Publications of the Astronomical Society of the Pacific, **111**:657–660, 1999 June

Invited Review

The Early History of Dark Matter

Sidney van den Bergh

Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, National Research Council of Canada, 5071 West Saanich Road, Victoria, BC V8X 4M6, Canada; sidney.vandenbergh@hia.nrc.ca

Received 1999 February 8; accepted 1999 February 18

ABSTRACT. The history of the discovery of dark matter in the universe is briefly reviewed. Special emphasis is placed on the early work by Zwicky, Smith, Babcock, and Oort.

It is not certain how these startling results must ultimately be interpreted.—Zwicky (1957, p. 132)

1. EARLY HISTORY

The discovery by Zwicky (1933) that visible matter accounts for only a tiny fraction of all of the mass in the universe may turn out to have been one of the most profound new insights produced by scientific exploration during the 20th century. From observations of the radial velocities of eight galaxies in the Coma Cluster, Zwicky found an unexpectedly large velocity dispersion, $\sigma = 1019 \pm 360$ km s^{-1}. (If the most deviant galaxy is rejected as a foreground object, the velocity dispersion becomes $\sigma = 706 \pm 267$ km s^{-1}.) It is noted in passing that Zwicky's velocity dispersion from only eight galaxies agrees well with the modern value, $\sigma = 1082$ km s^{-1} obtained by Colless & Dunn (1996). Zwicky concluded from these observations that, for a velocity dispersion of 1000 km s^{-1}, the mean density of the Coma Cluster would have to be 400 times greater than that which is derived from luminous matter. Zwicky overestimated the mass-to-light ratio of the Coma Cluster because he assumed a Hubble parameter $H_0 = 558$ km s^{-1} Mpc^{-1}. His value for the overdensity of the Coma Cluster should therefore be reduced from 400 to $\sim$50.[1] Zwicky writes (my translation): "If this [overdensity] is confirmed we would arrive at the astonishing conclusion that dark matter is present [in Coma] with a much greater density than luminous matter." He continues: "From these considerations it follows that the large velocity dispersion in Coma (and in other clusters of galaxies) represents an unsolved problem." It is not yet clear what the basis was for Zwicky's claim that other clusters also exhibited a missing mass problem. Not until 3 years later (Smith 1936) was it found that the Virgo Cluster also appears to exhibit an unexpectedly high mass. Smith made the interesting speculation that the excess mass of Virgo "represents a great mass of internebular material within the cluster." In his famous 1933 paper Zwicky also writes: "It is, of course, possible that luminous plus dark (cold) matter[2] together yield a significantly higher density." A quarter of a century later Kahn & Woltjer (1959) pointed out that M31 and the Galaxy were moving toward each other, so that they must have completed most of a (very elongated) orbit around each other during a Hubble time. Assuming that M31 and the Galaxy started to move apart 15 Gyr ago, these authors found that the mass of the Local Group had to be $\gtrsim 1.8 \times 10^{12}\ M_\odot$. Assuming that the combined mass of the Andromeda galaxy and the Milky Way system was $0.5 \times 10^{12}\ M_\odot$, Kahn & Woltjer concluded that most of the mass of the Local Group existed in some invisible form. They opined that it was most likely that this missing mass was in the form of very hot (5×10^5 K) gas. From a historical perspective, it is interesting to note that Kahn & Woltjer did not seem to have been aware of the earlier papers by Zwicky (1933) and Smith (1936) on missing mass in clusters of galaxies.

2. THE DARK AGES

Six years after Zwicky's paper, Babcock (1939) obtained long-slit spectra of the Andromeda galaxy, which showed

[1] It is of interest to note that Hubble's prestige was so great that none of the early authors thought of reducing Hubble's constant as a way of lowering their mass-to-light ratios.

[2] Zwicky's use of the words "*dunkle* (*kalte*) *Materie*" might be regarded as the first reference to cold dark matter, even though this expression was not used exactly in its modern sense. The term "cold dark matter," with its modern meaning, was introduced by Bond et al. (1983).

that the outer regions of M31 were rotating with an unexpectedly high velocity, indicating either (1) a high outer mass-to-light ratio or (2) strong dust absorption. Babcock wrote: "The great range in the calculated ratio of mass to luminosity in proceeding outward from the nucleus suggests that absorption plays a very important rôle in the outer portions of the spiral, or, perhaps, that new dynamical considerations are required, which will permit of a smaller relative mass in the outer parts." Subsequently, Babcock's optical rotation curve, and that of Rubin & Ford (1970), was extended to even larger radii by Roberts & Whitehurst (1975) using 21 cm line observations that reached a radial distance of ~ 30 kpc. These observations clearly showed that the rotation curve of M31 did not exhibit a Keplerian drop-off. In fact, its rotational velocity remained constant over radial distances of 16–30 kpc. These observations indicated that the mass in the outer regions of the Andromeda galaxy increased with galactocentric distance, even though the optical luminosity of M31 did not. From these observations Roberts & Whitehurst concluded that the mass-to-light ratio had to be $\gtrsim 200$ in the outermost regions of the Andromeda galaxy. It is interesting to note that neither Babcock, nor Roberts & Whitehurst, cited the 1933 paper by Zwicky. In other words, no connection was made between the missing mass in the outer region of a spiral and the missing mass in rich clusters such as Coma (Zwicky 1933) and Virgo (Smith 1936). Roberts & Whitehurst suggested that the very high mass-to-light ratio that they observed in the outer regions of M31 might be attainable by postulating the presence of a vast population of dM5 stars in the outer reaches of the Andromeda galaxy. Regarding the flat outer rotation curves of galaxies, M. S. Roberts (1999, private communication) recalls that this result "was, at best, received with skepticism in many colloquia and meeting presentations."

From a historical perspective the paper by Roberts & Whitehurst was important because it, together with papers on the stability of galactic disks by Ostriker & Peebles (1973), and on the apparent increase of galaxy mass with increasing radius (Ostriker, Peebles, & Yahil 1974), first convinced the majority of astronomers that missing mass existed. Ostriker & Peebles concluded that barlike instabilities in galaxy disks could be prevented by a massive spherical (halo) component. They wrote that "the halo masses of our Galaxy and of other spiral galaxies exterior to the observed disks may be extremely large." However, this conclusion was later contested by Kalnajs (1987), who concluded that massive bulges are more efficient at stabilizing disks than are halos. "In the end it may well be that a massive halo is an important stabilizing influence on most galactic disks" (Binney & Tremaine 1987).

Observations obtained during the last quarter-century have strongly supported the conclusions by Ostriker, Peebles, & Yahil that (1) the mass-to-light ratios of galaxies grow larger with increasing radius and (2) this missing mass is large enough to be cosmologically significant. The inference that observations of the inner regions of galaxies underestimate their total mass had already been anticipated by Zwicky (1937), who wrote: "Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained." It is noted in passing that Zwicky (1937) also points out that gravitational lensing might provide useful information on the total masses of galaxies.

