyle, 1972; Hufbauer, 1990; Kargon, 1977; Knill, 1998; Krauss, 1989; Lageman, 1949; Payne-Gaposchkin, 1974; Rubin, 1997; Trimble, 1992 & 1993b; White, 1946; Wild, 1989; Wilson, 1974 & 1975; as well as Zwicky's own publications.

picturesque, spicy, strong expressions, sometimes cryptic even to those who knew him and the matter he treated. And in the desire to tell as much as possible in a short time, he sometimes made terrific condensations and abbreviations."[4] Zwicky's coarse attitude did not facilitate the delivery of his arguments; perhaps it even dissuaded his colleagues from attempting to examine what he was saying. He has become a legendary figure, as people of eccentric character often do, disguised by the tales of his tempestuous and often preposterous nature.[5]

Zwicky spread his interests over a myriad of disciplines: astronomy, physics, rocketry, jet propulsion, philosophy, humanitarism, and mountain climbing. He was curious and explored the unknown without restraint, striving "to find all the possible answers and solutions."[6] He was committed to science and to the betterment of society. He was an active participant in numerous academic and charitable organizations, including the American Physical Society, the Swiss Physical Society, and the American Astronomical Society. He was also the founder and the chair of the Committee for Aid to War-Stricken Scientific Libraries, a trustee and the president of the American branch of the Pestalozzi Foundation for aid to orphanages, the vice-president of the International Academy of Astronautics, and the founder and the president of the Society for Morphological Research. He was the research director of Aerojet Engineering in Pasadena from 1943 until 1949 and a researcher for the corporation until 1961. He was a faculty member at the California Institute of Technology in the position of assistant professor of theoretical physics from 1927 until 1929, associate professor of astronomy

[3]Kaempffert, 1933.
[4]Wild, 1989, p. 396.
[5]Wild warns of journalists "slandering Zwicky as kind of an ugly monster," claiming that "Nobody ever doubted Zwicky's moral integrity. His sharpest weapon was his abusive language." Wild, 1989, p. 396.

from 1929 until 1942, and professor of astrophysics from 1942 until his retirement in 1968. He was an observer at Palomar Observatory, which was operated by Caltech, and upon the merging of Mount Wilson and Palomar Observatories in April 1948, he was appointed astronomer at the two observatories. He was also a participant in literature seminars held at Caltech.[7] He received the Presidential Medal of Freedom from Harry Truman for his contributions to the Air Force in 1949, the Pestalozzi Foundation's gold medal in 1955, and the Gold Medal of the Royal Astronomical Society in 1973.

Fritz Zwicky was born in Varna, Bulgaria on February 14, 1898 to Fridolin and Franziska (Wrcek) Zwicky. He spent his school years in Glarus, Switzerland with his grandparents. He studied engineering, mathematics and physics at the Federal Institute of Technology in Zurich, Switzerland, obtaining his Ph.D. on ionic crystals under Paul Scherrer (1890-1969) and Peter Debye (1884-1966) in 1922.[8] Following the completion of his studies, he worked with Scherrer and Debye in Zurich for three years. Zwicky was ready to move on just as American science began to draw European scientists in an "intellectual migration."[9] The internationalization of science led the United States into a major role in the scientific world. Between 1924 and 1930, post-doctoral fellowships from the International Education Board of the Rockefeller Foundation were granted to 135 European physicists, a prelude to the 1800 scientists who flocked to North America

[6]Wilson, 1975, p. 107

[7]Zwicky was a regular participant in English professor Clinton Judy's graduate seminar in literature, which attracted a remarkable cross-section of the Caltech community. The topics of discussion were diverse and included the influence of scientific ideas on literature, the philosophy of John Dewey, practical applications of science, Nietzsche, and genetics. Goodstein, 1991, p. 141.

[8]Zwicky, 1922.

[9]I do not wish to imply that this was a transient movement. Scientists still migrate to the United States. However, when Adolf Hitler was appointed State Chancellor and the reign of National Socialism began in Germany, terror and harassement caused thousands of Jewish people to emigrate. Jewish scientists were expelled from German and Austrian universities, but were welcome in the United States. Mendelsohn, 1966, p. 582.

between 1933 and 1938.[10] Fritz Zwicky was one of those migrant physicists, having obtained a Rockefeller postdoctoral fellowship in 1925. He came to North America at the age of 27 to work with Robert A. Millikan (1868-1953) and Paul Epstein on the equations of state for gases, liquids, and solids,[11] and although he resided in the United States until his death in 1974, he maintained his Swiss citizenship.[12]

B. Zwicky's Switch from Physics to Astronomy

The timing of Fritz Zwicky's arrival at Caltech was crucial to his future endeavours. Although he was a physicist, he quickly became wrapped up in Millikan's research on cosmic rays, Hubble's work on the distance-redshift relation, and Hale's realization of a 200-inch telescope on Mount Palomar. He was essentially at the right place at the right time. His arrival coincided nicely (and unexpectedly) with the decision that the 200-inch telescope was to be associated with Caltech. Zwicky's opportunity to have access to what would be the largest telescope in the world was not something that he would pass up. He, Sinclair Smith,[13] and John Strong,[14] all staff members of the Caltech physics department, shifted their interests to astronomy and astrophysics.[15]

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[10]Wiener, 1969, p. 196.

[11]Millikan was the head of the California Institute of Technology at the time. Although Amos G. Throop founded the school in 1891, Millikan essentially acted as the founder of the school. He built up a first-rate physics faculty, inviting prominent and promising physicists to join the staff or to deliver lecture series. Zwicky and Epstein were both recruited by him. Goodstein, 1991.

[12] Zwicky kept his Swiss citizenship throughout his whole life, claiming that naturalised citizens were treated like *"second-class"* citizens and were *"subject to special rules."* (*Time*, 1955, p.67 and *Aviation Week*, 1955, p. 14.) Zwicky was not required to contribute to the efforts of the U.S. military, nor to the Swiss military, during the Second World War. Baade, of German citizenship, spent his time during the war observing at Mount Wilson, taking advantage of Los Angeles' many black outs. American scientists however were not so free in their pursuits. See *Science News Letters*, 1941.

[13]Sinclair Smith had followed up on Zwicky's 1933 publication with a study of the Virgo cluster in 1936. the article will be discussed in Chapter 4.

[14]John Strong concentrated his research on planetary astronomy.

[15]Zwicky, 1971b, p. 325.

Zwicky's first astrophysical publication appeared in 1928 and was titled *Thermodynamic Equilibrium of the Universe.*[16] It was the common opinion that the universe was "far from a state of thermodynamic equilibrium and running down irrevocably toward a state of highest entropy."[17] Zwicky attempted to show that thermodynamic equilibrium could be demonstrated if all mass-energy reactions were considered. Without going into the details of the paper, I can point out a result of his statistical calculation that will be mentioned later: vapour pressure, he argued, would cause intergalactic dust to evaporate so that matter would "exist either in the gaseous form or else concentrated in stars only."[18]

Zwicky's switch into astronomy and astrophysics from physics contributed to his creative endeavours. He was a very successful astronomer and astrophysicist.[19] He did not have a "classical" astronomical training, and thus had a clear and fresh perspective that is perhaps necessary to see what has not been seen before. It should be noted that a fresh approach to astronomical research would most likely have differed from the approaches of his colleagues and it might not have been acceptable to the more conservative among them.

[16]Zwicky, 1928.
[17]Zwicky, 1928, p. 592. Zwicky referred to Jeans, *Nature*, April 28, 1928 for more details.
[18]Zwicky, 1928, p. 596. He did not consider his statistical treatment to be complete and suggested that the problem be reconsidered "on a broader basis."
[19]Note that his success was not recognized in his time. "In the 1930s and 1940s, many of Fritz Zwicky's colleagues regarded him as an irritating buffoon. Future generations of astronomers would look back on him as a creative genius." Thorne, 1994, p. 164.

C. Zwicky's Contribution to Two Great Dilemmas: Redshift and Cosmic Rays

i. Redshift

In 1915 Albert Einstein (1879-1955) had found that the general theory of relativity implied that the universe must collapse. There had been no observational evidence of contraction or expansion, so as he believed the universe to be stationary Einstein introduced the cosmological constant, Λ, as a means to counteract the destabilizing influence of gravity.[20] He later called the insertion of the cosmological constant his greatest blunder. In 1917 Vesto Melvin Slipher (1875-1969) first observed the Doppler-like shifts toward longer wavelengths in the spectra of galaxies that would be later called redshifts. The fact that the spectral lines shifted toward longer wavelengths implied that the body producing them was moving away from the observer. (A blueshift is produced when the spectral lines of an object are shifted towards shorter wavelengths and implies motion toward the observer.) The early years of extragalactic astronomy saw many astronomers attempting to explain why the great majority of objects were moving away from us. In 1929 Hubble found a linear relation between redshift and distance such that a galaxy with a recessional velocity of 500 km s^{-1} was at a distance of a million parsecs.[21] The direct implication of the relationship was that the universe was expanding. Following Hubble's 1929 publication, there were numerous attempts to both verify the linear relation and to give some other explanation.

[20]The cosmological constant corresponded to an additional force which was repulsive over large distances. When it was found that the universe was expanding the need for the cosmological constant disappeared.
[21]Hubble, 1929. Note that the Hubble constant is presently estimated to be less than 100 km s^{-1} per megaparsec.

Zwicky was among several astronomers not convinced by Hubble's arguments, and he published two articles on the subject in 1929.[22] He proposed that two physical explanations could account for the redshift of spectral lines: (1) the Compton-Doppler effect on free electrons, and (2) the gravitational "drag" of light. Zwicky explained that the Compton effect could shift the spectrum of a distant light source, because the free electrons in interstellar space would scatter the incoming photons, the photons would lose energy to free electrons, and since energy E and frequency ν are directly related ($E = h\nu$, where h is Planck's constant) a shift to lower frequencies of the light would be observed.[23,24] However, the idea was dismissed because the number of collisions necessary to shift the wavelength to the extent observed in galaxy spectra would result in light scattering in all directions, such that interstellar space would be opaque. Alternatively, the gravitational "drag" of light was consistent with redshift observations.[25] Because a photon has gravitational mass given by $m = h\nu c^{-1}$, where c is the speed of light, the wavelength of a photon would be altered when it interacted gravitationally with a massive body, and as a consequence, it would transfer momentum and energy to the body. In his article, Zwicky suggested that further investigation would be worthwhile.

Zwicky also outlined three observations for determining whether redshifts were tied to the geometry of an expanding universe, as Hubble had suggested, or to the physical explanations that he, Zwicky, had put forth. Those observations were: (1) a dependency of redshift on direction, especially within the Milky Way; (2) variations in

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[22]Zwicky, 1929a & b.
[23]A. H. Compton (1892-1962) first observed the Compton effect in 1923.
[24]Zwicky deduced the presence of free electrons in interstellar space from observations of Ca II absorption lines. The presence of ions in interstellar space necessitated the presence of free electrons. Zwicky, 1929a, p. 774.
[25]Zwicky called this "a sort of gravitational analogue to the Compton effect." Zwicky, 1929a, p. 773.

redshifts of galaxies within a cluster (larger than the variation caused by the peculiar motions of the galaxies); or (3) a difference in the redshift from the far and near edges of an inclined galaxy.[26] Furthermore, Zwicky's exploration of the possible cause of the redshift was in some respects a critique of the relation proposed by Hubble. Zwicky had supported Richard Tolman's study of the discrepancies found in the redshift-distance relationship.[27] But his own ideas did not gain credibility. George Sweetnam has suggested that it was his questioning of the origin of redshifts that earned Zwicky his "maverick standing."[28]

ii. Cosmic Rays

Cosmic radiation was discovered accidentally at the turn of the century.[29] It appeared as an incredible energy penetrating ionisation chambers and affecting experiments measuring the conductivity of gases. The origin of cosmic rays was a mystery because they were not identifiable with any luminous source and because their energy was so incredibly high. Initially they were thought to be electromagnetic waves emanating from the Earth's crust. In 1913 Victor Hess (1883-1964) and W. Kolhoerster found that atmospheric ionisation did not increase as one moved closer to the Earth's surface but, in fact, increased in strength beyond 1500 meters above ground level, thus it was established that cosmic radiation was of extraterrestrial origin. The flux of the radiation did not alter between day and night or with the position of the Milky Way and

[26]Zwicky, 1929b.
[27]See Tolman, 1929.
[28]Sweetnam, 1997, p. 581.
[29]Jauneau, 1966; Sandström, 1965; Friedlander, 1989.

so it was determined that the rays were not of solar, and not likely, of stellar origin. The very penetrating charged particles were observed to have an energy of 10^9 GeV or more.

