Astronomers' Universe

Wolfgang Kapferer

The Mystery of Dark Matter

In Search of the Invisible

Springer

Astronomers' Universe

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ISSN 1614-659X ISSN 2197-6651 (electronic)
Astronomers' Universe
ISBN 978-3-662-62201-8 ISBN 978-3-662-62202-5 (eBook)
https://doi.org/10.1007/978-3-662-62202-5

The translation was done with the help of artificial intelligence (machine translation by the service DeepL.com). A subsequent human revision was done primarily in terms of content.

Responsible Editor: Lisa Edelhaeuser
This Springer imprint is published by the registered company Springer-Verlag GmbH, DE part of Springer Nature.
The registered company address is: Heidelberger Platz 3, 14197 Berlin, Germany

Foreword

Today, the concept of "dark matter" has undergone an exciting two and a half centuries of history. From initially postulated dark stars to understand the strange movements of some luminaries on the firmament, to hypothetical planets in the outer reaches of our solar system, time and again it was possible to wrest matter from its darkness and, with advancing observation techniques, to discover its true nature.

At the beginning of the twentieth century however, a large gap regarding the masses of large-scale structures in the universe derived by various methods was discovered. The larger the structures, the greater the difference between masses derived from direct observations and masses derived from the dynamics of these objects. The successful concept—dark matter—was and is an approach to resolve this contradiction. It calls for an all-encompassing, purely gravitationally interacting substance in the universe, which is otherwise—at least until now—completely invisible. This concept of hidden matter that only reveals itself to us indirectly was and is very successful. A well known example of this is the theory of the formation and development of large-scale structures in the cosmos.

To the layman however, this concept often seems erratic and arbitrary. The aim of this book is, on the one hand, to show the great historical successes of the concept of dark matter in astronomy. The most important key observations in this field of research and their interpretations will be presented. These numerous observations have led to a world view in which our universe is mainly dominated by a form of matter as yet unknown to us. On the other hand, the potential candidates for dark matter are also presented, and the reader is familiarized with the great experiments in this highly topical field of research, the search for them and the most promising results to date.

The search for the nature of dark matter resembles a quest of the grail, transported into the modern age of the natural sciences. The book cover is dedicated to this parable. It shows the “artistic” visualization of a simulated galaxy rotation curve, which resembles a chalice when it is mirrored and rotated accordingly. In the course of the book, you will learn that galaxy rotation curves are among the central key observations for the phenomenon of dark matter and how laborious the search for a satisfactory answer to the question of the nature of this matter is. I hope you find this search as exciting as I do.

Telfs
June 2017

Wolfgang Kapferer

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Introduction

If you search for answers to the question “What is dark matter?” in *the* information source of our time, the Internet, you will be well served quantitatively. The simple question **“What is dark matter?”** entered into a common Internet search engine will bombard you with about 20 million hits in a flash. I admit not to have read all pages found, but after a short review of the list of results, one must assume that dark matter is most probably something

- invisible,
- mysterious,
- dominant,
- to be believed in,
- …

These are all attributes that are difficult to combine with the methods of natural science. It quickly becomes clear that almost all large structures in the universe, such as galaxies, groups of galaxies and clusters of galaxies, predominantly consist of dark matter. And one learns in several treatises that no dark matter has yet been found directly on Earth or by space probes within our solar system. One reads that it must be a form of matter that hardly resembles the matter we are familiar with. It is so weakly interacting that it permeates every material in our world, almost without any sign of interaction with the elements we know. The adverb *almost* in the last subordinate clause is of particular importance. Because in order to detect dark matter directly in experiments, we need some kind of interaction with the particle physicists’

W. Kapferer, *The Mystery of Dark Matter*, Astronomers' Universe,
https://doi.org/10.1007/978-3-662-62202-5_1

instruments, apparatus from the type of matter we are familiar with. At least this is the hope scientists currently foster with their experiments.

The most successful theory of structure formation in the universe to date states that all the matter in our universe consists of about 85 % of this mysterious substance - dark matter. And it should not be unmentioned at this point that there is an even more significant player on the cosmological stage: dark energy, which according to the present knwoledge dominates the universe even more on large scales. However, as this book deals with the phenomenon of dark matter, dark energy will only be touched upon briefly.