With his unusually fine nose for "smelling" the presence of interesting astronomical problems, Oort (1940) studied the rotation and surface brightness of the edge-on S0 galaxy NGC 3115. He found that "the distribution of mass in this system appears to bear almost no relation to that of light." He concluded that $M/L \sim 250$ in the outer regions of NGC 3115. However, this value is reduced by almost an order of magnitude if modern distances to this galaxy are adopted. Oort ended his paper by writing that "there cannot be any doubt that an extension of the measures of rotation to greater distances from the nucleus would be of exceptional interest." Again no connection was made between the missing mass in this S0 galaxy and the Zwicky/Smith missing mass problem in rich clusters of galaxies. Finally, X-ray observations of early-type galaxies (Forman, Jones, & Tucker 1985), which provide a unique tracer for the gravitational potential in the outer regions of these objects, confirmed that they must be embedded in massive coronae.

No good detective story is complete without at least one false clue. Oort (1960, 1965) believed that he had found some dynamical evidence for the presence of missing mass in the disk of the Galaxy. If true, this would have indicated that some of the dark matter was dissipative in nature. However, late in his life, Jan Oort told me that the existence of missing mass in the Galactic plane was never one of his most firmly held scientific beliefs. Recent observations, which have been reviewed by Tinney (1999), show that brown dwarfs cannot make a significant contribution to the density of the Galactic disk near the Sun.

A third line of evidence (see Table 1) for the possible existence of dark matter was provided by a statistical analysis of the separations, and velocity differences, between the members of pairs of galaxies. The data in the table are seen to be somewhat ambiguous, but not inconsistent with the notion that significant amounts of nonluminous matter might be associated with galaxy pairs. The idea that we are looking at the same missing mass phenomenon in galaxies, in pairs, and in clusters was first discussed in detail at the Santa Barbara Conference on the Stability of Systems of Galaxies (Neyman, Page, & Scott 1961). In his introduction to this conference, and after excluding various alternatives,

TABLE 1

MASS-TO-LIGHT RATIOS IN BINARY SYSTEMS[a]

Galaxy Type	M/L Page 1960	M/L van den Bergh 1961
E + E	66 ± 27	35 ± 14
E + S..................	34 ± 20	18 ± 16
S + S and S + Ir......	0.2 ± 0.2	3 ± 3

[a] $H_0 = 70$ km s^{-1} Mpc^{-1} assumed.

Ambartsumian (1961) concluded: "Thus there is only one natural assumption left relating to the clusters cited above—they have positive total energies." If this conclusion were correct, then rich clusters of galaxies would disintegrate and scatter their galactic content into the field, on a timescale that is short compared with the age of the universe. However, van den Bergh (1962) pointed out that this hypothesis had to be incorrect because such a large fraction of all early-type galaxies are presently cluster members. He therefore concluded "that such a large fraction of all galaxies are at present members of clusters suggests that most clusters are stable over periods comparable to their ages." If clusters of galaxies are stable, then we are stuck with the high mass-to-light ratios, which are calculated from application of the virial theorem. Einasto, Kaasik, & Saar (1974) first pointed out that the gas in such rich clusters, which had been discovered from its X-radiation, did not have a large enough mass to stabilize these clusters. For an excellent review on dark matter during the "Middle Ages" the reader is referred to Ashman (1992).

3. RECENT HISTORY

By 1975 the majority of astronomers had become convinced that missing mass existed in cosmologically significant amounts. However, it was not yet clear whether this mass was in the form of late M dwarfs, brown dwarfs, white dwarfs, black holes, very hot gas, or in some, as yet unsuspected, form. Rees (1977) concluded: "There are other possibilities of more exotic character—for instance the idea of neutrinos with small (few ev) rest mass has been taken surprisingly seriously by some authors." In other words it was not yet clear in 1977 that a paradigm shift (Kuhn 1962) would be required to interpret the new observations that seemed to support the ubiquitousness of missing matter in the universe. Alternatively, it has also been speculated (Milgrom & Bekenstein 1987) that such a paradigm shift might not be required if Newton's laws break down at small accelerations. The idea that neutrinos (hot dark matter) could provide the missing matter was downplayed by White, Davis, & Frenk (1984), who concluded that "the properties of the neutrino aggregates expected in a neutrino-dominated universe are incompatible with observations irrespective of the efficiency with which they form galaxies." The very high dark matter densities in dwarf spheroidal galaxies, in conjunction with the Pauli exclusion principle, also place severe constraints on neutrino dark matter models (Tremaine & Gunn 1979). The idea that the missing mass might be in the form of "cold dark matter," which dominates current speculation on this subject, appears to have been introduced by White (1987). Current "best buy" models of the universe (Roos & Harun-or-Rashio 1999; Turner 1999) suggest that cold dark matter accounts for $30\% \pm 10\%$ of the closure density of the universe, compared with only $0.04\% \pm 0.01\%$ in the form of baryonic matter. If such models are correct, then more than $\frac{2}{3}$ of the closure density is in the form of vacuum energy, or in even more exotic states (Wang et al. 1999).

It is a pleasure to thank Dick Bond, Don Osterbrock, Jim Peebles, Mort Roberts, and Simon White for sharing some of their historical reminiscences with me. I also wish to thank the editors of the PASP for inviting me to expand a short talk on the early history of dark matter, which I gave at the Dominion Astrophysical Observatory last year, into a paper for these Publications.

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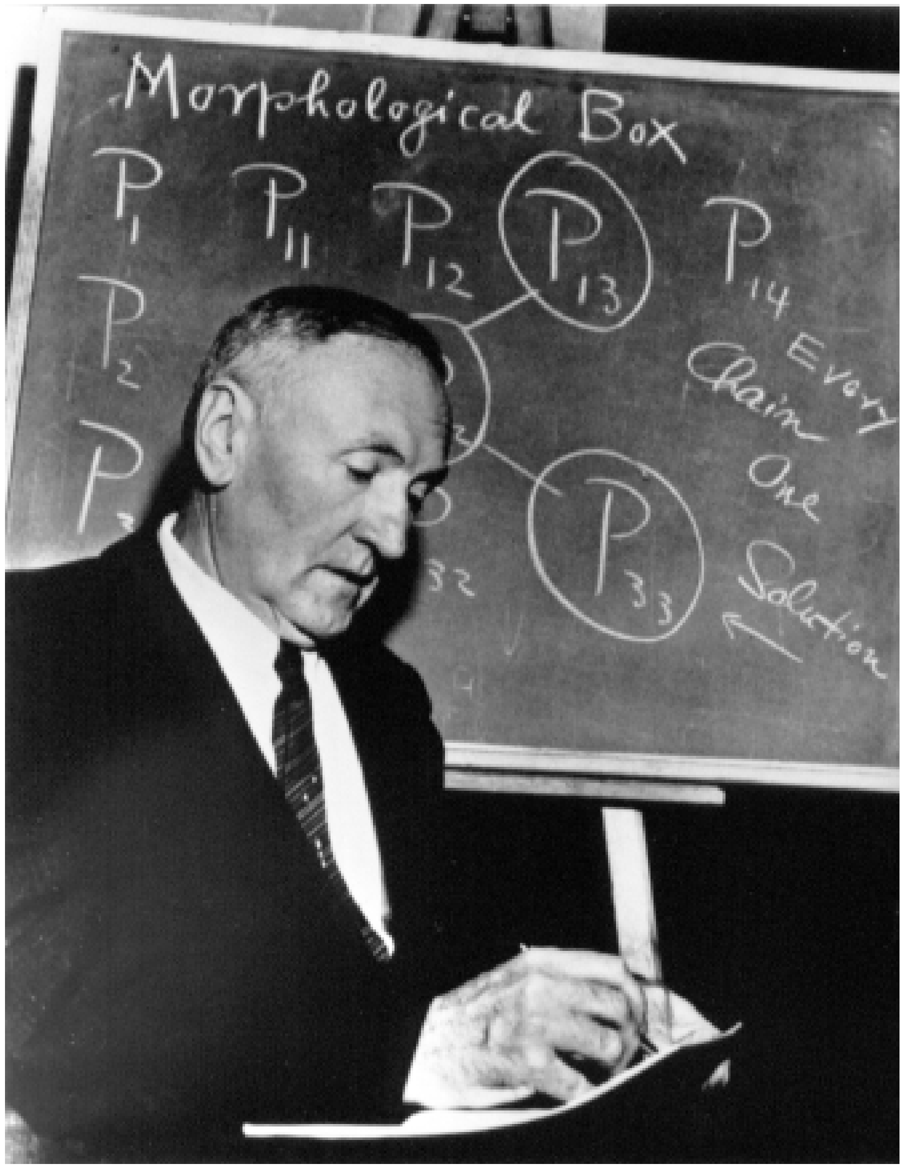
by STEPHEN M. MAURER