Zwicky referred to the creation of cosmic rays as "one of the darkest mysteries of modern science."[30] In his early years at Caltech, he had worked alongside Millikan, who had suggested that cosmic rays were interstellar, originating in "atom-building processes."[31] Zwicky contributed to the debate by suggesting that they were created in

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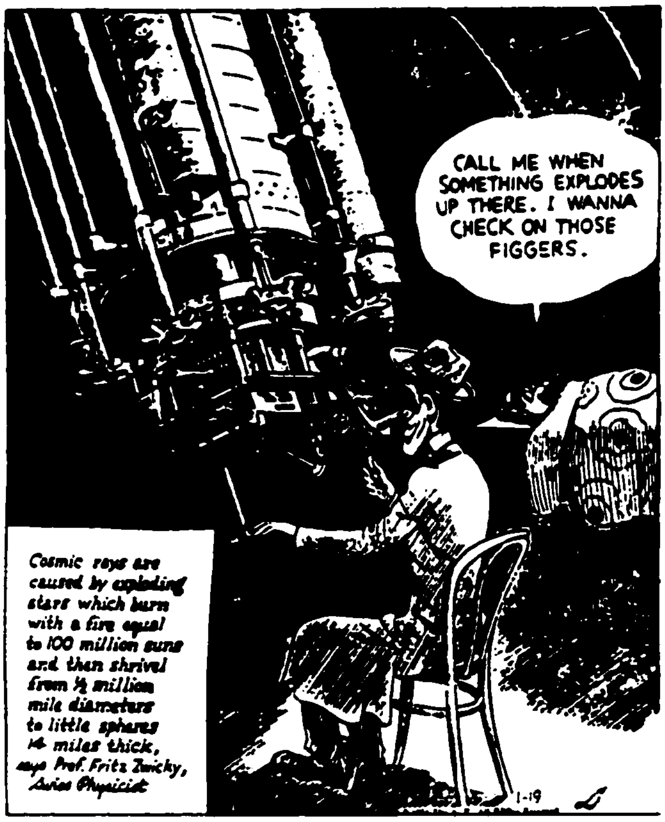

(Los Angeles Times, December 8, 1933)

supernovae explosions.[32,33] The suggestion was perceived as "probably the most daring theory of cosmic ray origin," and a *Los Angeles Times* comic titled "Ol' Doc Dabble"

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[30]Zwicky, 1934, p. 138.
[31]Millikan, 1931.
[32]Baade & Zwicky, 1934b.

was directed at the incredible nature of his cosmic ray, supernova, and neutron star theories. The statement wrapped up three of Zwicky's recent predictions: the origin of cosmic rays in supernovae, the size and luminosity of supernovae, and the association of supernova with neutron stars. Zwicky claimed it to be "one of the most concise triple predictions ever made in science."[34] His supernova and neutron star predictions *were* confirmed. The origin of cosmic rays in supernovae satisfied many of the facts known about the radiation, notably the high energies required to produce them, and the hypothesis was added to the list of the many possible sources of the radiation.[35]

D. Zwicky's Reputation

Zwicky classified scientists into two categories, eagles and low-fliers, placing himself in the latter, of course.[36] His self-esteem was renowned and it was considered intolerable by some of his colleagues; "Zwicky possessed that necessary concomitant of greatness, the generation in others of a strong positive or negative response... Those who see further or deeper are not universally admired."[37] Paul Wild recalled an argument in which Zwicky claimed, "I have been here since 25 years, and have argued with most of my colleagues, and was always right in the end. Now you just have come from Switzerland; don't imagine that you already have a good chance to win."[38] Wild continues, "All those who worked with Fritz Zwicky or near him have experienced memorable situations and utterances, but we must consider how easily the truth in a so-

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[33]Zwicky, 1933b.
[34]Zwicky, 1971a, p. xv.
[35]Baade and Zwicky, 1934b.
[36]Greenstein, 1974, p. 15.
[37]Wilson, 1974, p. 18.
[38]Wild, 1989, p. 396.

called "good story" gets exaggerated and distorted."[39] In any case, Zwicky's assertive character stirred in him the motivation to predict *and prove* new and sometimes incredible ideas. Zwicky persisted when he thought he was right, and is quoted to have muttered often, "I'll show those bastards."[40] In this section, I will illustrate Zwicky's strength as he stuck to his convictions. He must have had great self-confidence in standing up for his own work when it was in direct opposition to his colleagues.

i. Supernovae: The Melding of Theoretical and Observational Science

Interest in novae and supernovae rose at the close of the nineteenth century with observations of "nova" Andromeda 1885. Unlike most novae, it was observable with the naked eye. (In fact, it was a supernova, although the distinction between nova and supernova was not made until 1919.) It was recognized that the "nova" of 1885 differed from the others. In 1919, Knut Lundmark (1889-1958) estimated the distance of the Andromeda galaxy to be 200 kpc. Therefore, the absolute magnitude of the nova of 1885 at its brightest would be –15.[41] In contrast, ordinary novae had been observed to typically reach maximum absolute magnitudes of about –8. Lundmark proposed that two types of novae existed: ordinary novae, as well as rare stars that reach a luminosity a thousand times greater than that of the galaxies in which they are embedded (which would later be called supernovae).[42] The "nova" of 1885, as well as other bright objects in history, were classified in the latter category. However, Lundmark's ideas were not

[39]Wild, 1989, p. 396.
[40]Bartusiak, 1993, p. 196.
[41]Shklovsky, 1968, p. 1. Shklovsky referenced K. Lundmark. (1920) Svenska Vetenkapsakad. *Handlingar*. **60** No. 8.
[42]Ordinary novae at maximum, increase to about an absolute magnitude between –6.5 and –9 (although they are not limited to such a range), whereas supernovae, averaging an absolute magnitude of –17 or –19

immediately accepted, and the interpretation of the unusual brightness of the supernova of 1885 varied with opinions concerning the distance of M31. It was only in 1924 that Hubble established that M31 was external to the Milky Way. Harlow Shapley (1885-1972), for example, thought an object of absolute magnitude −15 to be "inconceivable" and used the argument in his 1920 debate with Heber Doust Curtis (1872-1942) on the distance scale of the universe.[43] Photography made further searches for novae feasible; by 1920 ten more had been observed and curiosity surrounded the temporarily bright objects.

The work of Lundmark impressed Zwicky and motivated him to find out what was actually happening. In the early 1930s Zwicky began referring to the bright novae as "super-novae."[44] By 1934 with a publication entitled "On Super-novae," the name had caught on (although the hyphen was dropped in 1938).[45] At the time only 12 supernovae had been observed, and it was generally believed that they were the result of the collision of two stars. Zwicky and Walter Baade (1893-1960), however, estimated the maximum brightness to be 63 million times the luminosity of the Sun, proposed that it was the final stage in the evolutionary process, and resulted in the creation of a neutron star.[46] Zwicky deduced that "the phenomenon of a super-nova represents the transition of an ordinary star into a body of considerably smaller mass," because the radiation emitted during the event would necessitate a great quantity of mass converted into energy.[47,48]

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at maximum brightness (Lundmark's estimate was not far from present accepted values), increase 10^5 times.

[43]Marschall, 1988, p. 100. For a full overview of the Shapley-Curtis Debate, see Trimble, 1995.

[44]Marschall, 1988, p. 101. Marschall also mentions that the terminology coincided with the appearance of Superman and was shortly followed by supermarkets and supersales.

[45]Baade and Zwicky, 1934a.

[46]Baade and Zwicky, 1934a; Zwicky, 1938c.

[47]Baade & Zwicky, 1934a, p. 258.

Observational data were scarce and there was almost no evidence for their ideas. In his book on supernovae, Laurence Marschall emphasized that, "Informed opinion, therefore, did not favour Baade and Zwicky... Based on the scarcity of supernova sightings at the time, Zwicky had little chance of success."[49]

In 1934 Zwicky began a search for supernovae with a 10-inch refractor he had purchased himself and mounted on the roof of the Astrophysics building at Caltech. In 1936 Millikan and Hale arranged for the 18-inch Schmidt telescope to be constructed on Palomar Mountain for the survey, and within four years of its completion Zwicky had used the telescope to discover eighteen supernovae, twelve of them in the first three years. *The New York Times* titled a short article on his success quite poetically, *Twelve Such Orbs Discovered in a Thousand Nights by California Astronomer.*[50] They ranged in brightness from 6 million to 600 million times the solar luminosity. Zwicky's observations demonstrated that on average one supernova per galaxy occurred every 430 years. He also found that plots of the variation in brightness with time (called light curves) exhibited two types of behaviour. The light curves characterized two types of supernovae, called Type I and II.[51] The photographic plates obtained for the supernova search focused on clusters of galaxies, which were "comfortably reached" (i.e. detected)

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[48]Zwicky's interpretation was incorrect. The mass loss in supernovae events are caused by the outer layers of the star being blown away. Supernovae are initiated by nuclear fusion and gravitational collapse.
[49]Marschall, 1988, p. 107.
[50]*The New York Times*, 1939, p. 40.
[51]Type I supernovae usually reach a maximum absolute magnitude of −19 and their magnitude declines smoothly over the period of one year. Type II supernovae reach a maximum absolute magnitude of −17 and their decline in brightness is step-like, as they have periods of gradual dimming and abrupt dimming. The phenomena of the two supernova are very different. Type II arise from the death of a massive star (exceeding eight solar masses) as nuclear reactions within the star come to an end and it collapses under its own gravity. Type Ia originate when a carbon-oxygen-rich white dwarf in a binary system receives enough mass from a companion to cause it to undergo runaway carbon burning in the core just before the Chandrasekhar limit of 1.4 solar masses is reached. The core is degenerate, pressure in the core cannot increase and it explodes (the inner shell is ejected at a relatively slow speed and the outer shell at a very high speed, $>10^4$ km s^{-1}) and the white dwarf disintegrates.

with the Schmidt and increased the likelihood of finding supernovae.[52] His search continued with the 48-inch Schmidt that was installed in 1948, and grew to involve fourteen observatories worldwide. At the time of his death, he had been working on a comprehensive catalogue of all known supernovae.

Initially, Zwicky's conviction that supernovae were giant exploding stars was not taken seriously, but he set forth to prove himself right, and eventually succeeded. It is one example of his ingenuity and competence in theoretical and observational astronomy, for which he gained much attention. *The New York Times* published updates of his supernova search on almost a monthly basis.[53] In 1934 he was featured in *Literary Digest's* "They Stand Out from the Crowd" column,[54] and in 1935 he gave a Science Service Radio Talk titled "Stellar Guests."[55] The spectacular appeal of such an unearthly phenomenon gained public interest, but the audience of importance was the astronomical community. Did his colleagues take his research more seriously after such success? I do not believe so. His supernova research remains one of his better known accomplishments, earning him a place in biographical dictionaries and encyclopaediae. But although he displayed incredible intuition and dedication, I do not think that his colleagues were convinced that his other ideas were legitimate. Dennis Overbye describes their lack of faith; "[he] had so many ideas it was almost impossible for other astronomers to sort the good from the off-the-wall."[56]

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[52]Zwicky, 1938b, p. 531.
[53]For example, Kaempffert, 1938.
[54]*Literary Digest*, 1934.
[55]Zwicky, 1935. The talk was named for the translation of the Chinese name for supernovae.

ii. Rocketry and Extraterrestrial Travel

While on a brief absence from astronomy during the Second World War, Zwicky contributed to the war effort by forming the Aerojet-General Corporation of Azusa, California, acting as a member of the Scientific Advisory Board of the Army Air Force and directing the development of JATO (Jet Assisted Take-Off) units, which were used to launch heavily-laden aircraft from short runways. After the war he continued to direct the development of rockets, missiles, torpedoes, and submarines, and acted as liaison to German and Japanese rocket experts for the Air Force. He also pursued a plan to launch "artificial meteors" into interplanetary space.[57]

Zwicky's aspirations for space research dated to 1928, which is when his interests were first turning to astronomy. He had stated, "First we throw a small slug into space, then a bigger one, then a shipload of instruments, and finally ourselves."[58] He envisioned an era when humans would alter the conditions of other planets so that they could be populated. Of particular interest is Zwicky's recognition of the advantages of observing, "without absorption, scattering, and other secondary disturbances due to the atmosphere."[59] His rocketry research was conducted for the most part in partnership with J. Cuneo, a patent attorney for Aerojet, with their own funds and on their own time.

His attempt to launch projectiles (copper, cone shaped objects) into space on December 17, 1946 gained much press coverage.[60] However, the rocket did not follow the anticipated trajectory and the launch was a failure. Unfortunately, scientists (including Fred Whipple, meteor and comet expert of Harvard University) reported to the

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[56]Overbye, 1991, p. 18.
[57]Zwicky, 1946.
[58]Zwicky, 1971b, p. 325.
[59]Zwicky, 1947, p. 64.

U.S. government that such activity should not be supported, and those types of launches were "blocked" for the subsequent eleven years.[61] It did not affect Zwicky's research, and he continued to solicit funding and opportunities from other sources, including the Board of Directors of 20th Century Fox Films.[62] He *claimed* to have launched the first human-made satellite into interplanetary space on October 16, 1957.[63] However, it was launched twelve days *after* the first Russian satellite *Sputnik*.[64] In any case, if his projectiles even entered space, his goal was largely achieved. His efforts stand as an example of Zwicky's tenacity. He set the goal of launching objects into space, a goal that others may have thought to be impossible without the support of large research teams or funding, and it was accomplished.

iii. The Morphological Outlook and Method

Zwicky held the view that science should be an initiator of humanitarian change and influence. He thought that an all-encompassing view of the world and its problems (which he called a "world image") could facilitate the advancement of science. As in his scientific research, when Zwicky was stirred, he acted. In an address to the Pestalozzi Foundation, Zwicky described what he set for himself,

> "After pursuing a dozen or so various activities ranging from mountain climbing and professional shorthand to physics, astronomy, engineering, languages, higher

[60]White, 1946, p. 15.
[61]Zwicky, 1971b, p. 330.
[62]His solicitations for funding reached the press, see *Newsweek*, 1953, p. 74.
[63]See Zwicky, 1971b, p. 332; Wild, 1988, p. 395. Zwicky claimed that the U. S. Air Force recorded data at the launch. However, he did not make reference to any military publication that might contain evidence of his success. Without such evidence, we cannot be certain that his projectiles obtained the necessary velocity to go into orbit.

education, national and international politics, and mutual aid with fair success, I still did not feel satisfied... It was difficult to account for the lack of satisfaction until it occurred to me that no stereotype activity in the books of the past corresponds to my personal genius. Its nature is such that it could become fully alive only through the creation of a new profession — the morphologist."[65]

He attempted to outline a method to ensure progress in the most beneficial directions with the utmost efficiency. He published two books and presented a variety of lectures to explain in great detail a methodology he called the morphological approach,[66] which was based on a Goethean theory of knowledge.[67] As Zwicky described it, the morphologist does not take any prior work for granted and does not consider the "conventional objections" because nothing is deemed impossible until it is clearly proven to be impossible, and aims at perfection and ultimate truths. Zwicky outlined a series of steps for confronting a problem that typify the morphological approach:

"1. The problem which is to be solved must be exactly formulated.

2. All of the parameters, which might enter into the solution of the given problem, must be localized and characterized.

3. The morphological box or multidimensional matrix, which contains all of the solutions of the given problem, is constructed.

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[64]Sputnik I was launched on October 4, 1957. It was the size of a basketball, weighed 183 pounds, and orbited the Earth in about 98 minutes. It was followed by Sputnik II on November 3, 1957, which carried a dog. See, for example, http://hq.nasa.gov/office/pao/History/sputnik/

[65]Wilson, 1974, p. 17.