A somewhat more intensive research on the Internet soon reveals to those interested that the term dark matter had already found its way into the literature of astrophysics in the 1930s and 1940s. If one takes the trouble to search for the number of all publications in which the term *dark matter* occurs in the text by means of a search engine for astrophysical literature (*NASA's Astrophysics Data System Bibliographic Services*), one gets as a result a search list with the "astronomical" number of almost 100,000 publications. About 67,000 of these are peer-reviewed publications (Fig. 1.1). But even more interesting than the sheer number of publications is the explosive

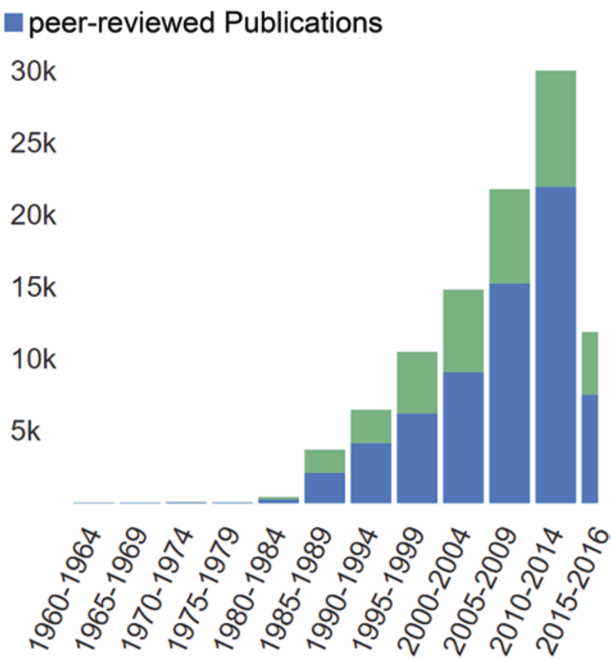

Fig. 1.1 Number of peer-reviewed publications containing the term *dark matter*. In the period 1960 to mid-2016, represented in units of 1,000. Source: *NASA's Astrophysics Data System Bibliographic Services*

increase in publications on dark matter starting in the early 1980s. To illustrate: In the years between 1930 and 1979, there were *in total only 428* publications in which the term dark matter appears.

Unfortunately, despite enormous efforts, the goal - the clear and direct detection of dark matter - has not yet been achieved. Not a single lump of this mysterious matter can be found in any astrophysical exhibition. And it seems that since the advent of the term dark matter in the astrophysical literature, the number of ideas and approaches to solving this problem has increased as rapidly as the presumed amount of dark matter in the universe.

Perhaps it is the same with the dark matter as once was with *ether* in the late 17th century. It was postulated in the models of these days as a medium for the propagation of light and gravity and was subsequently sought in vain by physicists for over two centuries. Nothing less than the successful theories of Einstein, Maxwell and Schrödinger mark the end of this long odyssey, describing the processes in our world completely without *ether*.

The aim of this book is to give the reader an understanding of the phenomenon of dark matter. It introduces the basic models of astrophysics, which lead to the conclusion that dark matter is the dominant matter-component in the universe. The book tries to answer the following questions:

- What major developments in the field of mass determination of astrophysical objects preceded the dark matter era? And above all, how is mass actually determined in astronomy?
- Which observations in the interplay to which models lead to the idea of dark matter?
- Which solutions without dark matter existed and why were they rejected?
- Which approaches and methods are currently being used to search for dark matter?
- Are there alternatives to the concept of dark matter?

A special focus in this book is on the methods applied in astrophysics. During my research, I found it amazing to see how many popular science books deal with topics like structure formation in the universe, speculations about parallel universes or the complex models of the first seconds after the Big Bang in only a few lines. Without a sound physical background, the danger of getting transfigured images of modern physics and astrophysics is very present. This must be prevented because what Marie von Ebner-Eschenbach (Austrian writer 1830–1916) once wrote is still relevant today:

Those who know nothing must believe everything.

2

The Art of Weighing a Star

What causes astrophysicists to postulate more matter than is observable? In order to answer this question, it is first necessary to digress into the history of natural sciences, explaining the concept of mass as used in the models of astrophysics and physics, in order to better understand the concept of dark matter.

The term *dark matter* already indicates what it is all about: matter that is not visible to the naked eye or to the sensitive instruments of astronomers. Matter that is literally "dark."

Especially when you consider that not too long ago only the range of light visible to the human eye was accessible to celestial explorers, it is not surprising that objects in the universe were still in darkness. However, even since we have been able to access ever larger areas of the spectrum of light as a source of information, the situation has not improved, only worsened.