IDEA MAN

Sixty years ago, Fritz Zwicky was the only astronomer who thought that dark matter, neutron stars, and gravitational lenses were worth worrying about.



Astronomical Society of the Pacific

WHEN FRITZ ZWICKY DIED IN 1974, he was remembered as a gifted observational astronomer who had discovered more supernovae than everyone else in human history combined. Today, Zwicky's reputation is bigger than ever, except that now astronomers think of him as a theorist. When researchers talk about neutron stars, dark matter, and gravitational lenses, they all start the same way: "Zwicky noticed this problem in the 1930s. Back then, nobody listened . . ."

Previous page: Fritz Zwicky invented a technique called morphology in order to think more efficiently. He is pictured here in the 1950s doing just that.
Opposite: Fritz Zwicky at the Mt. Wilson 24-in. telescope in approximately the late 1930s. (Courtesy of the Archives, California Institute of Technology)

Fritz Zwicky was born in Bulgaria in 1898 but went to live with his grandparents in Switzerland at age six. In 1916, he enrolled in Zurich's Swiss Federal Institute of Technology to study mathematics, engineering, and physics. With World War I raging, Switzerland provided a haven for many of Europe's greatest minds. Zwicky met Albert Einstein, Wolfgang Pauli, and Vladimir Lenin. After graduation, Zwicky stayed on to pursue a degree in theoretical physics. His thesis applied the new science of quantum mechanics to crystals. He received his doctorate in 1922.

In 1925, the Rockefeller Foundation—eager to bring quantum mechanics to the United States—gave Zwicky a fellowship. A lifelong skier and mountain climber, Zwicky asked the Foundation to send him "where there are mountains." Trying to comply, the Foundation sent him to the California Institute of Technology. Zwicky grumbled that Pasadena only had "foothills." Nevertheless, Caltech was a happy choice. At nearby Mt. Wilson, Edwin Hubble was working on his famous redshift relation. Zwicky began thinking about astronomy. When his fellowship ended, Caltech hired Zwicky as a professor.

ZWICKY BEGAN collaborating with a fellow German-speaker named Walter Baade in 1931. Astronomers knew that certain stars flared abruptly from time to time. Although most of these "novae" were close to the Earth, Baade noticed that a few old records described novae inside galaxies. During the 1920s, astronomers at Mt. Wilson had shown that galaxies were immensely distant. In order to be seen at all, Baade and Zwicky realized that these "super-novae" had to be enormously bright (100 million times brighter than the Sun). They announced their discovery at an American Physical Society meeting in late 1933.

Not content with this empirical result, Baade and Zwicky added two key theoretical insights. First, they connected supernovae to the mysterious high altitude particles known as cosmic rays. Unfortunately, their evidence—which was limited to the "surprisingly good agreement" in energy between the two phenomena—remained circumstantial. Although Zwicky spent much of the 1930s trying to explain how particles heated inside an exploding supernova could escape into space, he admitted that his results fell "well short" of what was needed. The correct answer was found in 1949, when Enrico Fermi realized that shock waves hitting interstellar gas could produce cosmic rays outside the supernova itself.

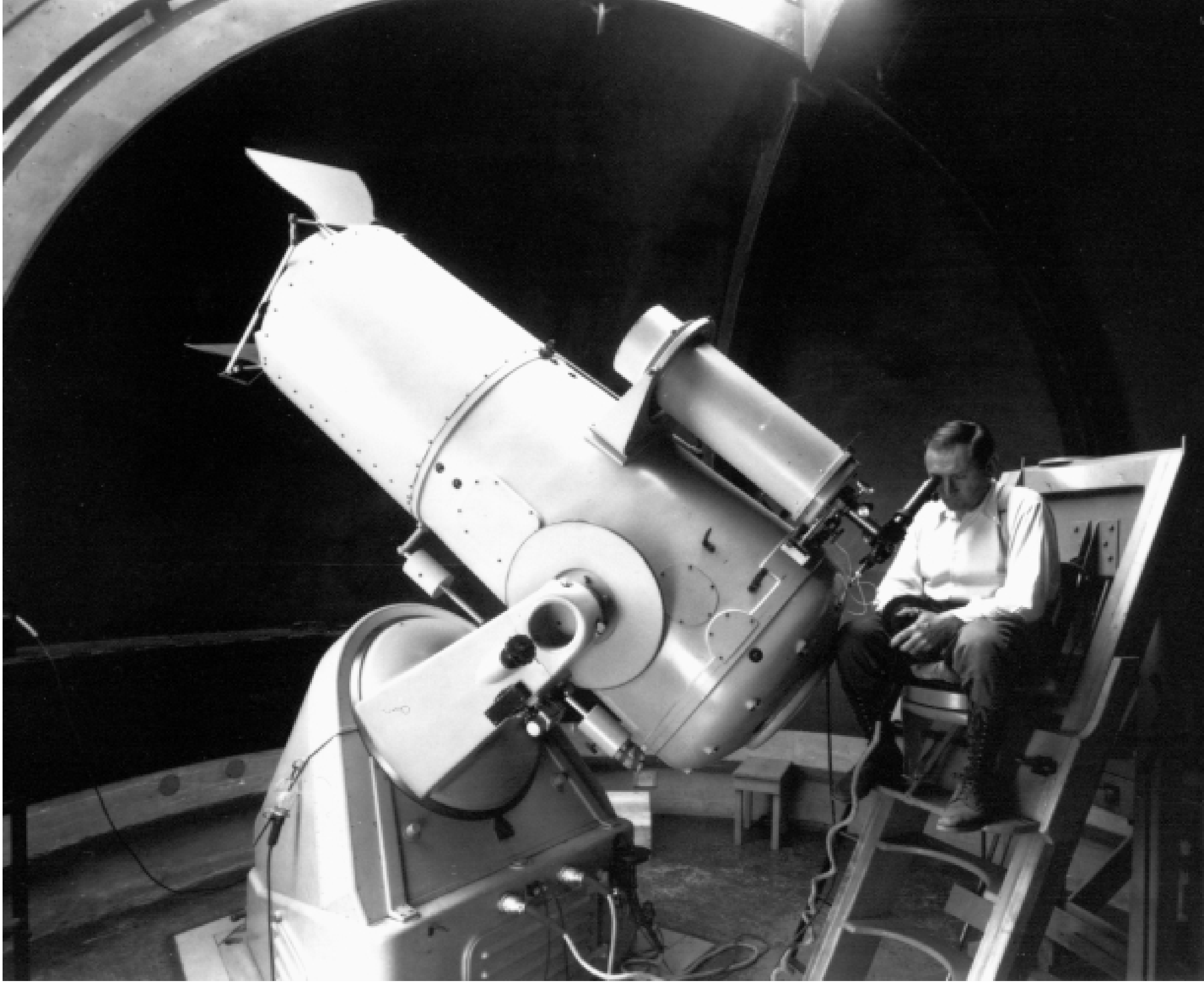
Second, Baade and Zwicky tried to explain how such titanic explosions could occur at all. Then as now, any reasonable theory had to involve gravitational collapse. However, a simple calculation showed that the collapsing progenitor star had to free-fall over enormous distances in order to liberate enough energy. Unless the supernova remnant was unbelievably small (and dense) the process would stop too soon. By the early 1930s, quantum calculations had shown that the required densities could not be met by any form of matter that contained electrons.