[66]Zwicky, 1933c, 1948, 1957a, 1967b, and 1969.

[67]Johann Wolfgang von Goethe (1749-1832) formed the basis of a theory of knowledge which has been explicitly interpreted in several ways, the most widely known being that of Rudolf Steiner (1861-1925). It is a theory of knowledge that employs direct thinking and direct action, contrary to Immanuel Kant's theory, which is based upon the usage of paradigms. See Rudnicki, 1989.

4. All of the solutions, which are contained in the morphological box, are closely analysed and evaluated with respect to the purposes which are to be achieved.

5. The best solutions are selected and are carried out, provided that the necessary means are available. This practical application requires an additional morphological study."[68]

His morphological method was meant to be clear and efficient enough that "if a possibility exists, nature will carry it out and scientists should discover it."[69] He claimed to have used the approach in most of his own research.[70]

By convincing scientists to adopt such a methodology, Zwicky hoped eventually to "restore to man his sense of wonderment, which he has so largely lost through specialization and the complexity of his existence."[71] He also aimed to "eliminate all human aberration."[72] That Zwicky believed he could reform and improve all of science is another example of his sense of self-importance. His overconfidence came across as arrogance since he imposed, rather than proposed, his ideas, under the assumption that his reasoning was inherently understood.[73] Zwicky's egotistical manners surely acted against his appeal to have his astronomical predictions and hypotheses heard.

E. Summary

Zwicky was an intellectually motivated and inspired character. Those traits, along with his bold interpretation of astronomical observations, allowed him to predict

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[68]Zwicky, 1967b, p. 285.
[69]Bartusiak, 1993, p. 195.
[70]For descriptions and examples of the application of the approach, see Zwicky, 1948, 1967b and 1957a.
[71]Zwicky, 1957a, p. 30.
[72]Zwicky, 1967b, p. 295.
[73]This aspect of his personality is described by Wild, 1989, p. 395-396 and Marschall, 1988, p. 103.

the existence of unimaginable things like neutron stars, and to spread his knowledge over many astronomical questions in theory, observation, and instrumentation.

Despite his accomplishments, Zwicky's unwavering firmness caused some friction with his colleagues and students at Caltech. A mischievous group of undergraduate students, aided by graduate students and faculty members, once invented an undergraduate student named Helmar Scieite to be Zwicky's adversary. The fictitious student professed an unpronounceable name and achieved perfect scores on all assignments, two attributes which would have embarrassed Zwicky tremendously. Apparently, Zwicky did not keep close tabs on his students and he could not identify faces with the names on his class lists. When attendance was called there would always be another class member speaking for the non-existent Helmar, and graduate students would complete all his assignments and exams. The student earned an A in Zwicky's extremely difficult analytical mechanics course, and on the final exam made such comments as "This is a very stupid and trivial question — why waste examination time on such tripe? This problem is all worked out in—. Can't you think of anything new?"[74] Zwicky's reaction to the joke is a mystery. A series of letters was written to *Engineering and Science* magazine in 1974 recalling the incident, but no one could tell anything of Zwicky's side of the story, aside from Jesse Greenstein's recollection of "explosive events occurring in the Registrar's Office when Fritz wished to record his first perfect grade for a non-existent student."[75]

The anecdote illustrates the reaction of Zwicky's students and colleagues to his personality; he was not well received by all. However, despite his own ego, Zwicky

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[74]J. B. Hatcher in *Engineering and Science*, 1974, p. 31.
[75]Greenstein, 1974, p. 15.

thought that it was "important to unhorse the pompous," and as an example to his colleagues he would periodically clean the washrooms and encourage them to do the same.[76] It appears he played the part of an eccentric among his colleagues, perhaps even taking some pride in the label.

In his forty-one years at Caltech he discovered 122 supernovae, coined the name "supernova," predicted the existence of neutron stars and dwarf galaxies, related cosmic rays and neutron stars to supernovae, supported and advanced theories of gravitational lensing[77] and black holes,[78] and proposed and applied the "morphological approach." In all, he wrote 562 articles, 10 books, 2 catalogues,[79] and held some 50 patents. Zwicky strove to reach the highest peaks. He was hard working and a dedicated researcher. However, the great number of Zwicky's achievements have only been recognized since his death. In life, was Zwicky's genius recognized? He himself said, in his later years, "In contradistinction to the professional astronomers, who ignored my views for thirty years, the reporters kept going strong on supernovae, neutron stars, and cosmic rays, at least for a few years."[80]

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[76]Wilson, 1974, p. 18.
[77]Zwicky, 1937b and 1937c. His research is outlined in a very interesting article on the history of gravitational lensing by Renn and Sauer, 2000.
[78]Zwicky, 1971a, p. xv. He had his own term for black holes, "object Hades."
[79]Zwicky, Herzog & Wild, 1961 and Zwicky, 1971a.
[80]Zwicky, 1971a, p. xv.

Chapter 3
Fritz Zwicky's Discovery of Dark Matter

> *"Although in the 1920s I started out as professor of theoretical physics at the California Institute of Technology in Pasadena, I occupied myself, in addition to the physics of gases, liquids, and solids, with abstract astrophysical subjects. I soon became convinced, however, that all theorizing would be empty brain exercise and therefore a waste of time unless one first ascertained what the population of the universe really consists of, how its various members interact, and how they are distributed throughout cosmic space."*[1]
>
> Fritz Zwicky

A. ***Something Amiss in the Coma Cluster***

i. *The Discovery*

Zwicky's interest in redshift and his observations of supernovae led him into the study of clusters of galaxies. In the previous chapter, I mentioned that he had written two articles on the subject of redshift early in his career.[2] But he also published a third article, in which he performed a statistical survey of the Coma cluster based on spectra of nine galaxies.[3] As an aside to his study, Zwicky realized that the high dispersion observed in the radial velocities of the galaxies implied that the cluster was unstable. The radial velocities, induced by the gravitational forces within the cluster, provided a means to measure its mass. The Virial theorem was used for such an analysis. (For more details, see Appendix A.) The application of the theorem required three assumptions: that the interactions between galaxies were governed by Newton's law of gravitation; that the full

[1]Zwicky, 1971a, p. v.
[2]Zwicky, 1929a & 1929b.

radius of the cluster was observable and measurable; and most noteworthy, that the system was bound and in equilibrium. Consequent to his analysis, Zwicky speculated that a large quantity of dark matter, i.e., invisible, non-luminous matter, was necessary to explain the large dispersion of velocities.[4]

It was a startling suggestion on Zwicky's part; it had been wholly unexpected. What could it mean? In 1933 it did not appear to mean much. After all, it had only been eleven years since Kapteyn's most recent model of the Milky Way had been published, nine years since distances to galaxies were measurable, six years since Jan Hendrik Oort and Bertil Lindblad (1895-1965) had determined that our Galaxy rotated, and five years since the rotation of distant spiral galaxies was observed. To say the least, extragalactic astronomy was in its infancy and it was not known whether the assumptions made in applying the Virial theorem were valid at extragalactic distances.

ii. The Solutions

What did Zwicky think of the mass discrepancy in the Coma cluster? What did he think dark matter was? Perhaps there was simply more luminous mass than that which had been observed. It had happened before; the undiscovered planets in our own solar system and the unseen companion to Sirius and to Procyon had posed a similar problem in the past. Did Zwicky see the parallel between those situations and the discrepancy in the Coma cluster? He did not comment on either. What explanations did he propose for the discrepancy?

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[3]Zwicky, 1933a.
[4]Zwicky, 1933a, p. 125.

Zwicky used the term dark matter (*dunkle Materie)* twice in his publication,[5] first in discussing the mean density of the universe, which was under debate.[6] Albert Einstein and Willem de Sitter (1872-1934) had found a density of 10^{-28} g cm^{-3} by theoretical means, and Hubble had found a value of 10^{-31} g cm^{-3} observationally. Zwicky suggested that if *"dark (cold) matter"* existed, then the theoretical and observational densities would likely agree.[7] Zwicky mentioned dark matter a second time in his discussion of the high velocity dispersion of the Coma cluster of galaxies. He suggested that the presence of dark matter could explain the dispersion, provided that the mean density of the cluster was 400 times greater than that observed. He also mentioned that, if dark matter did not exist, the cluster could be unstable and "flying apart."[8] But in that case remnants of other clusters should be observed as isolated galaxies with individual peculiar velocities as high as cluster galaxies (1000 to 2000 km s^{-1}).[9] However, isolated galaxies with peculiar velocities exceeding 200 km s^{-1} had not been observed.[10]

Zwicky did not discuss the composition of dark matter in the 1933 article, but it is interesting to note that Zwicky had called it *"dark (cold) matter."*[11] Perhaps the label should be examined. In his review of the history of dark matter, Sidney van den Bergh alleged that the modern sense of the term as non-baryonic matter was only adopted in

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[5]Zwicky, 1933a, p. 122 and 125.

[6] The uncertainty in the quantity and nature of absorption led to difficulties in measuring the density of the universe and even of the Milky Way galaxy, because it meant uncertainties in the observed mass. The measurement itself was important in determining cosmological models. In 1922, Aleksandr Friedmann (1888-1925) had shown theoretically that if the universe had a mean density exceeding 5×10^{-30} g cm^{-3} collapse would ensue. In the 1930s, most observational estimates were 10 to 100 times greater than Friedmann's critical value.

[7]Zwicky, 1933a, p. 122.

[8]Zwicky, 1933a, p. 125.

[9]The peculiar velocity of an isolated galaxy is the velocity of its motion through space, that is, the component is not arising from expansion. Within a cluster, the peculiar velocity is the deviation from the average orbital velocity of the cluster galaxies.

[10]Zwicky, 1933a, p. 125.

[11]Zwicky, 1933a, p. 122.

1983,[12] but many of Zwicky's contemporaries used the term freely to refer to the dust and gas of space. In a discussion on interstellar absorption, Robert A. Trumpler (1886-1956) questioned the possibility of absorption being caused by the "presence, distribution, and constitution of dark matter."[13,14] Kapteyn also called the obscuring matter in the Galaxy by the same name in 1922,[15] as did Oort in 1927.[16] Is absorbing dust the same material that Zwicky was referring to in his famous suggestion that "dark matter exists in much greater density than light-emitting matter"?[17]

Previously Zwicky had provided two arguments against the existence of intergalactic material. He had found, with observations made with the 100-inch telescope, a uniform distribution of galaxies over the whole sky. That, he claimed, was an argument against the possibility of extragalactic absorption and scattering, since a uniform distribution "would be skewed by absorption."[18] He appeared to be alone in thinking that uniformity implied the absence of such material.[19] His second argument

[12]Baryonic matter is matter consisting of protons and neutrons, whereas non-baryonic matter is a hypothetical form of matter that is not made up of protons and neutrons.
[13]Trumpler, 1930, p. 214.
[14] Physical theories suggested that light could be affected in four ways: refraction; absorption by free atoms or molecules; scattering by free electrons, atoms, molecules, or small solid bodies; and obstruction by larger bodies. Although the first evidence of interstellar matter dated to 1904 with the discovery of ionized calcium in interstellar space by Johannes Franz Hartmann (1865-1936), its existence was only established as a result of the studies of Robert Trumpler, John Stanley Plaskett (1865-1941), A. S. Eddington (1882-1944), and Otto Struve between 1925 and 1930 (Hartmann 1904; Eddington 1926). In a 1930 review article on the question of interstellar matter, Samuel Thorndike contended: "the mere existence of a diffuse cloud filling the Galaxy is now definitely indicated, although its nature and properties are but vaguely understood" (Thorndike 1930, p. 99). He also concluded with the words "the evidence now favours the idea of an approximately homogeneous, excessively rare cloud of metallic atoms interpenetrating the universe," suggesting that the medium might extend beyond the galaxy (Thorndike 1930, p. 104).
[15]Kapteyn, 1922, p. 302 and 314.
[16]Oort, 1927, p. 275 and 281.
[17]Zwicky, 1933a, p. 125.
[18]Zwicky, 1933a, p. 114.
[19]The distribution of galaxies was an important question for the structure of the universe and was connected to the question of absorption. In the region of the Milky Way, the distribution was irregular: the Milky Way, along with M31 and M33 formed a group, similar to many groups and clusters that were observed. Shapley ventured to say that if the non-uniformity of the distribution of galaxies was caused by obscuring matter then it must exist outside the Milky Way Galaxy. (Holmberg 1937 explained Shapley's view; for

against intergalactic matter was presented in his article on thermodynamic equilibrium; it was, simply, that vapour pressure theoretically would cause small dust particles and bodies to evaporate, such that "matter should exist either in the gaseous form or else concentrated in stars only."[20] Here, I doubt that Zwicky was referring to the absorbing dust which Trumpler, Kapteyn, and Oort had called dark matter.

The conclusion of the discussion on the velocity dispersion of the Coma cluster was that it was "a problem not yet solved."[21] Zwicky did not treat the problem as a major part of the publication, merely a curiosity. The significance of the mass discrepancy was not realized, or at least, not verbalized. We cannot know if at that time Zwicky attributed the discrepancy to a problem with Newton's law of gravitation.

