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Fritz Zwicky: An Extraordinary Astrophysicist

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Introduction

As a boy and also later, I often listened to lengthy interviews with Fritz Zwicky, which he regularly gave at the Swiss radio when he returned home for short visits. I found them always interesting, although I was too young to understand the importance of what he told the public about supernovae and other discoveries in astronomy. Later, my scientific activities had for about two decades almost nothing to do with astronomy. For this reason, I never met Fritz Zwicky personally, and saw him only once in action when he gave a general, but quite unusual physics colloquium at ETH. Therefore, I can only comment on Zwicky's outstanding contributions in astrophysics. However, the reader is strongly invited to learn a lot about Fritz Zwicky in all his colorful facets and activities from the biography: *Fritz Zwicky: Genie mit Ecken und Kanten* [1], that has recently been translated into English [2].
Gustav Andreas Tammann and I have written more extensively about Zwicky's most significant contributions to astrophysics and observational astronomy in a special contribution to the cited books [1], [2]. Below, I shall give an abbreviated version of our article [1].

Zwicky as the father of dark matter

Fritz Zwicky was the first to recognize that in rich clusters of galaxies, a large portion of the matter is not visible. In his pioneering work, which he published as early as 1933 in *Helvetica Physica Acta* he estimated the total mass of the COMA cluster of galaxies from the motions of the galaxies within that cluster. Using the virial theorem he came to the conclusion that the galaxies were on average moving too fast for the COMA cluster to be held together only by the mass of the visible matter. In Zwicky's words:

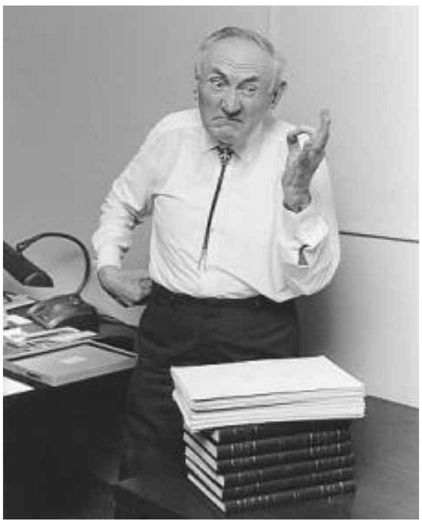

Figure 1: Fritz Zwicky

"In order to receive an average Doppler effect of 1000 km/s or more, which is what we have observed, the average density in the COMA system would have to be at least 400 times greater than that of visible matter. If this can be shown to be the case, then it would have the surprising result that dark matter is present in the Universe in far greater density than visible matter."

Zwicky's analysis at the time was of course quite rough. It was deduced from very limited statistics, an uncertain radius of the cluster and on a distance scale, based on a value of the Hubble constant that was for a long time about seven times too large. Surprisingly, his results have stood the test of time as reasonable estimates.
In recent times lots of investigations at all astrophysical length scales have confirmed that the vast majority of material in the Universe is of totally unknown nature. The ratio of known to unknown is about 5:1. (We do not discuss here attempts to replace dark matter by modifications of general relativity.) One favored hypothesis is that dark matter might consist of heavy elementary particles which interact, like neutrinos, only weakly with matter known to us. So far, direct, indirect and collider searches have only led to upper limits. The goal of dark matter identification has eluded us for long, but prospects for discovery in the coming years remain intact.

Zwicky as the father of neutron stars

In 1931, Zwicky started working with the outstanding astronomer Walter Baade, who had just come to the Mount Wilson Observatory, after working in Hamburg and Göttingen. Soon they were closely collaborating. Their main topic were the rare "novae" in distant galaxies. Because of their great distances, compared to the novae in the Milky Way, they must have enormous luminosities. For this reason they coined the term "supernovae" for these bright events.
Over the past two millennia, eight long-duration "new stars" have been seen with the naked eye and on the basis of the recorded observations they must certainly have been supernovae. The brightest was the supernova of 1006, which was also registered in St. Gallen. The Chronicles of the Monastery record that the very bright star appeared just over the rocky alpine horizon (Alpstein). Thanks to this description of the position, the Einstein Röntgen Observatory was able to find the remnants of this historical supernova. Its appearance is similar to that of the famous Crab Nebula, shown in Fig. 2.
From existing data, Baade and Zwicky deduced that supernovae had enormous luminosities of about 10^8 times that of the Sun. Their estimate is about 100 times too small because in the 1930s extragalactic distances were underestimated by a factor of approximately 7. On the other hand, Baade and Zwicky did estimate the total energy release more or less correctly. Admittedly, the way that they arrived at it was incorrect in that it relied on exaggerated expectations of the proportion of ultraviolet light and X-rays which at the time had not yet been observed. (Nowadays we know that 99% percent of the total energy released is in the form of neutrinos. Incidentally, the gigantic neutrino pulse was first observed in the supernova event of 1987 in the Large Magellanic Cloud by underground detectors on Earth. This may be regarded as the birth of "neutrino astronomy".)