The breakthrough came when English physicist James Chadwick discovered the neutron in 1932. Suppose that the star's electrons and protons could be turned into neutrons? "With all reserve," Baade and Zwicky wrote in March 1934,

> ". . .we advance the view that a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the 'gravitational packing' energy in a cold neutron star may become very large, and, under certain circumstances, may far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such."

Zwicky spent the next forty years pointing out that this comment had "checked out in all essential aspects." However, it was largely ignored until Robert Oppenheimer and George Volkoff worked out the detailed physics of stellar collapse in 1939 without mentioning Zwicky's research. Even then, final confirmation had to wait until radio astronomers discovered the extraordinarily dense objects called "pulsars" in 1967.

IN ORDER TO LEARN more, Baade and Zwicky had to discover new supernovae. However, the chance of finding a supernova in any given galaxy was small, and conventional telescopes could only examine a few galaxies at a time. Fortunately, Baade had heard of a special telescope that could capture huge numbers of galaxies in a single, wide-angle photograph. Zwicky persuaded



Caltech to build an 18-inch "Schmidt camera" in 1936. Zwicky used this instrument for the rest of his life, finding 129 supernovae in all. Beyond their intrinsic interest, Zwicky believed that supernovae would "eventually allow us to survey the universe to distances of billions of light years." That dream is only now coming true. (See "The Fate of the Universe" by Gerson Goldhaber and Judith Goldhaber in the Fall 1997 *Beam Line*, Vol. 27, No. 3.)

Zwicky's supernova search had an unexpected spinoff. Conventional telescopes had shown that a few nearby galaxies were part of larger clusters. Now, Zwicky used the Schmidt to find new and more distant examples. These observations proved that clusters were the rule and not the exception.

ASTRONOMERS HAD already measured velocities for most of the galaxies inside Zwicky's clusters. In 1937, Zwicky used astronomy's "virial theorem" to infer the clusters' masses from these data. (The virial theorem says that the total mass of a group of orbiting bodies can be estimated from the velocity of its components. This is because, all else being equal, bodies in more massive systems must travel faster in order to resist the increased pull of gravity.) This led to a paradox. Based on data from the Milky Way, Zwicky should have been able to guess each cluster's mass from its observed brightness. This estimate turned out to be 500 times too small. Had Nature hidden the extra mass in a second, unseen component? Zwicky dubbed the substance "dark matter."

Most astronomers ignored Zwicky's result, much as Zwicky himself had

Zwicky believed that supernovae would "eventually allow us to survey the Universe to distances of billions of light years." That dream is only now coming true.

ignored an earlier paper by Johannes Kapetyn and Sir James Jeans on the ground that stellar motions inside the Milky Way were too complicated to interpret. Undaunted, Zwicky spent most of the next two decades conducting searches for previously overlooked gas and dust. In 1950, this dim object search uncovered starry "bridges" between galaxies, which Zwicky correctly attributed to near-collisions. Later searches found "pygmy stars" within the Milky Way and "faint blue stars" that were actually distant galaxies. Today we know that the latter objects are closely related to quasars.

Beginning in 1974, cosmologists began to rediscover the arguments for dark matter. Today, it is one of astronomy's hottest research topics.

THE IDEA that massive bodies can act as lenses goes back to the eighteenth century and received its most famous formulation in Albert Einstein's 1916 General Theory of Relativity. In 1935, a Czechoslovakian engineer named R. W. Mandl wrote to Einstein suggesting that nearby stars could act as gravitational lenses by bending light from more distant objects. (The physicist Oliver Lodge had made a similar suggestion in 1919.) Initially intrigued, Einstein soon became discouraged after calculating that the lensed image would almost certainly be overwhelmed by glare from the foreground star.

Meanwhile, word of Mandl's ideas had reached Zwicky. Zwicky realized that foreground glare could be overcome if searchers used galaxies instead of stars. In 1937, Zwicky published three articles predicting that lensed galaxies would not only be amplified, but also bent into a distinctive ring. For the rest of his life, Zwicky begged astronomers to search for lensed galaxies. Finding even one lens, he insisted, could test general relativity; deliver light from unprecedented distances; and give astronomers a new way to detect dark matter. These are the same reasons that astronomers give for studying lensed galaxies today.

Zwicky was so confident of his prediction that he sometimes wondered why lensing hadn't been noticed already. In fact, the first gravitational lens was found five years after Zwicky's death.