B. The Virgo Cluster Examined by Sinclair Smith

Three years later, in 1936, Sinclair Smith published an article on the Virgo cluster. It was the first publication to refer to Zwicky's 1933 article; in fact it was the only one to address it directly. Smith found that there was also a mass discrepancy in the Virgo cluster. The radial velocities of thirty-two members were used to derive the mass of the cluster and an average galactic mass. Smith attributed the mass discrepancy to an underestimate of the mean galaxy mass. Whereas the accepted value for the mean galaxy mass had been determined by Hubble to be 10^9 solar masses, the mean mass of the individual galaxies in the Virgo cluster was found to be 2×10^{11} solar masses, a difference of two orders of magnitude. A possible source of error, Smith suggested, was

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further details see Shapley, 1932, *Harvard Bulletin 890.)* Hubble, however, claimed that uniformity was masked by absorption in the Milky Way and could only be recovered when the effects were removed. (Hubble 1936a, p. 30) He did not discuss the presence or possible influence of intergalactic matter.
[20]Zwicky, 1928, p. 596.

the unlikely prospect that the Virgo cluster was "simply a statistical fluctuation in space density."[22] However, the following year Zwicky found that the galaxies in the Coma cluster also had a high average mass (4.5×10^{10} solar masses).[23]

Smith also discussed the presence of "internebular material, either uniformly distributed or in the form of great clouds of low luminosity surrounding the nebulae."[24] In 1934 Joel Stebbins (1878-1966) and Albert E. Whitford had found observational evidence for a halo around M31.[25] Smith implied that such a halo might be associated with the unobserved mass. In general, Smith gave more attention to the mass discrepancy than Zwicky. The significance of the quandary was emerging, although Smith could not pursue the matter because he died of cancer shortly after his paper was published.[26]

C. *Zwicky Reconsiders the Masses of Galaxies in Clusters*

In 1937, after having photographed the Coma cluster with the 18-inch Schmidt telescope, Zwicky published an article focusing on the masses of galaxies and of clusters of galaxies.[27] By way of introduction, he stated that the two methods of determining masses of galaxies were unreliable because they could only determine a lower limit. The first method, the derivation of mass from its the estimated absolute luminosity of the galaxy, was deemed unreliable because the mass-to-luminosity relation for different stellar types was not well understood, nor were estimates of the quantity of dark matter and the effects of internal absorption satisfactory. The second method, the determination

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[21] Zwicky, 1933a, p. 126.
[22] Smith, 1936, p. 29.
[23] Zwicky, 1937a, p. 232.
[24] Smith, 1936, p. 30.
[25] Stebbins & Whitford, 1934.
[26] The only obituary or biographical publication about Smith I could find was Anderson, 1938.
[27] Zwicky, 1937a.

of mass from internal rotations, was considered unreliable because models could not include a realistic viscosity (i.e., gravitational interactions between individual stars). Zwicky's treatment of the masses of galaxies was thorough and built a firm case for the uncertainties of mean galactic mass estimates. If the mean galaxy mass determined by Hubble was incorrect, there might not be a mass discrepancy. Smith had been the first to suggest that there was a problem with Hubble's estimate of the mean galaxy mass, and Horace Babcock and Erik Holmberg joined Smith to challenge Hubble.[28,29] In establishing the problems with mass measurements, Zwicky hinted at that possibility but did not state it outright. It must be understood that the astronomical community held Hubble's estimate in high regard. Hubble was a highly respected astronomer. He had established himself with the discovery of the redshift-distance relationship, and his estimate of the average galaxy mass was not immediately questioned. On the other hand, he did not make any other comments or publish any further information on the masses of galaxies.

Once he had explained the problems with previous methods of mass determination, Zwicky proposed three "new" approaches to the measurement. They were based on the Virial theorem, gravitational lensing, and the statistical distribution of different types of galaxies. Zwicky had already applied the Virial theorem in his 1933 study of the Coma cluster. But, in his 1937 study of clusters of galaxies, Zwicky had found the Virial theorem to imply a mass-to-luminosity ratio of 500 in the Coma cluster.[30] Zwicky's interest in gravitational lensing was sparked by Einstein's 1936 article showing that the gravitational field of an intervening star could cause the deviation of the

[28]Babcock, 1939.
[29]Holmberg, 1937 and 1940.

light of another star so that the latter might appear brighter than it actually was.[31] Zwicky suggested that galaxies could also cause a lensing effect, and pointed out that there would be a much greater chance of observing the effect because galaxies were so much more massive.[32] If the effect was observed, then the spectra of very distant and previously unobservable galaxies could be photographed. Such observations, he thought, would be useful in improving the determination of galaxy masses and perhaps would "clear up the discrepancy" found in the Coma and Virgo clusters.[33] The last of Zwicky's three mass measuring methods used the statistical distribution of galaxies to define a probability function weighted according to the energy of the cluster and the mean energy of the galaxies. With the observed radial velocities and distances of the galaxies, the probability function could be used to determine a relative mass.

D. Zwicky Observes Many Clusters of Galaxies

In the fall of 1936, Zwicky began his supernova survey with the new 18-inch Schmidt telescope at Mount Palomar. The first survey took four years and consisted of over one hundred photographs based on ten to thirty minute exposures.[34] The photographs revealed several new clusters of galaxies and huge extensions of the boundaries of previously observed clusters.[35] Zwicky published the observational data collected during his supernovae search: data on the distribution of galaxies in the Coma,

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[30]Zwicky, 1937a, p. 232.
[31]Einstein, 1936.
[32]In fact, he published two articles treating gravitational lensing of galaxies: Zwicky, 1937b and 1937c.
[33]Zwicky, 1937b, p. 290.
[34]I mentioned in Chapter 1 that the magnitude limit was reached with the telescope with exposures of about forty minutes.
[35]Zwicky would later refer to the study, which encompassed four years of observing (1936-1940), as the first morphologically conceived observing program. See Zwicky, 1957a, p. 27.

Cancer, Hydra, Pegasus, Perseus, and Pisces clusters.[36] He maintained that, as the largest aggregates of matter, clusters of galaxies were the keys to extragalactic astronomy and "their investigation provides the last stepping stone for the investigation of the accessible fraction of the universe as a whole."[37] They could "throw new light on such problems as the determination of galaxy masses, on the redshift of light from galaxies, and on the evolution of stars and galaxies as well as their evolution as a whole."[38] Zwicky took it upon himself to "undertake a more concentrated study of clusters of nebulae than hitherto attempted."[39]

His papers included a list of the member galaxies in each cluster along with their approximate brightness, a discussion of the distribution of the galaxies, the distance to the cluster, the velocities of recession of a few galaxies, and in some cases a diagram that illustrated their positions. Most clusters were found to be larger than previously thought. Zwicky also noted that the Coma, Hydra, Perseus, and Cancer clusters were spherically symmetrical and thus concluded that they were not expanding or contracting. The increased evidence for clustering and the increase in the size of clusters led him to suspect that clusters were "the rule rather than the exception."[40]

The question of a mass discrepancy was not mentioned, and in only two cases did Zwicky even mention the mass of individual galaxies. First, he mentioned that the velocity dispersion of the Hydra cluster was not known and without it an estimate of an

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[36]Edson & Zwicky, 1941; Zwicky, 1937d, 1938a, 1941, 1942a, 1942b, 1942c, 1942d, 1942e, 1942f, 1950a, 1950b, 1951. Zwicky also photographed the Virgo, Canes Venatici, Fornax, Ursa Major, and Centaurus clusters, but it does not appear that he published the observational data.
[37]Zwicky, 1938a, p. 219. As an example Zwicky stated that "the counts of the nebulae in the Coma cluster have furnished the first and, so far, only proof that in the first approximation Newton's law of gravitation adequately describes the interactions among nebulae."
[38]Zwicky, 1937d, p. 251.
[39]Zwicky, 1937d, p. 251.
[40]Zwicky, 1957a, p. 43.

average galaxy mass could not be made.[41] Secondly, while the velocity data of the Perseus cluster were *"still very scant,"* they were sufficient for an estimate to be made. It was found that the average mass of the galaxies was of order 5×10^{10} solar masses, "unless faint nebulae or dark matter contribute far more to the mass of the Perseus [cluster]."[42] That was a factor of 50 greater than Hubble's accepted galaxy mass of 10^9 solar masses. Zwicky could not focus on the mass discrepancy without enough radial velocity measurements to determine the velocity dispersion, but why he did not make such measurements is unclear. I suspect that it was partly the result of Zwicky not receiving any observing time on the Mount Wilson 100-inch telescope. The 100-inch telescope was Edwin Hubble's telescope and the conflict between him and Zwicky could be one reason why Zwicky did not receive any observing time. However, it is also possible that there existed a general bias against his proposals. Further investigation of the Mount Wilson Observatory archives would be necessary to pursue this matter.

It is surprising that Zwicky did not discuss the mass discrepancy in his various studies of galaxy clusters, but perhaps that was not the goal of his analyses. In fact, Zwicky stated an ulterior purpose for publishing the data: "We shall simply count galaxies more or less naively, as has been done in the past. This procedure is quite sufficient to demonstrate that most of the counts of galaxies made with the large reflectors are subject to grave doubts."[43] What did those grave doubts entail? Zwicky clearly thought them to be of importance. In fact, he was referring to the luminosity function, which describes the distribution of galaxy brightness, within a cluster or in a region of the general field, as the number per unit volume per unit magnitude interval.

[41]Zwicky, 1942a, p. 153-154.
[42]Zwicky, 1942c, p. 358.

Hubble had claimed that the luminosity function had a maximum value, to which Zwicky replied "Simple theory indicates that no maximum can exist."[44] The tone with which Zwicky made his statement was one of exasperation. Was he hoping to defy Hubble and theories that were perhaps too readily accepted? The introduction to his 1971 catalogue of compact and post-eruptive galaxies provides insight into that question. Zwicky spoke of Hubble, among others, quite vehemently, calling him names and accusing him of ignoring his research.[45] On the subject of the luminosity function (as well as the presence of intergalactic matter), he accused Hubble, Baade, and their "sycophants" of possibly "doctoring their observational 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."[46]

Another aspect of his studies of clusters of galaxies was a survey of the large-scale distribution of galaxies (i.e. on a scale much larger than an individual cluster).[47] Hubble had found that "to the twentieth magnitude perhaps one cluster per fifty square degrees may be expected."[48] Zwicky made a very different observation: he found one cluster per several square degrees in several regions of the sky,[49] and thus pronounced that clustering was predominant in the distribution of galaxies. In later years he claimed

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[43]Zwicky, 1951, p. 61.
[44]Zwicky, 1951, p. 62.
[45]Zwicky, 1971a. His name-calling included the labels "sycophant," "plain thieves," "high priests," and "scatter-brains." Hubble was among the "high priests" and the "plain thieves." As an example of his mistreatment, he recalled an occasion when credit for the discovery of the first dwarf galaxies was almost attributed to Baade by Hubble when it was Zwicky that had made the observation. A second anecdote is told regarding blue compact galaxies that Zwicky had identified in 1963. In 1965 Sandage submitted a paper on "blue quasi-stellar galaxies" which presented evidence for a closed universe. Subrahmanyan Chandrasekhar (1910-1995), the editor of the *Astrophysical Journal*, rushed the manuscript through the press without sending it to referees. However, Sandage had prepared the paper without acknowledgement of Zwicky's work. By coincidence, Chandrasekhar was rumoured to have an aversion to Zwicky.
[46]Zwicky, 1971a, p. vi.
[47]Zwicky, 1952b and 1953a.
[48]Hubble, 1936a, p. 76.

that Hubble's observations were "faulty" and his statistics "incorrect," which resulted in the persistence of "glaringly incorrect conclusions."[50] Clearly there was some conflict between the ideas of Zwicky and Hubble.

E. Intergalactic Matter: A Possible Source of Unobserved Mass

When Zwicky first discovered a mass discrepancy in the Coma cluster of galaxies, he did not support the explanations that it might be a product of intergalactic dust or extragalactic absorption. It was not long, however, before matter of another nature was observed between close pairs of galaxies. P.C. Keenan, for example, found in 1935 a faint band of luminous connective matter associated with the tidal interactions between the double galaxy pair NGC 5216 and 5218.[51]

Zwicky expressed interest in the theoretical possibilities of intergalactic debris in his 1937 publication. As he sought to account for the mass-to-luminosity ratio of 500 in the Coma cluster,[52] he predicted that "a considerable number of stars, as well as matter in dispersed form from disrupted nebulae, [were] scattered through the internebular spaces within clusters."[53] Zwicky tried to elucidate the composition of the faint matter that he would look for, suggesting that it might be in the form of cool and cold stars, macroscopic and microscopic solid bodies, and gases.[54]

Once again Zwicky, convinced of his own hypothesis, set out to observe the material with the 18-inch Schmidt telescope. His search for intracluster matter began in

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[49]Zwicky, 1953a, p. 216.
[50]Zwicky, 1971a, p. vii.
[51]Keenan, 1935.
[52]Zwicky, 1937a, p. 232.
[53]Zwicky, 1937a, p. 237.
[54]Zwicky, 1937a, p. 218.

the late 1940s and was first reported in the *Carnegie Institution of Washington Yearbook* report on the Palomar Observatory in 1948.[55] However, it was only in 1950, after the 48-inch Schmidt was in use, that great quantities of intergalactic luminous tidal debris were observed. Zwicky used "fast emulsions and, last but not least, careful work."[56] His first article on intergalactic matter was published in *Experientia* in 1950.[57]

Zwicky drew media attention for his observations of intergalactic debris.[58] Articles in *Time* and *Life* magazines claimed that mass and distance measurements would be drastically altered by the discovery, implying that the foundations of astronomy were being shaken. However, his colleagues had not shared the enthusiasm. Zwicky alleged that his first reports dating to the 1940s "had been arbitrarily (and illegally) censored by our observatory committee and withheld from publication in any of the regular American Journals."[59] He was forced to publish his results in European journals, i.e., *Experientia, Acta Astronomica*, and others.[60] He claimed that his observations raised the possibility that the density of the universe was much greater than previously thought, perhaps even as high as 10^{-26} g cm^{-3}. If that were true it would eradicate the mass discrepancy, but would also put a snag in the Einstein-de Sitter cosmological model that many had adopted, in which the mean density of the universe was the same as the critical density, which at the time was thought to be 10^{-28} or 10^{-29} g cm^{-3}.[61] Nonetheless, Zwicky did

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[55]Carnegie Yearbook, 1948.
[56]Zwicky, 1953b, p. 7.
[57]Zwicky, 1950c, p. 441.
[58]*Time*,1952, p. 64-66; *Life*,1952, p. 51; Candee, 1953.
[59]Zwicky, 1971a, p. ix. This statement was amongst his bold remarks about his colleagues and their attitudes, in the introduction of the *Catalogue of Selected Compact Galaxies and of Post-Eruptive Galaxies*.
[60]For example, Zwicky, 1950c.
[61]It predicts that the universe will expand forever with a decreasing expansion rate.

publish an article on intergalactic matter in *Publications of the Astronomical Society of the Pacific* in 1952.[62]

F. Faint Galaxies: Another Possible Source of Unobserved Mass

i. The Luminosity Function

The luminosity function was a subject of debate between Zwicky and Hubble. Hubble had proposed a bell-shaped (Gaussian) luminosity function with a maximum at an absolute magnitude of $M_0 = -14.2$, and not unlike his mean galaxy mass estimate it was readily accepted.[63] Zwicky objected to the implications of such a function, claiming that there was no maximum and that faint, dwarf galaxies existed in greater quantities than Hubble allowed. He stated repeatedly that there were huge problems with Hubble's luminosity function.[64] Zwicky argued that the luminosity function for galaxies could not be derived from pure observation, but that theoretical considerations had to be taken into account. He suggested that faint member galaxies were a possible source of missing matter, because they were often overlooked.[65] The detection of such faint objects was highly dependent on the quality of photographic plates. Gibson Reaves alleged that they were difficult to recognize because their light was not as centrally concentrated as other galaxy types and thus they were not readily recorded photographically.[66]

A discrepancy was found in Hubble's luminosity function for the Local Group after three faint dwarf member galaxies were discovered. The discrepancy was in Zwicky's favour. The mean absolute magnitude of the Local Group before the discovery

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[62] Zwicky, 1952a.
[63] Hubble, 1936a, p. 149.
[64] For example, Zwicky, 1942d, 1957a, 1964, 1971a.
[65] Zwicky, 1942d, p. 489.

of the faint galaxies was −14.0, in good agreement with the value of M_0. Hubble had difficulty reconciling the presence of dwarf galaxies in his Gaussian luminosity function and stated that "their presence in the Local Group appears to be a unique feature of the group, and they detract from its significance as a fair sample of nebulae in general."[67] Hubble maintained, with conviction, that his luminosity function was correct. Hubble was not alone; another highly influential astronomer, Walter Baade, also expressed the conviction that Hubble's luminosity function was "well-established."[68] Did Hubble really believe that the Local Group was unique? Or that existing observing capability was so effective?