1 Unfortunately, we can not recommend the English translation of our article. We were not asked to correct its distortions and errors. For example, our German expression for "synchrotron radiation of electrons" was translated as "synchrotron radiation of neutrons".

Figure 2: Crab Nebula in the constellation of Taurus. This is the relict of a supernova from the year 1054, which was described in detail in the Chinese year books of the Sung dynasty. The bluish glow from the central region of the nebula is due to synchrotron radiation by high energy electrons moving in weak magnetic fields. In the red filaments recombination radiation of electrons with protons in the hot gas dominates. Near the centre of the nebula is a rapidly rotating pulsar.

What was the primary source of the enormous energy release in supernova events? Zwicky's most outstanding contribution to astrophysics may have been his bold hypothesis, that when a supernova occurred, a *neutron star* was formed in the centre. Recall that the neutron was discovered by James Chadwick in February 1932. Zwicky immediately developed the idea that when the central region of a high-mass star collapses, a very dense core mainly consisting of neutrons is formed. He estimated the released binding energy as the mass equivalent of about 10% of the solar mass. This was sufficient to cover the energy requirements of a supernova. In fact only about 1% is released as explosion energy and the rest is lost within seconds in a gigantic neutrino pulse. Zwickly correctly guessed that the outer layers would be heated to high temperatures by the energy of the explosion and would lead to an enormous eruption into the interstellar space. He quickly came to the conviction that cosmic rays were also generated in supernova events. Although there are other sources of cosmic rays, such as in the central regions of active galaxies, supernovae presumably generate a significant proportion.

In autumn of 1933, Baade and Zwicky presented their considerations at a meeting of the American Physical Society at Stanford University. An edited version was published on 15 January 1934 in *Physical Review*. In the summary, the two authors wrote:

> "*With all reserve we suggest the view that supernovae represent the transition from ordinary stars to neutron stars, which in their final stages consist of extremely closely packet neutrons.*"

For decades, these far-sighted predictions were more or less ignored. Articles relating to neutron stars could, for many years, be counted on the fingers of one hand. This may in part be because to many questions Zwicky did not know the answer. He did not know what the cause for the collapse was, nor did he have detailed suggestions for the behavior of the collapsing core and its transformation into a neutron star. To some extent this was simply because the necessary foundations of physics were lacking. Nuclear physics was in its very early stages, and even today we still do not fully understand how the primary energy triggers a supernova explosion. Current research centres on increasingly realistic simulations. Zwicky missed the opportunity of underpinning some of his claims with detailed investigations. For example, in 1934 it would have been possible to perform calculations on the structure of neutron stars, which in fact is what Oppenheimer, Volkov and Tolman did four years later, and thereby recognized that neutron stars can only exist with masses less than a few solar masses. (The largest neutron star mass discovered so far is close to two solar masses, a fact that has important implications on the equation of state above nuclear densities.) It appears that Zwicky was not interested in "technical details" of this type. For him it was sufficient to develop a qualitative understanding of the phenomena, and he certainly had a good nose for that. Another critical factor was his unusual ability to grasp the relationship between different phenomena intuitively. So in addition to the conjecture that supernovae obtain their energy from the collapse of a massive star whose central region becomes a neutron star, he recognized at the same time that the energy released in supernovae events could account for high energy cosmic rays. Following that, he worked for decades on a comprehensive search for supernovae. Zwicky was strengthened by his exceptional self confidence and he never experienced the fear of being seen to fail.

It must, however, be admitted that some of Zwicky's work shows obvious weaknesses. For example, his article *On the Theory and Observation of Highly Collapsed Stars*, written in 1939, is for the most part rather disappointing and some of it is simply wrong. His use of simple things in general relativity shows that he had too little understanding of it. It is also irritating that he does not cite the brilliant work of Oppenheimer and Volkov.

Zwicky's scenario has survived until the present day. It took decades until neutron stars were discovered as radio pulsars. The Milky Way may well contain about a billion of them.

Zwicky and gravitational lenses

Zwicky was also the first to recognize the astronomical potential of the gravitational lens effect, on which he published in 1937 two remarkable short papers in *Physical Review*.