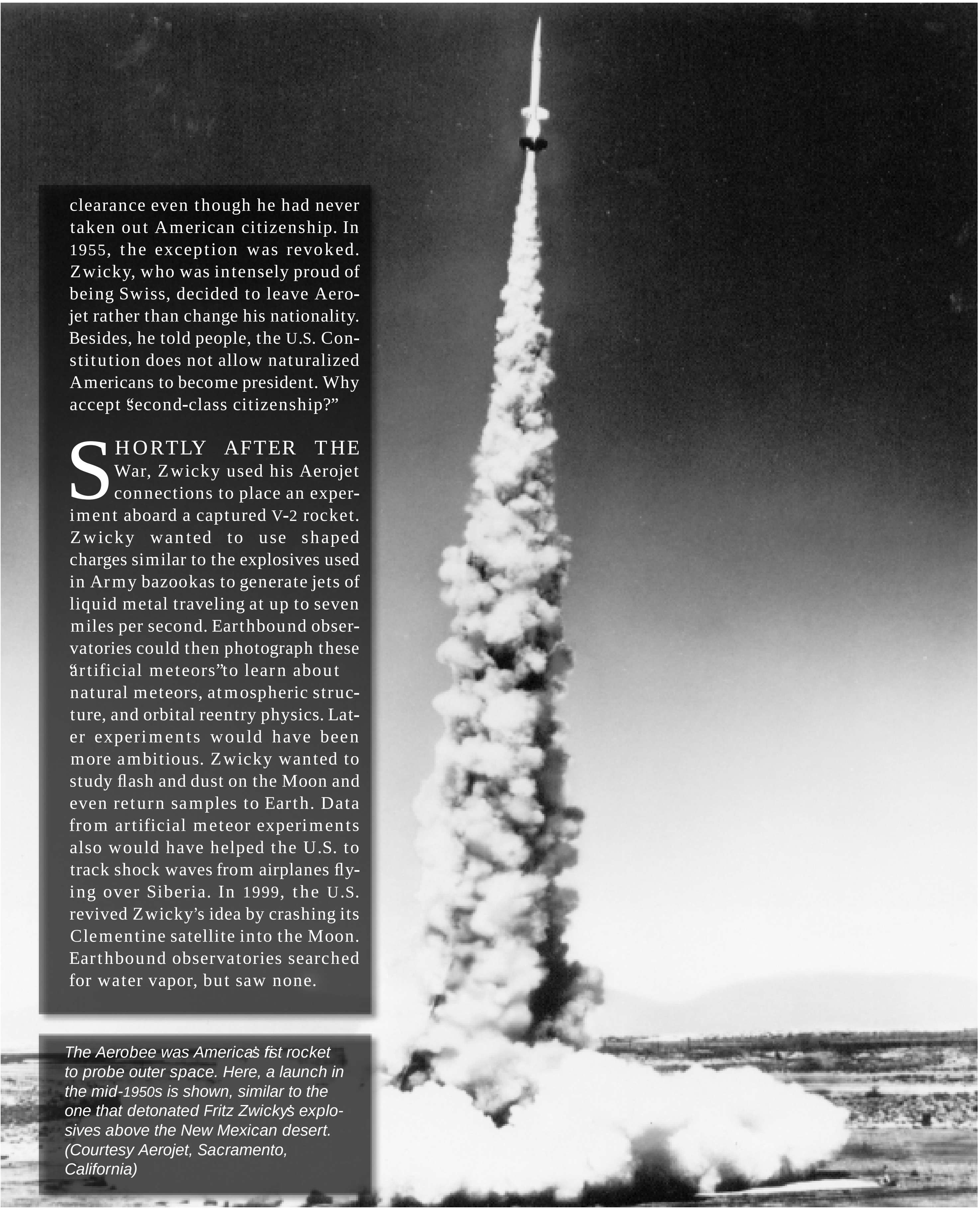
ZWICKY WAS NEVER shy about describing himself as a "romantic figure out of the Renaissance" or "lone wolf" genius. In fact, he invented a technique ("morphology") which supposedly allowed practically anyone to think one hundred times more efficiently. Zwicky credited the technique for most of his insights.

Naturally—to hear Zwicky tell it—genius was persecuted. Friends say that Zwicky could explain his ideas patiently and was given to boisterous laughter. This did not stop him from railing against astronomy's "self-interested cliques" and "high priests." One of his favorite jokes was to call enemies "spherical bastards" ("spherical," he explained, because they still looked like "bastards" from every possible angle). Zwicky even convinced himself that Baade had stolen his ideas. The famously gentle Baade was afraid that Zwicky might try to kill him.

DURING WORLD WAR II, the U.S. Army needed rockets to get heavily-loaded bombers airborne. Caltech aerodynamicist Theodore von Karman founded a corporation called Aerojet and won the contract. In 1943, Aerojet asked Zwicky to run its research department. At War's end, Zwicky toured secret weapons programs in Germany and Japan. Later, he helped Aerojet develop many of the high-energy fuels used in today's solid rocket boosters.

Corporate life did not improve Zwicky's people skills. Once, Zwicky met a visiting delegation (including two admirals) at the plant gate and ordered them to leave. To hear Zwicky tell it, they were a bunch of unqualified civilians who had somehow wangled commissions. Aerojet old-timers also claim that Zwicky liked to win arguments with his fists. "But he was a small guy," they usually add, "so it wasn't hard to pull him off."

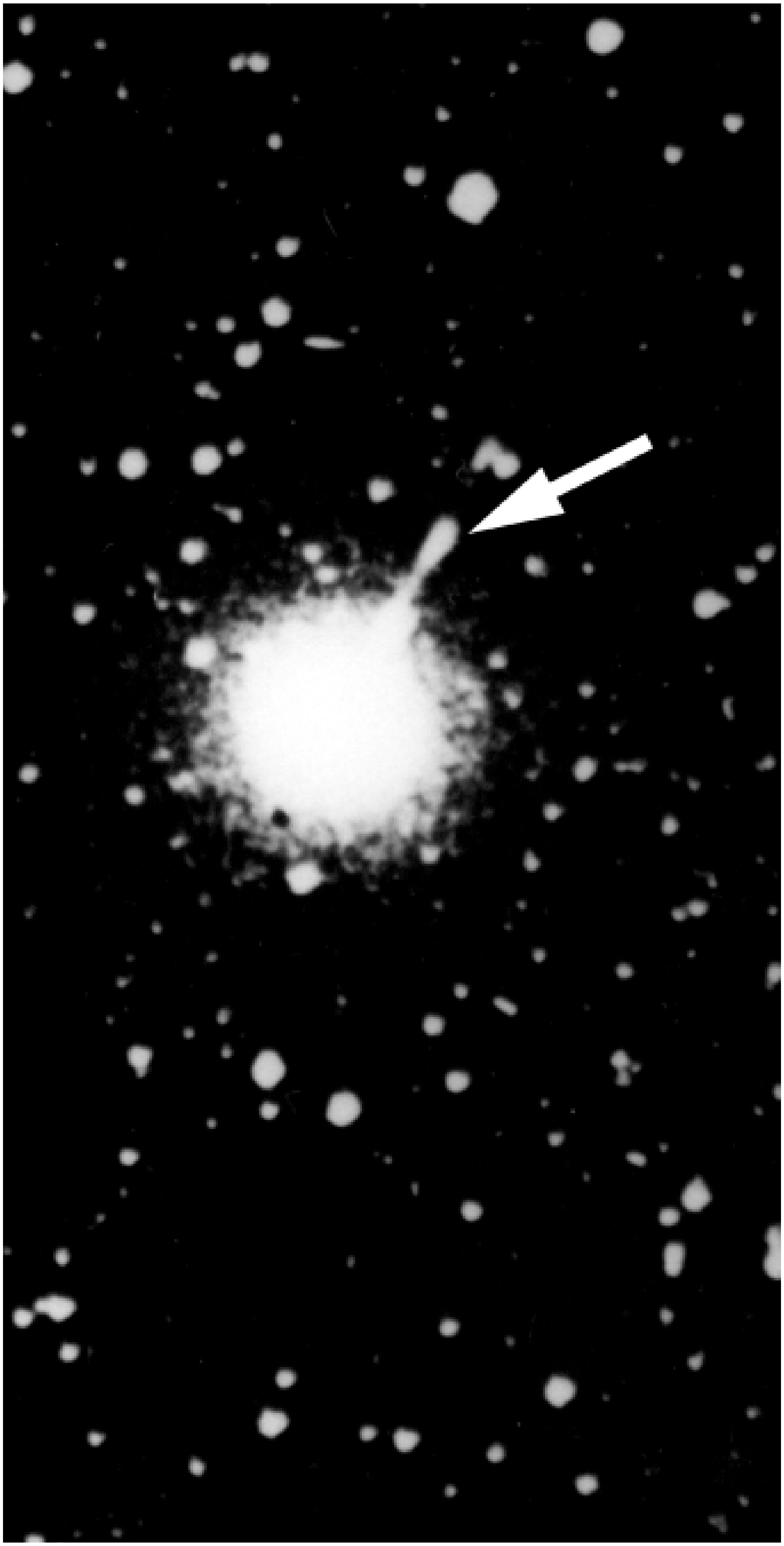
During the Second World War, the government gave Zwicky a security



clearance even though he had never taken out American citizenship. In 1955, the exception was revoked. Zwicky, who was intensely proud of being Swiss, decided to leave Aerojet rather than change his nationality. Besides, he told people, the U.S. Constitution does not allow naturalized Americans to become president. Why accept "second-class citizenship?"