The question that naturally arises at this point is: What causes astrophysicists to postulate more matter than can be observed? In order to answer this question, it is first necessary to make an excursion into the history of the natural sciences, explaining the term *mass* as it is used in the models of astrophysics and physics, to better understand the concept of dark matter.

W. Kapferer, *The Mystery of Dark Matter*, Astronomers' Universe,
https://doi.org/10.1007/978-3-662-62202-5_2

2.1 Mass Determination in the Cosmic Front Yard - The Solar System

The concept of mass as a measure of the gravitational attraction of bodies first appeared in astrophysics: in the exploration and mathematical modelling of the orbits of planets in the solar system. This is an example of how the astrophysical experiment, the observation, in combination with theoretical modelling leads to theories that enables us to predict the future state of astronomical systems. In the particular case about the orbits of the moons and planets of our solar system.

This exciting story began in the heyday of the Renaissance. Art and culture underwent a revolution and brought new ideas into the world, which would reverberate for centuries. During this time, our knowledge about the processes in the cosmos was realigned. The combination of detailed observations and their evaluation using theoretical-mathematical models made it possible to calculate the planetary orbits, predict their positions on the firmament and thus transfer them from the world of myths to the scientifically rational world of the Enlightenment. And, as almost always in the history of science, it was not a simple, direct path to the first useful models of planetary motion; it was rather a tortuous path of trial and error, as complicated as the planetary orbits in the night sky itself.

In our history, three great natural scientists and their work are in the focus of our interest: *Tycho Brahe, Johannes Kepler* and *Sir Isaac Newton*. Of course, this is an abbreviated approach and any historian of natural sciences would have to dismiss this approach as inadequate, but for the introduction of the concept of mass it seems sufficient to me at this point.

Let us first approach the person Tycho Brahe. He was one of the most important astronomers of his epoch. He studied philosophy, rhetoric, law, humanities and natural sciences from the middle of the sixteenth century at the universities of Stockholm, Leipzig, Wittenberg, Basel and Rostock - a true universal scholar of his time. The fact that he was able to represent his points of view vehemently was already shown in a duel at the age of 20 years, in which he lost part of his nose. According to many sources, it was a mathematical problem that he was truly passionate about, literally fighting out with his fellow students. However, he did not go down in the annals of the history of science because of his special dueling skills, rather he was one of the greatest astronomers of his time because of his exact observations of the sky. He made these observations completely without the astronomical telescope of Galileo Galilei, but only with - from today's point of view - primitive technical means, such as the wall quadrant (see Fig. 2.1). This

Fig. 2.1 Tycho's wall quadrant

is a simple but very effective instrument for measuring the positions of the stars on the firmament. The wall quadrant provides accurate viewing angles on a north–south axis. This allows the measurement of the highest position of an object on its path across the sky and the time of this event. These are two important quantities to describe the orbit of a celestial body in the sky. If you like, it was a large protractor for celestial objects.

Exact measurements of the courses of the wandering stars, as planets were called at that time, were scarce at that time. Tycho Brahe, with the help of several employees, collected data on the positions of celestical bodies on the firmament in a quality and quantity as never before. Brahe wanted to refute the burgeoning heliocentric world view at his time with his excellent data. He rejected the idea that the Sun was at the center of the universe and that the earth rotated not only around the central star but also around its own axis. He said that this could not be reconciled with his everyday observations either. That's why he developed his very own world view, the *Tychonian Planetary Model*. It described the orbits of the planets and the Sun in such a way that the earth remained in the center of events and the Sun and planets revolved around it. In order to be able to reconcile all his observations with this model, he had the planets known at that time (Mercury, Venus, Mars, Jupiter and Saturn) all