Zwicky had proposed that the luminosity function rose monotonically. His suggestion was based on theoretical grounds long before he actually derived the luminosity function observationally in 1957.[69] He modelled the members in clusters of galaxies as a function of their brightness, such that the number $N(M)$ of galaxies of absolute magnitude M was determined by $N(M) = constant \times 10^{M/5}$. He did not receive much support for his alternative version. However, in 1950 Holmberg demonstrated that faint dwarfs did indeed skew Hubble's Gaussian curve, and that the M81 and M101 galaxy groups had luminosity functions quite different from Hubble's relationship.[70] To understand the controversy further, it must be realized that Hubble and Zwicky were looking at different populations. Hubble concentrated on bright galaxies while Zwicky's observations encompassed dimmer galaxies. Their different instruments fashioned their

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[66]Reaves, 1956.
[67]Hubble, 1936a, p. 149.
[68]Baade, 1938, p. 286.
[69]Zwicky, 1957a, p. 171-176.
[70]I have not read Holmberg's publication *(Holmberg, 1950, Medd. Lunds Astr. Obs. Ser. II. No. 128)*, but it is discussed in Reaves, 1956, p. 69, Zwicky, 1964, and Binggeli, Sandage & Tammann, 1988, p. 514.

results, since Hubble used the 100-inch reflector at Mount Wilson, which could not observe faint cluster members without impossibly long exposures and distorted images, and Zwicky used the Schmidt telescopes at Palomar, which were ideal for observing faint objects.[71]

ii. Zwicky's Observation of Faint Galaxies

The first dwarf galaxies were observed when supernovae, which reached luminosities much brighter than their parent galaxy, appeared within them. The number of faint objects noted in the supernova observations was great enough to initiate a search program with the 18-inch Schmidt telescope. As Zwicky had predicted, two of the first six faint objects identified were indeed new extremely faint galaxies in the Local Group. In 1942 he quite strongly asserted (from theoretical arguments) that "a large number of intrinsically faint galaxies representing more than half of all of the matter in the visible universe is predicted which to date must have been overlooked."[72]

In 1951, in an article on the Coma cluster, Zwicky discussed his discovery of faint galaxies and of intergalactic matter. He found that the faint material in the clusters of galaxies caused them to "grow not only in population but also in geometrical dimensions."[73] At the then accepted distance for the Coma cluster, 13.8 Mpc, the dimensions of the cluster increased from a diameter of 4 million light years in 1937 to 9 million light years in 1951.[74] However, Zwicky did not discuss the possible association of such faint objects with the mass discrepancy. That might have been because his

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[71]However, Gibson Reaves would observe more faint galaxies with the Palomar 200-inch. Reaves, 1956 and 1966.
[72]Zwicky, 1942d, p. 489.
[73]Zwicky, 1951, p. 62.

observational results did not support such speculation. Zwicky's own suggestion in 1942 was that faint galaxies increased the amount of luminous matter by perhaps only a factor of two. Thus, the mass contributed by faint galaxies might not approach the amount needed to solve the mass discrepancy.

G. *The Outcome of the First Unveiling of "Dark matter"*

Zwicky was a man of strong personality and was well known for it. He has been described as "tempestuous, imaginative" and "a scientist who has always been regarded by some staid colleagues as a controversial man — part genius, part eccentric."[75] As well as, "an irascible maverick, Fritz Zwicky had a penchant for investigating extreme phenomena, speculating outside the confines of prevailing theory, and undertaking ambitious observational programs."[76] Were his eccentric tendencies recognized at the time of his 1933 publication? He asserted late in his life that he was not treated fairly by his colleagues,

> "The fact that, except for some outstanding exceptions like George Ellery Hale, the members of the hierarchy in American Astronomy have no love for any of the lone wolves who are not fawners and apple polishers was made clear to me and to my independent friends on many occasions."[77]

However, despite "unfair" treatment, Zwicky persisted with his scientific pursuits. In an obituary, Albert Wilson described Zwicky's research tactic: "For Zwicky theories

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[74]Zwicky, 1937a, p. 231 and 1951, p. 62.
[75]*Life*, 1952, p. 51
[76]Hufbauer, 1990, p. 1011
[77]Zwicky, 1971a, p. viii.

were platforms for exploration. He could pick up and set aside a theory as one does a tool. His unwillingness to dogmatize theories and thereby restrict himself made him appear somewhat radical to many of his colleagues."[78] We can see evidence of that tactic in his discovery and pursuit of dark matter; he spoke of it in 1933 and then in 1937, but he did not address the subject in his publications where he continued to study clusters of galaxies in his search for supernovae. He was capable of working on a diversity of projects simultaneously. Is it reasonable to expect him to have recognized (or expressed) the importance of the discovery in his publications or to have linked the discrepancy to his other lines of research? The answer to that is beyond the scope of this thesis because it would entail an examination of the refereeing process and of Zwicky's personal notes. One can speculate, however, on the basis of a statement of his. "Just what will be recorded, for instance, when the stars, nebulae, and other aggregations of matter are observed in radiations now blocked out by the atmosphere, staggers the imagination."[79] Perhaps he imagined the problem would only be solved with further advances in technology.

It is important to understand that Zwicky's observations of clusters of galaxies did not coincide with the general opinions held by astronomers in the 1930s, which were as follows:

> "(1) There is no observable intergalactic matter, either luminous or dark, in the universe. (2) Only about five per cent of all galaxies are physical members of clusters, the rest being free-field galaxies. (3) The indicative diameters of the large clusters are of the order of at most 3,000,000 pc or, with a red shift constant

[78]Wilson, 1975, p. 107.
[79]Zwicky, 1947, p. 64.

of 550 km/sec per million parsecs then on the books, of the order of 0.5 million parsecs."[80]

Zwicky noted that in the 1930s, scientists thought that they "knew it all."[81] The over-confidence held by those scientists did not affect Zwicky; he was able to keep a clear view of the reality of scientific unknowns and uncertainties. He did not overestimate the significance of Coma's missing mass, nor did he underestimate it.

[80]Zwicky, 1967a, p. 271.
[81]Zwicky, 1971a, p. v.

Chapter 4
The Skeleton in the Cupboard

> *"The dynamical energy of the 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. This skeleton in the astronomers' cupboard rattles ever more loudly as the years pass by."*[1]
>
> Fred Hoyle

A. The Years Following Zwicky's Discovery

In the previous chapter, we saw that in the 1930s Fritz Zwicky and Sinclair Smith were at the forefront of the mass discrepancy problem in clusters of galaxies. The majority of historical reviews of the problem leave a gap between the initial work of the 1930s and the renaissance of the problem with the work of Vera Rubin, Kent Ford, Jeremiah Ostriker, and James Peebles (among others) in the 1970s. Although publications on the subject were sparse during those 40 years, the dark matter problem was not completely disregarded. This chapter outlines the contributions to cluster dynamics and galaxy masses of the 1940s to the 1970s, and continues to explore Zwicky's role.

i. The Mass Discrepancy in Individual Galaxies

In 1939 Horace Babcock published his doctoral thesis, a study of the Andromeda galaxy (M31) focusing on the rotation and mass of the galaxy.[2] Because of its close proximity to the Milky Way, M31 was ideal for observation, and spectrographic data were available in abundance. By plotting circular velocity against radius to produce a

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[1]Hoyle, 1972, p. 483.
[2]Babcock, 1939.

rotation curve, Babcock found that there must be significant mass in the outer regions of the galaxy. The mass-to-luminosity ratio ranged from 1.6 at a radial distance of 0.5 arcminute from the galactic centre to 62 at a radius of 80 arcminutes, with an overall average of 50. He attributed the high ratio in the outer part of the galaxy to two possible causes, either absorption or a need for "new dynamical considerations."[3] At the time, the accepted mass-to-light ratio was 2 to 3 for spiral galaxies.[4] He found the total mass of M31 to be 1.02×10^{11} solar masses, a value similar to Smith's 1936 estimate of the mean galaxy mass in the Virgo cluster. As a doctoral student, Babcock was not influential and his results did not have any weight in the astronomical community. He was discouraged from publishing his paper in *Astrophysical Journal*. Perhaps he was also shocked or embarrassed by his results; he did not pursue further studies of galaxies, but subsequently turned his interest to solar astronomy.

Nicholas Mayall and Lawrence Aller followed Babcock's study of M31 with a study of M33.[5] They did not evaluate the mass-to-luminosity ratio of the spiral galaxy, although they did plot the rotation curve. Masses were calculated for the Galaxy, M33, M31, NGC 4594, and NGC 3115, ranging from 1.7×10^{9} to 2×10^{11} solar masses. The values were deemed "average values," because four of the six were "giant systems."[6] Thus, it seems likely that they expected the mass of a typical galaxy to be similar to Hubble's estimate. A. B. Wyse and Mayall also examined M31 and M33.[7] They computed values for the mass-to-luminosity ratio and found them to agree with Babcock's results. Wyse and Mayall implied that the high ratios could be explained by the presence of "faintly luminous matter," but they claimed that prediction or speculation of the properties of the matter was beyond the scope of their paper.[8] However, they did

[3]Babcock, 1939, p. 50.
[4]Oepik(1922) quoted James Jeans' value of 3.2 for the Milky Way, and Oort had found a value of 1.8.
[5]Mayall & Aller, 1942.
[6]Mayall & Aller, 1942, p. 21.
[7]Wyse & Mayall, 1942.
[8]Wyse & Mayall, 1942, p. 38.

make the suggestion that perhaps mass was *not* concentrated in the centre of the galaxies, and that observations of the Milky Way had been misinterpreted.[9]

Another example of the problem of missing mass in individual galaxies dates to 1939. In that year Jan Oort presented a paper at a symposium held for the opening of the McDonald Observatory, in which he discussed the Milky Way and the elliptical galaxy NGC 3115.[10] He found the mass-to-luminosity ratio for the solar neighbourhood to lie between 2 and 7, and marvelled at the high mass-to-luminosity ratio of NGC 3115, which was between 150 and 250. In a 1952 study of double galaxies, Thorton Page (1913-1996) also found unusually high mass-to-luminosity ratios. He found the mean galaxy mass of double galaxies to be 8.0×10^{10} solar masses.[11] The mass estimate was similar to Smith's and the mass-to-luminosity ratios were surprisingly high, ranging from 171 to 620.[12] Page explained that high values were in part caused by poor data: "luminosity data [were] too poor to allow identification of luminous giants with massive heavy weights."[13]

With the evidence for high mass-to-luminosity ratios in individual (and double) galaxies, it is puzzling that the parallel problem in clusters of galaxies was not given more attention. Since the two discrepancies were uncovered in the same era, the manner in which each problem was examined and interpreted is of interest. One might have expected that astronomers would have made a connection between them, especially upon their initial discovery. Babcock, however, was the only one to refer to the mass discrepancy in clusters in discussing the problem for individual galaxies. The problem with galaxy masses supported the discrepancy Zwicky uncovered in clusters, but it does not seem to have contributed to the recognition of the importance of the discrepancy. It is important to understand that for many years the mass discrepancy in individual galaxies was treated as a distinct problem from that in clusters of galaxies.

[9]Wyse & Mayall, 1942, p. 42.
[10]Oort, 1940.
[11]Page, 1952, p. 76.
[12]Page, 1952, p. 78.
[13]Page, 1952, p. 80.

ii. Clustering Tendencies

Erik Holmberg published a study on clustering tendencies in 1940.[14] He considered galaxies with hyperbolic orbits to be "temporary members" of a cluster, and estimated that twenty percent of Virgo cluster members were transient.[15] That, he claimed, might explain the high velocity dispersion found in the Virgo and Coma clusters. He thought that solution to be "more plausible" than non-luminous intergalactic mass.[16] In determining the percentage of temporary members in the Virgo cluster, Holmberg assumed the average mass of an individual galaxy to be 10^{11} solar masses. He justified his use of the value by referencing the mass estimates of Smith from the radial velocities of members of the Virgo cluster, his own 1937 study of double galaxies, and Babcock's study of M31.[17],[18],[19] Holmberg argued that internal obscuration of the galaxies was neglected in Hubble's mean mass determination and therefore his value was an underestimate.[20] Holmberg's solutions for the discrepancy deserved attention, but the astronomical community did not seem to pay any more attention to his publication than they had to those of Zwicky and Smith.