SHORTLY AFTER THE War, Zwicky used his Aerojet connections to place an experiment aboard a captured V-2 rocket. Zwicky wanted to use shaped charges similar to the explosives used in Army bazookas to generate jets of liquid metal traveling at up to seven miles per second. Earthbound observatories could then photograph these "artificial meteors" to learn about natural meteors, atmospheric structure, and orbital reentry physics. Later experiments would have been more ambitious. Zwicky wanted to study flash and dust on the Moon and even return samples to Earth. Data from artificial meteor experiments also would have helped the U.S. to track shock waves from airplanes flying over Siberia. In 1999, the U.S. revived Zwicky's idea by crashing its Clementine satellite into the Moon. Earthbound observatories searched for water vapor, but saw none.

The Aerobee was America's first rocket to probe outer space. Here, a launch in the mid-1950s is shown, similar to the one that detonated Fritz Zwicky's explosives above the New Mexican desert. (Courtesy Aerojet, Sacramento, California)



In 1957, Fritz Zwicky used high explosives atop an Aerobee rocket to blast jets of metal into space. Tracking cameras proved that at least one jet escaped Earth (arrow) and became the first man-made object to achieve its own independent orbit around the Sun. (Courtesy AP/Wide World Photos)

Zwicky's V-2 flew on December 18, 1946. The *New York Times* called the experiment "a symbolic milestone in man's exploration of the universe" which might "open the secrets of travel between the planets." But while the rocket behaved flawlessly, observatories and amateur astronomers saw nothing. Zwicky believed that the charges had fizzled and asked for a second chance.

The Army said "no" and went on saying "no" until Sputnik was launched in 1957. Twelve days later, an Aerojet Aerobee rocket detonated three shaped charges 54 miles above the New Mexican desert. (This time, Zwicky installed the explosives himself.) Three jets were observed as far away as Mt. Palomar. Tracking cameras confirmed that at least one centimeter-sized projectile had become the first man-made object to escape the Earth and enter a separate orbit around the Sun.

ZWICKY HAD criticized President Harry Truman for dropping the atomic bomb on Japan. Now he brooded "that scientists' inventions have gotten completely out of hand." "I myself," Zwicky said, "can think of a dozen ways to annihilate all living persons within one hour." Zwicky even claimed (mistakenly) that future weapons or misguided fusion experiments could reduce the Earth to a miniature neutron star.

Zwicky's dreams were usually less gloomy. During the war, Zwicky had patented an air-breathing "pulse jet" similar to Germany's V-1 buzz bomb. Why stop there? By the late 1940s, Aerojet was testing a "hydropulse" engine that "burned" water (using sodium fuel) to make steam. And if water could burn, why not rock? Zwicky dreamed of the day when "terrajets" would burn minerals (using fluorine) in order to spit out jets of lava and gas. Zwicky claimed that the technology could dig tunnels and colonize the planets. Military versions could attack straight through the earth.

Terrajets were only the start. Eventually, atomic power could hollow out the moon, give it an atmosphere, or even move it elsewhere. And if mankind needed living space—for example, to separate its warring ideologies—the giant planets could be shattered into convenient, earth-sized pieces. Finally, future engineers could fire particle beams at the Sun to create a fusion-powered hot spot. This would generate enough thrust to move the whole solar system to Alpha Centauri in just 2,500 years.

FRITZ ZWICKY HATED the idea that galaxies were rushing apart because it implied a starting point, that is, that the Universe was young. He therefore called Hubble's redshifts "indicative" or "symbolic."* But if the Universe was not expanding, why was distant light redshifted? Zwicky offered three answers. First, Einstein's laws implied that photons passing a star would first gain and then lose energy. Zwicky argued that the first effect was slightly larger, producing "gravitational drag." Second, small overlooked terms in Maxwell's equations and quantum mechanics might allow light to become "tired" after billions of years. Finally, the physical laws themselves might have changed: Why shouldn't light emitted billions of years ago be redder than it is today?

Strangely, the man who had shown that most galaxies reside in clusters refused to admit that "super clusters" (clusters of clusters) existed. This led to a series of acrimonious debates with astronomer George Abell during the 1950s. Zwicky even claimed that the absence of superclusters showed that gravity stopped working beyond 60 million light years or so thereby invalidating General Relativity and the Big Bang. According to Zwicky, a "graviton" weighing 10^{-64} grams "explained" the effect quite nicely.

Finally, Zwicky concocted a wild theory in which chunks of neutron matter ("goblins") orbited deep inside massive stars. Goblins were ordinarily invulnerable, since a 10-meter (10^{29} ton) object would cut through the star like tissue paper. Occasionally, however, a close encounter between two goblins would boost one of them to a higher orbit. No longer stabilized by the star's high pressure core, the unlucky goblin would explode producing flare stars and gamma-ray bursts.

BELIEVING that educated people owe a debt to society, Zwicky organized a program after World War II that collected and shipped 15 tons of scientific journals to war-damaged libraries around the world. He also directed an organization that supported orphanages.

Charity reinforced Zwicky's contempt for the "inhuman and idiotic treatment" of native peoples under colonialism. "We are not likely to succeed in unifying the world," he warned, "as long as the Americans and the British, or for that matter any other people, feel and act as if they are better and superior to all others."

ZWICKY BECAME professor emeritus in 1968. Thereafter, he traveled extensively and opened a second home near Berne, Switzerland. Friends thought that he wanted to become a member of the Swiss Parliament. He died six days before his seventy-sixth birthday, on February 8, 1974. He was buried in Switzerland.

Zwicky often joked that he wanted to live to be 102, since hardly anyone gets to live in three centuries. He would have enjoyed his current reputation. In the final analysis, though, Zwicky probably didn't care whether people believed his ideas or not. Zwicky knew. That was enough.

**In 1939, Zwicky "proved" that the Universe had to be much older than Hubble's law implied. Many clusters, he argued, were beautifully spherical. But the laws of physics said that an initially chaotic group of galaxies could only become symmetrical through a series of close encounters among three or more galaxies. Since such encounters were fantastically rare, the Universe had to be at least 10^{18} years old.*

Engineering and Science, California Institute of Technology, March-April 1974, S. 15-19

Remembering Zwicky

Fritz Zwicky - Scientific Eagle

By Jesse L. Greenstein, *Lee A. DuBridge Professor of Astrophysics*

An active and extraordinary scientist, still full of ideas and personal drive, Fritz Zwicky, professor of astrophysics emeritus, died suddenly on February 8.