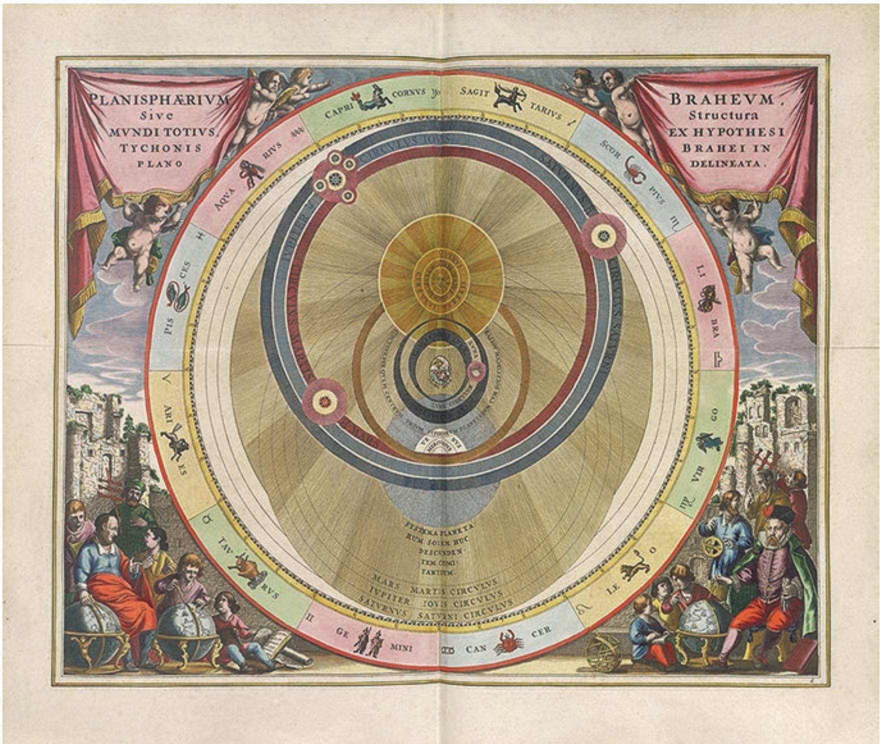

Fig. 2.2 The Tychonian Planetary Model. Source: Andreas Cellarius: Harmonia macrocosmica seu atlas universalis et novus, totius universi creati cosmographiam generalem, et novam exhibens. 1661

revolve around the Sun, see Fig. 2.2. The model was very complex and mathematically hardly controllable. A myriad of parameters were required, which almost always indicates that the model does not describe reality well.

And this brings us to the second protagonist of our story. So Brahe was missing a stable, elegant, theoretical *construction* based on the mathematics of those days, to help his model achieve a breakthrough. Therefore he hired Johannes Kepler as an assistant. Kepler was known and respected for his mathematical abilities. But the cooperation was not fruitful in the sense of Brahe. Kepler was not a good observer and, what was even worse, he was not convinced of the world view of his financier. And Brahe was afraid that Kepler might achieve fame on the basis of his great observations and that he would not receive the appropriate recognition.

Kepler, on the other hand, a number mystic, saw primarily mathematical relations as the underlying order of nature. Thus he initially thought that the planetary orbits followed five perfectly nested spheres within regular

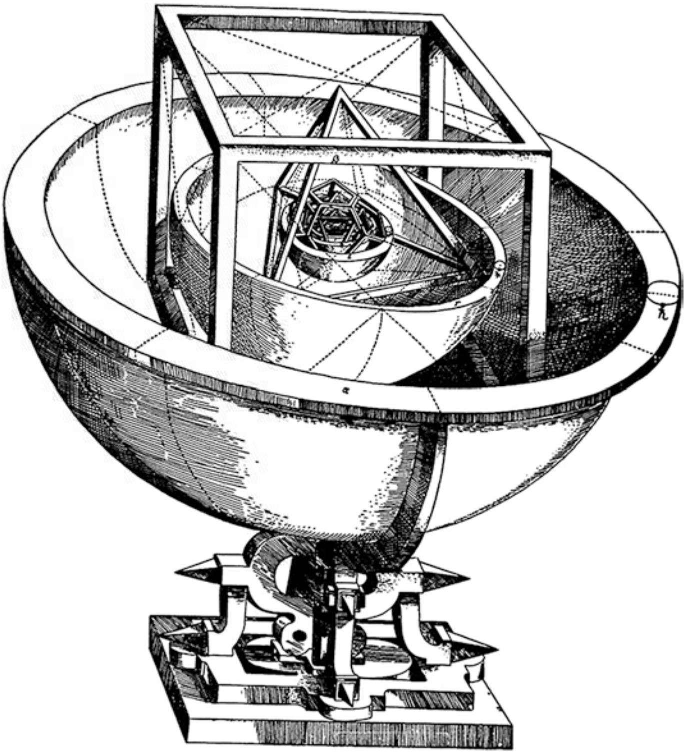

Fig. 2.3 Kepler's initial model of the solar system. *Mysterium Cosmographicum (1596)*

polyhedra (see Fig. 2.3). Different geometric shapes should describe the orbits of the planets exactly.