The 1940s were essentially devoid of cluster studies (aside from those of Zwicky, which were discussed in Chapter 4). A 1943 paper by Merle Tuberg, however, did refer to Zwicky and Smith.[21] Tuberg suggested that Chandrasekhar's theory of dynamical friction, which was developed for star clusters, could be extended to clusters of galaxies for the determination of an upper limit to the time scale (or age) of the universe.[22] The

[14]Holmberg, 1940.
[15]Holmberg, 1940, p. 220.
[16]Holmberg, 1940, p. 220.
[17]Smith, 1936.
[18]Holmberg, 1937.
[19]Babcock, 1939.
[20]Holmberg, 1937, p. 101.
[21]Tuberg, 1943. Smith, 1936 and Zwicky, 1942e are referenced.
[22]See Chandrasekhar, 1943a, b, c.

theory was applied to the Coma and Virgo clusters using Smith's and Zwicky's observational data, notably Smith's mean galaxy mass of 2×10^{11} solar masses.

In 1954, C. D. Shane and C. A. Wirtanen performed a survey of galaxy distributions,[23] following Hubble's suggestions to update his 1936 study.[24] They noted that "one is tempted to speculate that clustering may be a predominant characteristic of nebular distribution."[25] But they did not give clustering any further consideration and maintained that the distribution was random. Nor did they mention Zwicky's 1952 or 1953 papers, in which clustering was observed to be a predominant feature of the large-scale distribution of galaxies.[26]

In 1954 Martin Schwarzschild (1912-1997) examined individual radial mass distributions of galaxies by fitting rotation curves to observations of galaxies, including the spirals M31 and M33 and the ellipticals NGC 3115 and M32.[27] He looked at the Coma cluster to obtain information on the average total masses of galaxies. With radial velocity measurements for 22 member galaxies, he found (with the Virial theorem) that the total mass of the Coma cluster was 3×10^{14} solar masses. He used Guy C. Omer, Jr.'s estimate of a total of 800 members to deduce a mean individual galaxy mass of 4×10^{11} solar masses.[28] Schwarzschild claimed that, with the adoption of a "new" distance scale,[29] the result was "entirely in agreement with the much earlier investigations by Sinclair Smith and Zwicky on clusters of galaxies."[30] From the resulting mean mass Schwarzschild found an average mass-to-luminosity ratio of 800. He thought it was a

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[23]Shane & Wirtanen, 1954.
[24]Hubble, 1936b and Hubble, 1951.
[25]Shane & Wirtanen, 1954, p. 298.
[26]Zwicky, 1952b and 1953a.
[27]Schwarzschild, 1954.
[28]Omer, 1952, p. 22.
[29]In the early 1950s a number of corrections were made to the distance scale. These included a correction to Shapley and Hertzsprung's calibration of the period-luminosity relation, increasing the distance scale by a factor of two. The original calibration suffered from neglect of interstellar absorption, poor data, and the unknown effects of galactic rotation on proper motions, radial velocities, and parallaxes. The error had persisted for forty years. For further information, see Fernie, 1969. Also, in 1956 Sandage corrected distances measured by Hubble, increasing them by a factor of three. Overbye, 1991, p. 52-53.
[30]Schwarzschild, 1954, p. 281.

"bewildering high value" but that it was "very uncertain since the mass and particularly the luminosity of the Coma cluster [were] still poorly determined."[31] He concluded, "observations now available permit the assumption that in any one galaxy the mass distribution and the luminosity distribution are identical." Though Schwarzschild referred to Zwicky's early work, he did not quote any of Zwicky's results nor did he refer to his later works on the subject. That is particularly curious because Zwicky had recently published an update to his earlier study of the Coma cluster, in which he increased his estimate of the total number of members to 8988, a much higher count than Omer's.[32] Van den Bergh has suggested recently that Schwarzschild's article delayed the recognition of the dark matter problem by a decade.[33] Schwarzschild's article was influential, but he did not present any new information and he blatantly denied the need for dark matter. Was his article "successful" in influencing his colleagues because his conclusion *stated* that there was no discrepancy, thus eliminating the complication presented by Zwicky and Smith?

iii. *Galaxy Counts of the Coma Cluster*

Galaxy counts and spatial distributions are two essential observations in determining the dynamics of clusters of galaxies. Although observational techniques had progressed since Zwicky's early analyses of the Coma cluster, there remained a great deal of disagreement concerning the composition of the cluster. The Coma cluster was deemed important because it was one of the nearest of the large spherically symmetric clusters. Omer and his collaborators claimed that, "It is, therefore, a good starting point for understanding the probable mechanisms of clustering, the age of the universe, and the nature of a gravitational field acting over large distances."[34] In his 1954 article,

[31]Schwarzschild, 1954, p. 281.
[32]Zwicky, 1951, p. 65. Curiously enough, in his article Zwicky did not state that the increase in the number of member galaxies could account for the mass discrepancy.
[33]van den Bergh, 2000, p. 5.
[34]Omer, Page & Wilson, 1965, p. 440.

Schwarzschild had referred to Omer's estimate for the number of member galaxies in the Coma Cluster. Omer's work on the Coma cluster was reported at four meetings of the American Astronomical Society (dating from 1949, 1952, 1966, and 1967) and in one article, co-authored by Thorton Page and Albert Wilson.[35] Schwarzschild had referred to the 1952 AAS meeting abstract, which summarized five independent galaxy count surveys:

> "1. The Coma cluster is 1.3 degree in radius. 2. The cluster contains about 800 members. 3. The luminosity function of this cluster is essentially the same as the function derived by E. Holmberg from the nearby nebulae. 4. The radial distributions of the bright and the faint members of the cluster appear to be identical."[36]

In a 1951 publication, Zwicky claimed that the Coma cluster had a radius of 6 degrees, a member count of 8988 galaxies, a monotonically increasing luminosity function, and a segregated spatial distribution of bright and faint galaxies.[37] His statistics clearly did not agree with those made by Omer. Zwicky had shown previously that the radial distribution within a cluster is like that of an isothermal sphere, in which Newtonian mechanics directed the interactions within the cluster. The spatial segregation of the two populations implied a dynamical stability. That was because repeated interactions between galaxies were necessary to establish an equipartition of energy, which then caused more massive members to have lower mean speeds and to be concentrated in the centre. That was an argument for long-term stability, because it was rooted in the fact that it is only over long periods of time that the two populations become segregated.

[35]Omer, 1949, 1952, 1966, 1967; (These were presented papers and only the abstracts have been published.) Omer, Page & Wilson, 1965.
[36]Omer, 1952.
[37]Zwicky, 1951.

In 1961 and 1963, Thomas Noonan and George Ogden Abell (1927-1983), respectively, argued against the segregation of brighter galaxies from dimmer galaxies in the Coma cluster.[38,39] Curiously, Noonan based his argument on a "re-interpretation" of Zwicky's 1951 and 1952 cluster counts. Abell, however, carried out his own observations with the 48-inch Schmidt at the Palomar Observatory. In 1966, Gibson Reaves observed the Coma cluster with the 200-inch reflector at Palomar.[40] His counts were "consistent" with Zwicky's, and he explained that the analyses performed by Noonan and Abell were at fault because they concentrated on "properties of the cluster outside the central region."[41] Reaves found 32 dwarf galaxies in the cluster, supporting Zwicky's prediction of their presence and their importance.

B. *The 1961 Santa Barbara Conferences*

In the late 1950s a desire to reconcile the problem of the masses of galaxies surfaced in the astronomical community. At the same time many arguments were formed against Zwicky's application of the Virial theorem to clusters, and against his observations of intergalactic material. The interest in galaxy masses and cluster dynamics culminated in two conferences held in Santa Barbara in August of 1961, one on *The Instability of Systems of Galaxies* and a second, the International Astronomical Union Symposium Number 15 on *The Problems of Extragalactic Research*.

The conference on *The Instability of Systems of Galaxies* was an opportunity to discuss the question of whether clusters of galaxies were expanding or stabilized by additional, unobserved mass.[42] In the conference foreword, Neyman, Page & Scott stated that a 1954 paper by V. J. Ambartsumian (1908-1996) formed the premise of the

[38]Noonan, 1961.
[39]Abell, 1963.
[40]Reaves, 1966.
[41]Reaves, 1966, p. 410.
[42]Neyman, Page & Scott, 1961a.

meeting.[43] Ambartsumian had proposed that the instability of clusters was a fact and that clusters *were* expanding.[44] However, by the closing of the conference the editors concluded, "It must be admitted that more questions have been raised than settled."[45]

Zwicky had been involved in research on cluster dynamics for nearly thirty years, and he had become quite confident that uncovering intergalactic matter would play a large part in understanding cluster dynamics. Essentially, the problem of the masses of clusters of galaxies lay in the inability to observe the non-luminous matter. Since his 1933 publication, Zwicky had initiated the first observational studies of clusters of galaxies, demonstrated that the luminosity function was monotonically rising, observed that faint and bright galaxies were segregated within a cluster, and found the first signs of great quantities of intergalactic matter. However, the credit given to Zwicky during the conference was meagre. It is reasonable that the presentations would concentrate on cutting edge observations, but I wonder if that justifies overlooking the early research on the "instability problem." Zwicky played a prominent role in the study of clusters of galaxies; however, his name was not listed among the sixty-two participants in the conference. Why was he not even in attendance? The foreword to the proceedings explained the circumstances leading to the conference: initially a few of the IAU Symposium participants decided to meet prior to the scheduled conference, but when the list of invited papers grew to 17, all of the IAU Symposium participants were invited.[46] There is no evidence that Zwicky was discouraged from attending, and there are many possible reasons for his absence, but perhaps Zwicky was not impressed by or interested in the congregation of those seventeen speakers.

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[43]Neyman, Page, & Scott, 1961a, p. 533.
[44]A source is not given for Ambartsumian's first proposal. However, most participants at the conference referred to the proceedings of the Solvay Conference, *Ambartsumian (1958) La Structure et l'evolution de l'univers (R. Stoops, Brussels, Belgium) p. 163.* I did not find this work, but I did find an article published in *The Observatory*. See Ambartsumian, 1955.
[45]Neyman, Page, & Scott, 1961b, p. 636.
[46]Neyman, Page & Scott, 1961a, p. 534.

Fritz Zwicky *did* attend the subsequent IAU Symposium on *Problems of Extragalactic Research* held the following week, and he presented a paper titled "New Observations of Importance to Cosmology."[47] The forty papers of the IAU Symposium spanned a broad spectrum of topics, ranging from normal galaxies as stellar systems to galaxies as members of the universe. The discussion following each presentation was published, and the dialogue between Zwicky and others is a vital resource. A scientist's view is often more readily perceived in conversation than in publication: scientific journal articles do not always tell what lies behind the research.[48] The participants in the conferences voiced opinions about extragalactic dynamics that would not have been stated otherwise.

i. The Evidence: Rotation Curves and Mass-to-Luminosity Ratios

Rotation curves had become an important indicator of the missing mass in individual spiral galaxies. The shape of the curve was expected to reflect the gravitational interactions of the stars. That is, the orbital velocities would rise rapidly with radial distance in the bright central regions and then fall in the dim outskirts. However, it was found that the orbital velocities did not decrease at large radial distances, as would be expected if the mass was concentrated like the luminosity at the centre of the galaxy. Many rotation curves were essentially "flat." That was a result of a constant velocity across a large part of the galaxy's disk, and it implied that the mass increased rapidly with the radius. However, because of the limitations of spectroscopic observations, velocity measurements were confined to distances relatively close to the nucleus, and the shapes of rotation curves were left somewhat ambiguous. The astronomical community convinced itself that at greater distances the curves *would* fall.

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[47]Zwicky, 1961.

[48]For discussion of this idea see Curtis, 1994. Note especially p. 444, where he refers to Mulkay who suggested that *"research literature has been dominated by a kind of empiricist monologue, other textual forms, such as the dialogue, may be less constricting and more suitable, and may allow the analyst to convey other conceptions of scientific rationality."*

In 1959 Gerard de Vaucouleurs (1918-1995) reached that conclusion on the basis of eight available rotation curves which looked as though they *could* fall.[49] Yet, however ambiguous, rotation curves were the key to measuring mass-to-luminosity ratios in galaxies.

At *The Instability of Systems of Galaxies* conference, van den Bergh reviewed the mass-to-luminosity ratios of individual galaxies.[50] He claimed that, in general, elliptical galaxies were found to have values less than 100 and spiral galaxies had values much less than 100. His discussion of clusters of galaxies echoed the fact mentioned already, that very high ratios of 400 to 900 were being found. At the same conference, Holmberg presented similar estimates for individual galaxies. He had found that spirals had mass-to-luminosity ratios of 2 to 20 and ellipticals about 80.

Van den Bergh found that, "no large systematic differences appear to be indicated between isolated individual galaxies and individual cluster galaxies."[51] The implication was that individual galaxies did not contain the source of the mass discrepancy found in clusters of galaxies; instead the solution would have to be sought in cluster dynamics or in intergalactic material. Vera Rubin, another well-known figure in the development of the dark matter problem, constructed rotation curves for many galaxies in the 1950s and 1960s. However, she says that she did not make a connection between rotation curves and the mass discrepancy problem of clusters.[52]

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[49]de Vaucouleurs, 1959. An important factor in the belief that rotation speeds would fall at larger distances was the behaviour near the radial limit of the observations. That is, the tail end of the curves available to de Vaucouleurs were slightly inclined. But once radial velocity observations were made for greater distances from the galaxy nucleus, it was found that rotation curves flattened out and did not descend.
[50]van den Bergh, 1961.
[51]van den Bergh, 1961, p. 570.
[52]Rubin 2000, private communication.

ii. Dynamical Solutions: Systems of Positive Total Energy. Subsystems and Supersystems

The root of the dark matter dilemma lay in the fact that (for the assumed mean mass of a galaxy) the total energy of clusters of galaxies was observed to be positive in many cases. Without any additional mass, the direct implication of a positive total energy was that the cluster was not bound, rather it was flying apart. V. A. Ambartsumian was the first to support the idea that systems of galaxies were disintegrating.[53,54] (He emphasized that it could not be assumed that all systems necessarily had positive energy, though the only system found to have negative energy was a group called Stephan's Quintet.) Zwicky had suggested in 1933 that clusters of galaxies might be flying apart, but he had quickly argued away the possibility.[55]

Ambartsumian did not completely ignore the arguments for additional mass in clusters. For example, he stated that the presence of dwarf galaxies in a system had "almost no influence upon the structure of the gravity field, which is determined chiefly by a small number of supergiants and partly by giant galaxies."[56] It was a view expressed by many astronomers, although they did not indicate who initiated the idea. I can point out that Ambartsumian accepted the evidence for a segregation of bright and faint populations in spherically symmetric clusters, as Zwicky had observed, but questioned whether it applied in irregular clusters. The instability was more pronounced in irregular clusters.