It is difficult to write a brief, conventional memoir about so unconventional a man. Fritz classified scientists into two categories, eagles and low-fliers; a low-flier like myself recognized clearly that Fritz was the high-flier.
He pursued an extraordinary range of personal interests: international charities, city-planning, mountain climbing, new explosives, exploding stars, crystals and dying stars, and, especially galaxies. He always saw the Universe in his own original way; he loved the extraordinary objects it contained, and he explained them in his own fashion, sometimes wrong but never dull.

He leaves, after nearly 50 years at Caltech, many loyal friends, scientists and public figures; his wife since 1947, Anna Margaritha; daughters Margrit and Barbara (of Berne and Pasadena) and a married daughter, Franziska Pfenninger (of Zurich).

Born in Varna, Bulgaria, a Swiss national all his life, he received his PhD from the Federal Institute of Technology in Zurich in 1922. He came to work at Caltech on the theoretical physics of crystals as a research fellow of the (Rockefeller) International Education Board, served as assistant and then associate professor of physics 1927-1941, and became a professor of astrophysics in 1942.
He was a member of the staff of the Mount Wilson and Palomar Observatories till his retirement in 1968, and a pioneer observer on Palomar where he realized the importance of, and exploited, the wide-angle schmidt telescopes for discovery of unusual types of stars and galaxies.

He climbed many scientific mountains, some with great success, many for the first time

Caltech graduates will remember his course in Analytical Mechanics, required for the PhD in physics. Astronomers will remember his advanced seminar, which covered the Universe and admitted "only students, assistants, faculty and visiting research personnel ... who have the time, inclination and ability to engage in active, constructive work. ... " Faculty wives and secretaries will remember his charitable activities, including an annual display in our board room of children's knitwear destined for schools for war-orphaned children. Although Zwicky had few formal students in later years, he retained a strong influence on recent scientific developments.

He became one of the founders (with Theodore von Karman, Clark Millikan, and others) of Aerojet Engineering, where he served as director of research 1943-49; he was research consultant at Aerojet-General and Hycon till 1960.
He held many patents on unusual concepts and devices in jet propulsion - air, water, and earth-borne. When he visited Japan and Germany for the U. S. Air Force, his strong interest in human causes led him to

individual acts of charity long remembered.
He had a strong interest in the Pestalozzi Foundation, was trustee and president of the American branch, and received its gold medal in 1955.
He organized a lengthy project for reconstruction of warstricken libraries; for years I struggled with Zwicky (always an administrator-baiter) to remove the many tons of books on their way to the Orient or Europe. For many technical services, and for his good works, he received the Medal for Freedom in 1949 from President Truman.

He was awarded the Gold Medal of the Royal Astronomical Society in 1973 for "his many distinguished contributions to the understanding of the constituents of the Galaxy and the Universe." The medal carries the motto *Quicquid Nitet Notandum* [Whatever shines is to be noticed], a phrase peculiarly suited to Zwicky's approach to astronomy.
Zwicky's response was equally apt - "I heard as a boy that there will always be an England, a place where debatable gentlemen will be recognized. I hope you have not made a mistake this time."

Zwicky wrote over 300 articles, 10 books, and held 25 patents.
From 1933 on he had a philosophical interest in morphological research, a systematic approach to science and technology; he was founder and president of the Society for Morphological Research, and recently a Zwicky Foundation was established in Glarus. He had a strong classical background in thermodynamics and statistical physics. These two threads, combined with a strong personality and bold mind, led him to contribute to astrophysics in a unique way. Lacking the repressions of many, he felt that if a "morphological box" - i. e., a possibility - existed, nature would have filled it and scientists should discover it. This characteristic pattern is found in many of his fields of study.

From 1921 to 1937 he studied secondary structure in crystals, cooperative phenomena, and the theory of cosmic rays; by 1928 he was interested in, and doubtful about, relativity; in 1934 he cooperated with Walter Baade of the Mount Wilson Observatory staff in the discovery of supernovae. He attempted to explain them as a collapse to the neutron-star state (1934), and as producing cosmic rays (1934).
Both the discovery of the supernovae and the theoretical links to neutron stars (only two years after the neutron was discovered) are extraordinary feats. A supernova explosion releases energy close to what the sun radiates in 10^{10} years! Neutron-star physics was, in fact, put on a sound theoretical basis by 1937 by Oppenheimer and Volkoff. And rotating neutron stars probably do accelerate cosmic rays; the Baade-Zwicky mechanism used electrostatic fields.
With many collaborators, Zwicky started a supernova patrol which discovered most of those now known, finding 100 himself. Baade and Rudolph Minkowski explored and classified their spectra, still an active topic of study and debate.
Zwicky carried the idea of collapse under gravity much further, contemplating "pygmy stars" (which do not exist) and "object Hades" (black holes, which probably do exist). Several threads of his work thus appear - interest in extreme types of objects; speculative, approximate theory based largely on classical models; and willingness to undertake systematic, very large, and long observing programs.

In studies of galaxies, which he began in 1929 with a note on the possibility of a gravitational drag on light, Zwicky combined a serious devotion to discovery and cataloging their properties with criticism of the expanding universe theory. He was constructively concerned about the applicability of the conventional definition of a galaxy as a large, closed system of a hundred billion stars - why not a billion or a million or ten stars? Why should not very dense galaxies exist? Could they be found? Look with the schmidt telescope! He studied interacting galaxies of strange shape, the forms of clusters of galaxies, searched for intergalactic matter and intergalactic stars.

One important result was the six-volume catalog of galaxies and clusters of galaxies, prepared with collaborators, which will be of permanent importance to extragalactic astronomy. The "compact" - i. e., relatively dense, high-surface brightness - galaxies have become of special importance with the discovery by Sandage, Schmidt, and others of the quasars, and of their large redshift; Zwicky made lists of compact galaxies, published a large, useful catalog, and had another in preparation.

Violent events in the nuclei of galaxies (which may vary in light in a few days) and explosive phenomena in Seyfert nuclei have been a major concern of astronomers and observers of the last decade. The trend of recent studies of galactic nuclei has been to reinforce our knowledge of high-energy events of still mysterious nature.
It is clear that Zwicky's intuition of the importance of implosion-explosion events was a valuable one. In a sense he was a pioneer of high-energy astrophysics. The strange shapes of interacting galaxies interested Zwicky in his search for intergalactic matter. Here, the recent discovery of X-rays from clusters of galaxies suggests that he had an early insight into still another important field.

With Milton Humason, he found the first "faint blue stars," 48 hot objects far from the galactic plane - objects on which I have worked, with pleasure, for many years.

Closer to home, Zwicky was interested in research in space by 1946; he attempted to launch artificial meteors from a rocket, and claimed to have shot the first object out of the gravitational field of the earth; he helped found the International Academy of Astronautics and lectured on legal problems of the use of space.

Zwicky, as a young man, was a good mountain climber. He was an extraordinarily live person. He climbed many scientific mountains, some with great success, many for the first time.