For him, as for many scientists of that time, geometric forms stood for a divine harmony, which had to be reflected in the paths of the stars. Today, one can hardly imagine the inner conflicts Kepler must have had when he found something other than this pure harmony in all the wonderful data of Tycho Brahe. Namely those relationships that we know today as the three Keplerian laws.

It was Kepler who recognized three fundamental connections in Brahe's data (see Fig. 2.4).

- The planets move on elliptical orbits with the Sun at one focal point.
- The imaginary direct connecting line Sun to planet sweeps over equal areas at equal times.
- The squares of the orbital periods of two planets behave to each other like the cubes of their large orbital axes.

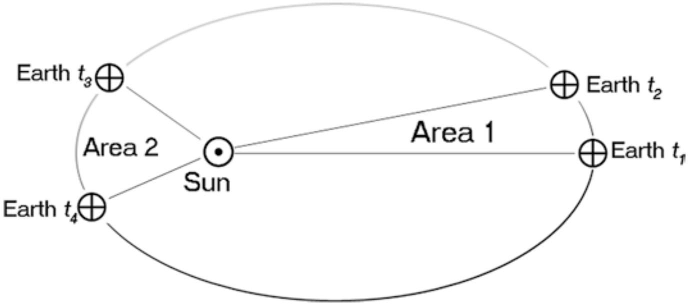

Fig. 2.4 Elliptical orbit of the earth around the Sun (strongly overdrawn, in reality almost circular) with our central star in one of the two elliptical foci. The time that the earth takes between the points t_1 and t_2 respectively t_3 and t_4 is equal. According to Kepler's second law - the imaginary connecting line between the Sun and the planets sweeps over equal areas at equal times - area 1 and area 2 are thus equal in size

But Kepler was not yet satisfied with these groundbreaking findings. He tried to find a causal effect for his observations. The natural scientist Kepler assumed that the Sun had a kind of magnetic effect on the planets. He himself described this effect as *anima motrix*, as *soul of the mover,* and already modelled for this long-distance effect a dependence entirely in the manner of the decrease of the intensity of the light with the distance from the shining star, see Fig. 2.5. This new force had been postulated by Kepler as the causal effect of the planetary orbits, which proved to be a very successful concept.

Fig. 2.5 Anima motrix distance behavior $1/r^2$. Assume that the attracting force has the value 1 at distance 1, and that it decreases quadratically along the drawn curve as the distance increases. At 10 times the distance the force is only a hundredth of the original value, but this force never disappears completely

Furthermore, in his model this force emanated from all bodies: the Sun, the planets, the moons, every lump of matter, no matter how small. Such a "magnetic" force effect of the bodies, the anima motrix, with its square decrease, has another interesting property: it will never completely extinguish. Even in the deepest depths of space, the Sun has its effect according to this model, but of course only to a very small extent. Yet this force will never disappear completely.

In *Astronomia nova,* 1609, Kepler's laws were not yet elegantly mathematically modelled, but rather formulated as loose axioms - a circumstance that was to change at the end of the seventeenth century.

With Sir Isaac Newton, the third actor in our history, and his major work, the *Philosophies Naturalis Principia Mathematica* (1686), a theory of the dynamics of bodies based on mathematical description appears for the first time at the stage of natural sciences. His theory formally brought together the observations of Galileo Galilei's fall-experiments and Kepler's laws of our nearest celestial bodies, thus creating a generally valid theory of gravitation (mass attraction). Newton's theory was unchallenged for several centuries and in many areas it still is today. It can be used to describe a large number of observations simply and elegantly.

Again, there are three connections, three laws, which describe the movements of the bodies and allow exact predictions of their paths:

- **Newton's first law or principle of inertia:** A body maintains its speed and direction as long as it is not forced to change its state of movement by external forces.
- **Newton's second law or principle of action:** The change in motion is proportional to the action of the force causing it and occurs in the direction of the straight line along which that force acts.
- **Newton's third law or interaction principle:** Forces occur in pairs. If one body exerts a force on another body (actio), a force of the same magnitude but in the opposite direction (reactio) - actio est reactio - acts in reverse.

The first important finding in Newton's model: The acceleration of bodies is caused by a force. In this abstract concept, a force always causes a change in direction and speed of the body's path.

The stronger the force, the stronger the acceleration, the stronger the change of path. Newton's second law describes the change of motion *proportional* to the acting force. So in equal proportion to a quantity that we could call **Mass**. This description also fits well with our everyday experiences. Just