It is not generally known that as early as 1912, Einstein realized that gravitational fields can have a similar effect on light propagation as optical lenses. Beside the lens effect, he also studied the induced changes of brightness, but did not publish his results since he saw no way to observe the predicted phenomena. It was only in 1936 that he was persuaded by the Czech engineer R. W. Mandl to write a short note on the subject. But even then, Einstein did not believe

that a cosmic Fata Morgana of this sort would ever be observed, if only because the telescopes of the time were not capable of measuring the minute differences in angle between possible double images.
Zwicky was familiar with Einstein's two-page publication in *Science* and one year later added that whole galaxies could be seen to act as lenses. In his first short article on the topic, he put it in these terms:

> "*Last summer Dr. V. K. Zworykin (to whom the same idea had been suggested by Mr. Mandl) mentioned to me the possibility of an image formation through the action of gravitational fields. As a consequence I made some calculations which show that extragalactic nebulae offer a much better chance than stars for the observation of gravitational lens effects.*"

Crucial for this prognosis was the fact that Zwicky had estimated the masses of galaxies as about 400 times larger than the estimates of his colleagues in astronomy. Without a major amount of dark matter, the lens effect would have been too small to form arcs and multiple images.
In his first article, Zwicky lists several reasons why the discovery of lens effects would be of considerable interest. Firstly, it would open the possibility of a new test of general relativity [2]. Secondly, Zwicky says, galaxies could be discovered at far greater distances as a result of brightness amplifications, a fact that indeed has become important. And finally, Zwicky's hope that the total masses of galaxies (and clusters of galaxies) could be determined using the gravitational lens effect has been realized far more effectively than he could ever have dreamt of.

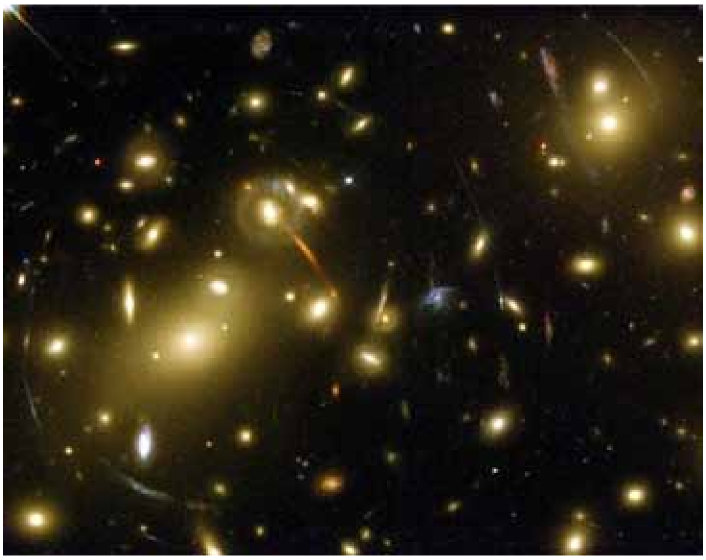

Figure 3: This color photograph of the rich galaxy cluster Abell 2218, taken by the Hubble space telescope, shows a number of arcs around the centre of the cluster, which is located near the high luminosity galaxy just below left of the centre. The observed distortions have been used to determine the total mass in the central region of the cluster. (Source: NASA/Andrew Fruchter and the ERO Team [STScI]).

2 So far this has not been possible, because astrophysical lenses are too complex.

In a second equally short paper, Zwicky arrives on the basis of simple estimations at the following almost visionary prediction, which was to prove correct almost 40 years later:

> "*Provided that our present estimates of the masses of cluster nebulae are correct, the probability that nebulae which act as gravitational lenses will be found becomes practically a certainty.*"

Fig. 3 shows an impressive example for this. Certain galaxies behind the galaxy cluster Abell 2218 look like arcs because of the distortion which is centred about the mid-point of the cluster. No doubt, Zwicky would have viewed images like this enthusiastically and derived great satisfaction from them. In recent times, gravitational lensing has become an important field with considerable potential for studying the distribution of matter on all scales.

Fritz Zwicky as an observing astronomer

As an observing astronomer, Zwicky was both innovative and controversial. He proposed a whole range of new methods, such as synthetic color photography of galaxies, a process whereby he added or subtracted various color filters to photographs already taken, and in this way separated out young blue stars from old red ones. Zwicky achieved two outstanding successes, namely the systematic search for supernovae and his great Catalogue of Galaxies in the northern sky – a milestone in extragalactic research. Space does not allow us to go into further details. More can be found in the article with Gustav Tammann in our contribution to [1] and [2]. There, we also wrote about Zwicky's relationships with colleagues that often included virulent attacks, mostly connected to priority issues. Among the many anecdotes he is "credited" with coining the term a *spherical bastard*, i.e. "He's a bastard no matter which way you look at him!"
There can be no doubt that Fritz Zwicky is one of the most original astrophysicists of the twentieth century and today nobody would question his intuitive genius in the field and his passion for science.

References

[1] A. Stöckly and R. Müller, *Fritz Zwicky: Genie mit Ecken und Kanten.* Verlag Neue Zürcher Zeitung (NZZ Libro) (2008).
[2] A. Stöckly and R. Müller, *Fritz Zwicky: An Extraordinary Astrophysicist.* Cambridge Scientific Publishers, Cambridge (2011).