Zwicky : Humanist and Philosopher

By Albert G. Wilson, *Director Society for Morphological Research*

The great majority of Fritz Zwicky's publications were in the field of astronomy. Most of the remainder were about his researches in solid state physics and jet propulsion technology. But Zwicky himself always felt that his greatest contributions were in philosophy, specifically in epistemology - in the development of new methods of thought and action. He wrote in 1971: "I feel that I have finally found the philosopher's stone in what I call the *morphological outlook and method.*"

Giving us an insight into how he came to feel this way, Zwicky said in addressing the Pestalozzi Foundation of America, of which he served as president of the board of trustees:
"After pursuing a dozen or so various activities ranging from mountain climbing and professional shorthand to physics, astronomy, engineering, languages, higher 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."

This is not the occasion to review the details of the morphological method. Suffice it to say that the morphological approach sought to be integrative, systematic, and trans-scientific, pushing consciousness to the limits of the conceivable.

Zwicky believed that if only we could free ourselves from our pedestrian patterns of thought and learn to think morphologically, the future could be shaped by our images - however bold - rather than by the inertias of existing institutions and investments. For Zwicky, the really revolutionary paradigm of morphology consisted in the replacement of *one* solution by *all* solutions, *one* path by *all* paths, *one* system by *all* systems. Only after the complete spectrum of possible solutions, theories, or systems is developed can the full energies of their mutual tensions become available to us.

Zwicky's "method of morphological construction" passed William James's test for great innovative ideas: "First the new idea is mocked as ridiculous and absurd, then it is admitted to be valid but overrated and of no particular significance, finally it is decided that the idea had been known long ago and that everybody had thought of it himself." So it was with morphology.

Zwicky possessed that necessary concomitant of greatness, the generation in others of a strong positive or negative response. Very few people were merely indifferent to him. His evocation of bi-modal responses was in part due to his phenomenal percipience. Those who see further or deeper are not universally admired.

Another cause was Zwicky's frequent distrust of those in the upper echelons: "Unfortunately many people, and in particular professional men, are impressed only by specific accomplishments in science, engineering, finance, politics and so on, which lead to fame or to material and spiritual ‚success' of one kind or another. Such men are a great obstacle to humanity in its march toward the realization of its inherent genius."

Zwicky felt that it was important to unhorse the pompous. He felt that all professors and executives should stay in touch with reality by periodically cleaning the wash rooms. He set the example by doing this himself. It would please Zwicky to say that "that bastard Chairman Mao" stole this aspect of the cultural revolution from him.

One of Zwicky's humanitarian activities was his organization of the Committee for Aid to War-Stricken Scientific Libraries. In order to establish closer scientific human relations, together with a small handful of volunteer assistants, Zwicky collected and distributed over a million dollars worth of scientific periodicals and books, sending them to university and other libraries that had been destroyed in the war - first to allied countries, later to former enemy countries. Zwicky devoted his weekends for several years to this task, personally carrying the heavy cartons of journals, cataloging, wrapping, and mailing.

But Zwicky had a second purpose in mind in organizing the Library Aid Committee. He said, "A common supposition is that activities of this kind require for their successful realization large organizations and considerable funds." Zwicky wanted to disprove this. He felt that the revitalization of democracy depended on "more initiative on the part of every individual as such." The book project was completed "without recourse to any funds except for a few dollars for wrapping paper, a card index, and some expenses for driving a car for the purposes of collecting the material."

Zwicky's point was that there are enough men and women of good will to make such projects a success if only they are pushed with determination. Availability of funds is not a prerequisite. He felt that such projects as the book distribution do more for establishing ties of confidence between different nations and races than can be achieved by speechmaking, legislation, or high-sounding efforts at international cooperation.

Zwicky was concerned with a second type of energy crisis, the drying up of spiritual energy: "There exists today no subject which would excite the imagination of men in a positive way, stimulating a constructive and happy life. The universal appeals of religion, art, political freedom, and science have faded to the vanishing point."

Zwicky's perception of the collapse of imaging power and its import for the Western World came two decades before other futurists finally woke up to its significance. In 1946, he wrote: "The world of today is in a state of disorder which is in conspicuous contrast to the avowed purposes of man ... the teachings of science, of education, and of religion seem to have become lost in an elaborate system of hypocrisy in which there is little relation between words and actions."

This was one of the earliest recognitions of the corruption of our culture through the distortion of language.

If a single theme dominates Zwicky's humanistic writings, it is the importance of unfettered individual creativity and effort. This viewpoint may not be shared by those who feel everything worthwhile that remains to be discovered or developed will require sizable federal appropriations.
Zwicky briefly went the grant and contract route but decided that the loss of the essence of creativity that was implicit in the federal funding system precluded its ever leading to any really basic discoveries. He returned to his original premise: The world's hopes lie in individual free agents, men and women of good will who can come together and work when the need be, but who form no permanent organizations or institutions.

One might wonder why a person of Zwicky's creative stature never attracted large numbers of followers. Discipleship was inconsistent with Zwicky's basic views. He held that everyone was a genius and that each person's life task was to find his own genius, not to follow some other genius. "Most individuals just never seem to realize that they possess unique potentialities and capabilities not to be matched by anybody else and that the penalty for not realizing one's genius is frustration and unhappiness."

Our present civilization is built on, and for, only a few types of geniuses. This is why so many are frustrated and unhappy. This malignancy will remain at the core of society until some way is found of restructuring so as to allow each person to discover his own innate genius.

Whether Zwicky's genius was to hear the beat of different drummers or whether it was the acuity to hear the fainter drummings of the same cosmic drummer that we all hear in part, his passing removes from our midst a creative source of great originality. With his departure the world becomes more homogenized and more mediocre; humankind loses a portion of its freedom and its dignity.

All who knew Zwicky would agree in the appropriateness of applying to him that eloquent eulogy first uttered by Winston Churchill on learning of the death of Rupert Brooke, which was later used at Churchill's own funeral:
Certainly, *we shall not see his like again*, and these are times when this world has a desperate need for Zwicky's particular type of genius.

Zwicky on Zwicky

Theodore von Karman was not only a brilliant scientist; he was also a man who knew his Zwicky, as indicated in this brief excerpt from a 1971 interview with Zwicky by R. Cargill Hall, historian at the Jet Propulsion Laboratory.

I think I was instrumental in talking Millikan into getting Von Karman here permanently in 1931-32 or so, and we were really old friends.
In all my attempts to get physics over into astronomy, engineering over into astronomy, and so on, he supported me heavily. While he was Director of the Scientific Advisory Board on the Air Force (on my

standing with my colleagues I would have never been on that), he insisted that I too should be on it. So, he pushed that through, and I am indebted to him for that, and also later on for having pushed me into the International Academy of Astronautics, and so on.

And it would have been quite impossible if all the hierarchy in power would have had their say, because they can not really admit a non-conformist like myself.

On the other hand, he had his little jokes with me. He thought I was treating people too abruptly, too roughly, and it would be better not to be that rough; but to commemorate this abrasiveness, he said, "Now we have an occasion to get you into history, and we must devise a unit for the roughness of airplane wings, the surfaces of missiles, and so on. The proper thing will be to name this unit a Zwicky."

But then on second thought, he said, "There is no such thing as a whole Zwicky except you - that's far too excessive - so the practical unit will be a *micro-Zwicky*!"