Van den Bergh and de Vaucouleurs both endorsed the idea of substructure in large irregular clusters of galaxies, such as the Virgo cluster.[57] This involved dividing a cluster into components and altering the dynamics so the cluster as a whole would be

[53]Ambartsumian, 1961, p. 538.
[54]He also had a hypothesis of disintegrating star systems, which was proven to be correct. See Ambarsumain 1955.
[55] Zwicky, 1933a, p. 125.
[56]Ambartsumian, 1961, p. 536.
[57]deVaucouleurs, 1961; van den Bergh, 1960 and 1961.

stable.[58] They both also endorsed the concept of clustering of clusters, or superclustering. Zwicky did not comment on subclustering, but he clearly voiced a disbelief in the evidence for superclustering in a 1957 article, as well as at the IAU symposium and in his classification scheme of clusters.[59] In response to Zwicky's denial of the existence of superclusters at the IAU conference, de Vaucouleurs pointed out that the largest clusters acknowledged by Zwicky, with diameters of 20 megaparsecs, were consistent with his definition of a supercluster. De Vaucouleurs' words were, "the disagreement is merely one of terminology, which is trivial."[60] It can be noted that Holmberg thought that foreground galaxies were polluting counts of clusters. In the discussion that followed Holmberg's presentation, Burbidge pointed out that if superclustering were inherent in cluster dynamics the foreground galaxies would be members of the supercluster of which the cluster was a member. He continued, "and the stability of the supercluster comes into question."[61] The dynamics of galaxy clusters was no simple subject.

iii. *Observational Solutions: Faint Galaxies and Intergalactic Matter*

At the IAU Symposium, Abell examined the two very distinct luminosity functions of Hubble and Zwicky, and argued against Zwicky's monotonically rising function. Zwicky defended himself by suggesting that, "to get away from the 'quaint' maxima in the luminosity function of galaxies, one must take very large samples. The luminosity function then rises monotonely."[62,63] Abell replied that, "All functions show the 'quaint' features you refer to... To date, detailed luminosity functions do not exist for a 'large sample' of clusters, so your conclusion that they 'rise monotonely' is purely

[58] By 1964, evidence of subclustering had been revealed in five of seven clusters under examination. See Abell, Neyman & Scott, 1964.
[59] Zwicky, 1957b and 1961. On the basis that very distant ($45{,}000 < V_r < 60{,}000$ $km\ s^{-1}$) clusters were uniformly distributed, he claimed that superclusters did not exist.
[60] Zwicky, 1961, p. 357.
[61] Holmberg, 1961, p. 628.
[62] Abell, 1961, p. 237.
[63] Zwicky had used the term "monotonely" to describe the monotonic rise of the function. However, this is not a word; "monotonically" is the correct term.

hypothetical."[64] Abell and Zwicky were both looking at rich clusters, but there was a clash in their interpretations. Zwicky suggested that a lack of a proper definition of a galaxy was the cause of "erroneous views of the luminosity function."[65]

I have already discussed the inconsistency of galaxy counts, which might have been a result of the inclusion or exclusion of faint galaxies. However, in 1959 the Burbidges argued for the insignificance of faint member galaxies,

> "These nebulae, if they are cluster members, are probably of much smaller mass than the average, in which case they will make an insignificant contribution to the kinetic and potential energy. If, on the other hand, their faintness is due to the fact that they are background objects, it would be incorrect to include them."[66]

Ambartsumian also accepted the idea that the influence of dwarf galaxies on cluster dynamics was negligible, but he pointed out that Zwicky had "rendered great service [by] proving the monotonic increase of the number of galaxies with decrease of luminosity."[67]

In 1933 it was generally believed that intergalactic matter did not exist. Zwicky agreed with the conclusion at the time, but little by little he came to believe that it might be a source of undetected faint matter, and he began a search for it. In 1950, he published his first article describing evidence for the matter.[68] Although the article captured the public's attention, astronomers were not quick to agree with him. A decade later, however, the existence of intergalactic matter was at least a subject of discussion. In 1959 Franz D. Kahn and Lodewijk Woltjer examined the stability of the Local Group and performed a study of intergalactic matter around the Milky Way.[69] They concluded that a distortion of 21-cm line velocities in the Milky Way's disk confirmed the presence of a surrounding intergalactic gas composed mostly of hydrogen and possibly some helium.[70]

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[64] Abell, 1961, p. 237.
[65] Zwicky, 1951, p. 61.
[66] Burbidge & Burbidge, 1959, p. 633.
[67] Ambartsumian, 1961, p. 536.
[68] Zwicky, 1950c.
[69] Kahn & Woltjer, 1959.
[70] Kahn & Woltjer, 1959, p. 707.

Kahn and Woltjer's study provided one of the first plausible cases for the presence of intergalactic matter in the Local Group. G. R. Burbidge authored a summary of the IAU symposium segment on multiple systems, clusters, and radio galaxies in which he stated, "I think that the consensus at the present time is that, in [clusters like the Coma cluster], intergalactic material is present in sufficient quantities to stabilize them."[71] The conclusion was in favour of Zwicky's argument for the importance of intergalactic material.

iv. Consensus of the Conferences

The general opinion among the participants of the two conferences was that the mass discrepancy in clusters of galaxies could be found to have a physical *or* a dynamical solution. The physical solutions included the presence of intergalactic matter and large numbers of faint galaxy members. Dynamically, it was believed that the instability of expanding clusters could explain the discrepancy, as could subcluster and supercluster dynamics. Holmberg ventured to propose, for the first time, that "a number of different effects" should be considered.[72] However, the three effects he outlined were suggestions of carelessness on the part of his colleagues. He thought that if subcluster dynamics were considered, systematic errors in the velocities of member galaxies were eliminated, and field galaxies were taken into consideration, then the problem would be eradicated.

Van den Bergh was the only one to suggest that Newtonian gravity might need to be reviewed.[73] His suggestion was explored in 1963 by Arrigo Finzi, who suggested that rather than follow the inverse square law, the gravitational attraction would decrease more slowly than r^{-2} at large r.[74] That, he claimed, would eliminate the problems of dark matter within galaxies and clusters of galaxies. Finzi's suggestion did not incite any

[71] Burbidge, 1961, p. 261.
[72] Holmberg, 1961, p. 627.
[73] van den Bergh, 1961, p. 570.
[74] Finzi, 1963.

published response (although in more recent years other forms of the law of gravitation have been proposed).

C. *The Popularization of the Dark Matter Problem*

Vera Rubin entered the field of galactic astronomy as a research student at the beginning of the 1950s. She was aware of the controversy surrounding galaxy masses and rotation curves as she began mapping her own rotation curves. It was accepted that there was something amiss in the area of study, but no one was prepared to attack it. Her reason for initiating such studies reflected something of the attitude in itself; it was a research program "that no one would care about while [she] was doing it."[75] By 1970 the use of image intensifiers had reduced photographic exposure times by a factor of 10, a huge advantage for observing galaxies. Rubin teamed up with Kent Ford and his spectrograph to map rotation curves that extended further than previous ones. Whereas previous curves did not clearly show the expected decline of orbital speed, the new observations made it clear that the decline had not been found; "All rotation curves are approximately flat, with only a slight rise or fall following the initial steep gradient."[76] The first dozen curves were met with scepticism and the comment was made: "Well that's because you've observed all the high-luminosity, brighter galaxies. Once you observe the lower luminosities, you'll find falling rotation curves."[77] The connection between the missing mass in clusters of galaxies and that in individual galaxies had been made at the *Conference on the Instability of Systems of Galaxies* in 1961.[78] At first, Rubin did not make the link between her flat rotation curves and the missing mass problem. The connection was demonstrated theoretically in 1974 by Ostriker, Peebles, and Yahil, and then confirmed observationally in 1978 by Rubin.[79,80]

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[75]Rubin, 1997, p. 158.
[76]Rubin, Ford & Thonnard, 1978, p. L107.
[77]Rubin, 1997, p. 160.
[78]Neyman, Page & Scott, 1961b.
[79]Ostriker, Peebles & Yahil, 1974.

D. Summary

The attention paid to the mass discrepancy problem in the 1950s and 1960s raised its profile amongst astronomical researchers. There was no longer much room for Zwicky; though he had discovered the problem and had proposed very credible solutions, he was placed on the sidelines. At the two Santa Barbara conferences, Zwicky's articles and his findings were mentioned in nearly every paper, but in most cases it was in a negative context because his observations were argued against. However, we cannot ignore, nor can we overstate, the victory marked by Burbidge's concession at the close of the talks at the IAU symposium: intergalactic material was present in clusters of galaxies.

Zwicky had been the first to uncover and confront the problems of extragalactic clusters and their mass discrepancy. His observations implied the presence of huge amounts of unobservable mass. Essentially, he was a great conjurer. Perhaps the fact that his name was often mentioned in a negative context was not so much to denigrate him, but to denigrate what he had found. As the first to see the problems of extragalactic dynamics, he dealt with them as he could, but he had broached the subject before its time.

Zwicky's dark matter found company with the great problems of twentieth century astronomy in 1978, four years after his death. The popularization of dark matter within the astronomical community did not come easily. Rubin recollects the reaction to her 1978 paper: "many people initially wished that you did not need dark matter. It was not a concept that people embraced enthusiastically. But I think that the observations were undeniable enough so that most people just unenthusiastically adopted it."[81] The problem had been denied and pushed around for forty-five years, 1933-1978. The problem in itself had not been understood and not many delved into clarifying it. Articles on the discrepancy were scarce, especially in the 1940s and 1950s, and those publications

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[80]Rubin, Ford & Thonnard, 1978.
[81]Lightman and Brawer, 1990, p. 296.

touched on the subject hesitantly and indirectly. No one was ready to confront the skeleton in the cupboard.

Chapter 5
Conclusion

"The pursuit of theoretical science demands as its first prerequisite the constructive imagination of the artist."[1]

James Murphy

"There are more things in the sky than even the most imaginative human mind can divine."[2]

Fritz Zwicky

A. Zwicky's Role in the Discovery of Dark Matter

Zwicky presented many new ideas to astronomy and astrophysics. Throughout his rich and full career, he was always busy with numerous projects. I have presented several of his ideas that were in direct contradiction to those of his colleagues. The outcome of his initial examination of the Coma cluster, in which he found a high velocity dispersion implying either an unbound system or the presence of dark matter, received little attention. He subsequently published many articles on clusters of galaxies in which he only dealt with the mass discrepancy indirectly. I suspect that although he did not verbalize it, he thoroughly understood the uncertainties in his measurements in 1933 and in the years that followed, and that might be why he did not push the issue any further. As I mentioned at the closing of Chapter Three, perhaps he was simply waiting for observation and technology to catch up with theoretical prediction.

[1]Murphy, 1933, p. 38.
[2]Zwicky, 1971a, p. vii.

In 1966 Zwicky recounted a principle that he claimed to have used during his previous 30 years of observing, which states that all matter seeks one of two ultimate states, either condensed in the most compact space or dispersed over the greatest volume.[3] I think it is an interesting principle because it might lead to insight on his ideas about dark matter. I wonder if Zwicky thought missing mass lay in a condensed or in a dispersed form. If it were condensed, would his neutron stars have been candidates to resolve the problem? I cannot find any mention of this suggestion in Zwicky's writings. A wide distribution of faint galaxies or intergalactic material, on the other hand, would fall into the category of dispersed matter.[4] In any case, Zwicky thought the problem lay in the limits of observational astronomy and the presence of matter that was difficult to observe. He expressed that in his observation of faint dwarf galaxies and intergalactic matter. He understood better than anyone else that such faint matter was natural and logical. If luminous matter exhibits itself in a variety of sizes and forms, there is no reason why faint matter should not do the same. Although faint matter may have contributed to the mass discrepancy, it did not eradicate the need for dark matter.

B. Reactions to the Discovery

For a seminal paper to be disregarded at the time of publication is not an uncommon occurrence, but it is not without cause. In looking at why Zwicky's startling result was not received with more enthusiasm, one must wonder if his articles were

[3]Zwicky, 1966. p. 73. He also published a review of compact and dispersed matter in *Advances in Astronomy and Astrophysics*, Zwicky 1970.

[4]In 1953 Zwicky claimed that the luminous intergalactic material was made up of faint, dwarf galaxies, individual stars, thin clouds of stars and dust, and perhaps gas. (Zwicky 1953b, p. 11) In 1967 he updated his inventory to include "intergalactic dust, hydrogen atoms, hydrogen molecules, individual intergalactic stars and pygmy galaxies, very compact luminous galaxies of stellar appearance and dark bodies (starting

widely read. A survey of publications in academic and popular journals reveals that Zwicky's controversial observations were not often cited.[5] The first paper was published in *Helvetica Physica Acta*, a Swiss journal, which van den Bergh has called "a relatively obscure journal."[6] Although that may have contributed to the small readership of his 1933 article, Smith's 1936 article on the Virgo cluster and Zwicky's 1937 studies of galaxy masses were published in the well-known *Astrophysical Journal*. It cannot be ignored that the startling discovery presented in the 1933 article played a very small role in the article itself, the discussion of the Coma cluster's large velocity dispersion being limited to only one of six sections. Concerning the general readership question, Derek Price argues that, "scientists have a strong urge to write papers but only a relatively mild one to read them."[7] Price also gives the following statistics,

> "The norm of the number of papers given as references in a research paper has for many years been constant at a little less than ten. Supposing we read, closely enough to cite them, about 10 papers for every one we actually cite, there would then have been about 100 papers read for every one published. Our tendency to faithfully repeat citations of our favourite and most useful papers only reduces this figure... Perhaps the true research man does not read at all but takes his input in other ways, orally and socially."[8]

Although it is worth consideration, I do not think that any conclusions concerning the lack of impact can be based on readership. We know that Smith had read the 1933 paper,

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from stones up to bodies of planetary size), and dark galaxies composed of cool stars." (Zwicky 1967b, p. 278)

[5]van den Bergh, 2000; also, Westbrook, 1960 and Fisher, 1959.

[6]van den Bergh, 2000, p. 1.

[7]Price, 1963, p. 69 - 70.

[8]Price, 1963, p. 72.

because he responded to it. Hubble must have read Smith's article because in 1936 he said of the discrepancy in the Virgo cluster, "The discrepancy seems to be real and important."[9] Price's final phrase in the above quotation is interesting however, because it opens the possibility that theories become acceptable if they were circulated in the right social circumstances. Steven Shapin supports such a suggestion; "it is the accepted knowledge of the community that adjudicates; reality is filtered through that knowledge and has no unmediated compulsory force."[10] In a similar argument, Fernie compared the astronomical community to "a herd of antelope," following their leader with "firm determination."[11]

Zwicky claimed that Hubble and Baade, two renowned astronomers in the 1930s, were at fault for having denied the existence of galaxies substantially less luminous than about one hundred million suns, the existence of intergalactic matter, and the tendency of galaxies to form clusters. He claimed that the ideas circulated by Hubble and Baade persisted "in the minds of most astronomers for decades."[12] The dominance of the views of those two highly respected astronomers could explain in part why Zwicky's ideas, many of which are now accepted as correct, were not given the attention they deserved. For example, the establishment of Hubble's average galactic mass is puzzling. The astronomical community readily accepted the estimate in an era when observational measurements contained more than their fair share of uncertainties.[13] Smith, Babcock, and Holmberg were alone in noting the inconsistencies between their own measurements and Hubble's mean galaxy mass estimate. Zwicky had also found problems with

[9]Hubble, 1936a, p. 180.
[10]Shapin, 1990, p. 163.
[11]Fernie, 1969, p. 719-720.
[12]Zwicky, 1971a, p. vii.

Hubble's luminosity function, and with his claim that galaxies were randomly distributed and did not tend to cluster. He blamed Hubble for the persistence of such "glaringly incorrect conclusions."[14] Although Hubble was generally a well-liked character, Allan Sandage recalls that he was "a very private man; he did not interact very much with his colleagues."[15] Walter Adams (1876-1956), the director of Mount Wilson in the 1920s and 1930s, wrote to his successor, Ira Bowen (1898-1973) in 1947 revealing "his deep distaste for Hubble, whom he claimed had done little work of the first order for twenty years and at sixty is still eager for notoriety and has his press agent continuously at work."[16] Perhaps the conflict between Hubble and Zwicky, and their respective scientific beliefs, was not only caused by Zwicky's character, but also by that of Hubble. The importance of such a conflict is difficult to argue without further details of the personal lives of the two astronomers, which is beyond the scope of this thesis.

Could Zwicky's personality have been a factor in the apparent unwillingness of others to pay heed to his discovery? There are undertones in obituaries and biographies that Zwicky was not an amiable fellow. Trimble expressed what I think might be the truth of the matter,

> "A good deal of secondary literature characterizes Zwicky as opinionated, cantankerous, and otherwise generally difficult to get along with, but these traits seem to have been strongly balanced by a deep devotion to family and close

[13]It is equally puzzling that the distance scale remained erroneous for four decades. See Fernie, 1969.
[14]Zwicky, 1971a, p. vii.
[15]Sandage quoted in Sharov and Novikov, 1993, p. 81.
[16]Osterbrock, 1995, p. 26.

friends, serious involvement in charitable endeavours, and a sort of old-fashioned chivalry toward those he perceived as relatively defenceless."[17]

Zwicky was arrogant, as we have seen in his preaching of the morphological approach. But he was successful, and although the value of his theories and observations was not immediately recognized, they have come to play a role in modern astronomy. Even his measurement of velocity dispersions in the Coma cluster is remarkable, given that it was based on the velocities of only eight galaxies. Zwicky estimated the value for the Coma cluster to be 1019 km s^{-1}, while it is established today to be 1082 km s^{-1}.[18,19]

It must not be forgotten that the late 1930s and the 1940s were tumultuous times. Not only had the Second World War put pure science research on hold, but the approach to the problems of astronomy was changing with advancements in technology. Zwicky was apparently not inhibited by the war, 1942 being a particularly productive year for him with six articles published on galaxy clusters.[20] Aside from those of Zwicky, publications relevant to the mass discrepancy problem were scarce in the 1940s and into the 1950s. It cannot be concluded that World War Two was the sole reason for the scarcity, because in the ten years following the end of the war only three articles were published on clusters of galaxies.[21] The mass discrepancy was an important problem for extragalactic astronomy and for cosmology, but few seemed to be concerned with it.

Alteration of established ideas does not come easily. Price has claimed that, "perhaps it is even desirable that many of the important discoveries should be made two

[17]Trimble, 1992, p. 294.
[18]Colless and Dunn, 1996.
[19]Although the two values are similar, they both contain error and it is really somewhat of a coincidence that they are so similar. I do not wish to imply that his measurement was that accurate.
[20]Zwicky, 1942a, 1942b, 1942c, 1942d, 1942e, and 1942f.
[21]Omer, 1952; Schwarzschild, 1954; Shane & Wirtanen, 1954.

or three times over in an independent and slightly different fashion."[22] In many cases, the acceptance of new ideas, no matter how lucid the evidence, takes time. That is perhaps an effect of the "herding" tendency. Rubin also recognized that with the comment; "We scientists really change our ideas very slowly. We demand (I think we have to) an enormous amount of evidence before we will change our minds."[23] Extragalactic astronomy only became a field of study in 1924, and early ideas concerning the structure and dynamics of the extended universe would have been met initially with caution.

The scarcity of interest in the problem can be attributed to all of the factors I have suggested — foremost are Zwicky's personality, his relationship with his colleagues, and the general hesitancy to accept that something was amiss in the "accepted" view of the universe, as well as the premature state of extragalactic astronomy and the influence of the Second World War.

C. *Lunatic on a Mountain*

I have addressed two questions: What was the actual sequence of events? What was Zwicky's role in the unveiling of one of today's leading astronomical mysteries? Essentially, Zwicky discovered dark matter before the astronomical community was prepared to fully comprehend its implications and deal with them. But his proposal that dark matter was a dominant feature in the universe was not erroneous, since his observations were supported by the later work of Smith, Holmberg, and Babcock.[24] A number of factors account for the lack of interest regarding the mass discrepancy and the need for dark matter, among them Zwicky's personality and reputation. A short

[22]Price, 1963, p. 70.
[23]Rubin, 1997, p. 160.

biography has been presented to explore that possibility. However, a more complete examination of Zwicky's life is needed to address such ideas in greater detail. It should provide further information about his role in the astronomical community and details regarding his relationships and conflicts with his colleagues.

All in all, now that the presence of dark matter has been established, we can appreciate that Zwicky demonstrated a principle that is essential for understanding the nature of our universe by showing that matter can be detected indirectly from its gravitational effects, even if it cannot be observed directly. He demonstrated that there is much more mystery in the universe than we can imagine. He demonstrated that wonderment, even in science, must never be forgotten. Zwicky searched out unconquered peaks and boldly surmounted them. Like Democritus, he may have sounded like a lunatic on a mountain, but he spoke from the deepest boundaries of his rational self.

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[24]Smith, 1936; Babcock, 1939; Holmberg, 1937 and 1940.

Appendix A
The Virial Theorem[1]

The (Scalar) Virial Theorem is derived using the mechanics of Newtonian gravitation, and its application to clusters of galaxies assumes that the cluster is time-independent and that the only interaction within the cluster is gravity. In 1870 Rudolf Clausius first formulated the theorem, which states that the average potential energy of a system is twice the average kinetic energy.[2] It is used to estimate the total mass of a galaxy or a cluster of galaxies.

Newton's fundamental law of motion for each galaxy i in a cluster is

$$\vec{F_i} = m_i \frac{d^2 \vec{r_i}}{dt^2} \qquad (1)$$

where $\vec{F_i}$ is the vector force acting on each galaxy, m_i is the mass of galaxy i, and $\vec{r_i}$ is the radius vector from the galaxy to the cluster centre of mass. The dot product of (1) with $\vec{r_i}$ yields

$$\vec{F_i} \cdot \vec{r_i} = m_i \left(\frac{d^2 \vec{r_i}}{dt^2} \right) \cdot \vec{r_i} \qquad (2)$$

We will first evaluate the right hand side,

$$\frac{d^2}{dt^2}\left(\vec{r_i}^{\,2} \right) = \frac{d}{dt}\left[2\vec{r_i} \cdot \frac{d}{dt}\vec{r_i} \right]$$

$$\frac{d^2}{dt^2}\left(\vec{r_i}^{\,2} \right) = 2\frac{d}{dt}\vec{r_i} \cdot \frac{d}{dt}\vec{r_i} + 2\vec{r_i} \cdot \frac{d^2}{dt^2}\vec{r_i}$$

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[1]Based primarily on Zwicky, 1937a, p. 227-237; Zwicky, 1957a, p. 129-134 .

$$\frac{d^2}{dt^2}\left(\vec{r}_i^{\,2}\right) = 2\left(\frac{d\vec{r}_i}{dt}\right)^2 + 2\vec{r}_i \cdot \frac{d^2}{dt^2}\vec{r}_i . \qquad (3)$$

By substituting (3) into (2) we have

$$\vec{F}_i \cdot \vec{r}_i = \frac{1}{2}\frac{d^2}{dt^2}\left(m_i \vec{r}_i^{\,2}\right) - m_i\left(\frac{d\vec{r}_i}{dt}\right)^2 \quad . \qquad (4)$$

The kinetic energy E_k and the moment of inertia I of the system of n galaxies are defined

as,
$$E_k = \sum_{i=1}^{n} \frac{1}{2} m_i \left(\frac{d\vec{r}_i}{dt}\right)^2 ,$$

and
$$I = \sum_{i=1}^{n} m_i \vec{r}_i^{\,2} ,$$

respectively. Now sum equation (4) over all galaxies and substitute the definition of E_k and I. When averaged over time the result is

$$\frac{1}{2}\left\langle \frac{d^2 I}{dt^2} \right\rangle = \left\langle \sum_{i=1}^{n} \vec{F}_i \cdot \vec{r}_i \right\rangle - 2\langle E_k \rangle . \qquad (5)$$

The Virial of Clausius is defined as

$$Virial = \sum_{i=1}^{n} \vec{F}_i \cdot \vec{r}_i .$$

The virial can be calculated for the mutual gravitation between galaxies i and j. Thus, it can be shown that

$$\sum_{i=1}^{n} \vec{F}_i \cdot \vec{r}_i = -G\sum_{i=1}^{n}\sum_{j\neq 1}^{n} \frac{m_i m_j}{\vec{r}_{ij}}$$

[2] Clausius, [1965(1870)].

where G is the gravitational constant and $r_{ij} = \left|\vec{r_i} - \vec{r_j}\right|$ is the distance between the galaxies i and j. The gravitational potential energy E_p is defined as

$$E_p = -\sum_{i=1}^{n} \sum_{j \neq 1}^{n} \frac{Gm_i m_j}{r_{ij}}$$

which leads equation (3) to become,

$$\frac{1}{2}\left\langle \frac{d^2 I}{dt^2} \right\rangle = \langle E_p \rangle + 2\langle E_k \rangle . \qquad (6)$$

For a stationary system, the moment of inertia becomes arbitrarily close to a constant when averaged over sufficiently long times, so that the time average of its derivatives is zero.

Thus, the relationship between the average total gravitational potential energy $<E_p>$ and the average total kinetic energy $<E_k>$ of a stationary bounded system can be expressed as,

$$\langle E_p \rangle = -2\langle E_k \rangle .$$

These terms can be written as

$$\langle E_p \rangle = \frac{GM^2}{aR}, \text{ and}$$

$$\langle E_k \rangle = \frac{1}{2} Mb\langle v^2 \rangle ,$$

where a and b are constants that allow for the fact that only projected separations and radial components of velocity can be observed. Therefore, the mass of the system M can be calculated as,

$$M = \frac{\alpha R\langle v^2\rangle}{G}$$

where R is the Virial radius of the system, $<v^2>$ is the velocity dispersion, and $\alpha = ab$ is a constant determined by the mass distribution in the system. A uniform spherical distribution is commonly assumed for a cluster of galaxies, for which case $\alpha = 5/3$.[3]

However, the standard form of the theorem may be modified in order to consider other sources of gravitational influence. D. Nelson Limber, in his 1959 article, discussed the application of the Virial theorem to clusters of galaxies, and he attempted to account for the effects of intracluster gas and dust by deriving a modified Virial theorem.[4] The result was the following expression for the velocity dispersion $<v_G^2>$:

$$\langle v_G^2\rangle = \frac{G(aM_G + bM_g)}{R}$$

where the mass of the galaxies M_G and the mass of the gas M_g are weighted with values for a and b that describe the relative spatial distributions of the two mass components, and R is the Virial radius of the cluster. Limber also discussed the Virial Theorem at the 1961 conference on the instability of clusters, where he addressed Chandrasekhar's tensor form of the theorem and the corresponding contracted scalar forms, as well as his own modified version.[5]

Possible background and foreground objects are source of great uncertainty. They can be identified and eliminated by considering their positions and radial velocities; for example, by examination of a plot of the right ascension and declination of galaxies in Cartesian coordinates, of a velocity histogram for the distribution of bound members

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[3]Zwicky, 1937a, p. 229.
[4]Limber, 1959.

(which is assumed to be Gaussian), and/or of a polar co-ordinate plot of right ascension and radial velocity for groupings of cluster members.

Once a total mass is identified for a cluster of galaxies, the mean nebular mass can be obtained by dividing the total mass by the number of members. Dark matter was revealed when the mass established from Virial estimates was compared with the mass inferred from the observed luminosities of cluster galaxies.

[5] Limber, 1961.

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