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Understanding Gaia

A Mission to Map the Galaxy

Springer

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All nature is but art, unknown to thee;
All chance, direction, which thou canst not see;
All discord, harmony not understood;
All partial evil, universal good.
And, spite of pride, in erring reason's spite,
One truth is clear, "Whatever is, is right."

Alexander Pope, An Essay on Man

To our families

Preface

This book started out as the evolution of a previous little book that one of us (GB) wrote on the occasion of the launch of Gaia, a satellite built by the European Space Agency. Its purpose was to exploit the occasion of this space mission as an opportunity to write a short and introductory text on astronomy and space science for the layman, but, at the same time, keeping one eye toward young people.

The popularization of science is anything but a simple profession, and it often requires expertise in different fields, so that a short book also represented a nice chance for the author to dust off the competence in regard to space science that she had acquired years before, while working on the Rosetta satellite. In that case, such expertise was very useful, but the goal of the present book required a longer and more detailed exposition, for which collaboration with a scientist who has worked on the Gaia mission for several years constituted a valuable addition.

The Gaia satellite, launched at the end of 2013, is responsible for a major advance in astronomy and astrophysics, leveraging the simple concept of providing a complete and high-precision map of the positions and velocities of the stars in our galaxy. No matter how simple, this idea is boosted by the sheer power of the vastness of such a map, and by one of its fundamental ingredients: the stellar distances.

Thanks to these ingredients, Gaia will revolutionize our knowledge on the origin and evolution of the Milky Way, on the effects of mysterious Dark Matter, and on the birth and evolution of stars and extrasolar planets. In other words, its results will foster a total breakthrough, whose consequences will span all of the realms of astronomy and astrophysics.

This space mission, therefore, represents a wonderful opportunity to talk about several aspects of this science that are often treated separately. Among them, a special place in this book is reserved for astrometry. Despite its fundamental importance, this branch of astronomy, which deals with the measurement of stellar positions, is poorly covered in popular science publications, which tend to focus on other, more popular fields. A satellite like this, instead, represents the perfect chance to explain what astrometry is and how it works.

Gaia produces a steady flow of data that, during the course of its operational life, will yield a massive database of raw measurements. One of the main difficulties of the mission is the processing of said data, namely, the transformation of this impressive amount of unorganized data into an invaluable vault of scientific information. Thus, a specific portion of the book is devoted to explaining this complex process and its scientific consequences.

Building and operating a satellite is always a difficult task that requires mastering a lot of knowledge, from astronautics to information technology. Here, we also used Gaia to take a fairly detailed look at these more specialized aspects of a space mission.

Finally, although it will require several more years to obtain the satellite's results in their final form, a series of intermediate releases have already been published. The last part of the book, then, is devoted to showing and explaining a selection of them.

In summary, this work will take the reader on an all-inclusive journey of discovery between the skies and the science and technology of a scientific satellite, showing, at the same time, how the data are collected, interpreted, and used for scientific purposes. To this aim, we used information available from publicly accessible sources only, but the resulting work benefits from the combined forces of a professional science writer and a scientist who was able to exploit his insider's point of view. We also wish to thank the following people who gave us feedback on various parts of the book or helped us find images: Beatrice Bucciarelli, Roberto Morbidelli, Paolo Tanga, and Claudia Travaglio.

Torino, Italy
October 2018

Gabriella Bernardi
Alberto Vecchiato

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Introduction

The year 1989 represents a historical moment for Astrometry. This is the year when Hipparcos, the first astrometric satellite, was launched, symbolizing the beginning of the modern era of astrometry.

Until then, in fact, this incredibly ancient and glorious branch of science had been undergoing a decline that lasted for more than a century, since the scientific and technological advances of the nineteenth century had given birth to and nurtured the development of Astrophysics.

Astrometry, intended as the way to measure the positions and motions of the stars in the sky, has accompanied humankind since its very beginning as a species. Some of the constellations, like the Big Dipper, Taurus, and others, are so familiar to us that it might seem as if they have existed forever. And this could be one of the cases in which our instinct is right, as some studies seem to have ascertained that they represent the heritage of an oral tradition that can be dated back to 17,000 years. In the Paleolithic era, well before the most ancient civilizations and even before human beings learned the art of writing, people felt a need to identify the stars in the sky, giving them names and making beautiful paintings of their stellar-inspired mythology in their caves.

In a certain sense, this cannot be surprising. Knowledge of the configuration of the stars and their motion told when the seeds could be planted, when the harvest could be gathered, or where the next hunting area was located. In other words, it represented the difference between life and death.

When the first civilizations appeared in history, the ability to predict astronomical events like eclipses added to this tradition, and the people who possessed these skills could interpret the will of the gods, or even command them!

With the advent and development of Astronomy as an exact science, Astrometry was the observational counterpart of Celestial Mechanics. These two scientific sisters constituted the entire realm of Astronomy. The systematic observations needed to obtain certain significant result required years of long, hard work, and a bit of luck, but such was the importance of discovering a new comet, or producing a precise stellar chart, that the reward could even change the life of the lucky, hard-working astronomer.

Then, Astrophysics completely subverted this scenario, and it happened so fast that, in a matter of just a few decades, Astrometry was left with no glory but just with the long and hard working. Suddenly, with the help of new astrophysical techniques, for the first time, scientists could understand what the stars were made of and how they evolved. They measured stellar temperatures and understood the secret of the incredible amount of energy within them. People were informed that stars assemble together into galaxies, and that galaxies group themselves into clusters and superclusters, and that the Universe was born about 13 billion years ago from a super-small, dense, and hot point, and is currently expanding at an incredible speed. Like a kind of lucky Pandora's Box, the coming of Astrophysics made a seemingly easy and unstoppable flux of new and incredible discoveries possible, along with the flourishing of new theories. Something that quickly dwarfed the labored achievements of a thousand of years-long tradition of Astronomy.

Positional astronomy continued to be practiced, but it compared to Astrophysics like a cornfield compared to the Klondike during the roughly contemporary Gold Rush, so the leverage had definitely and permanently moved elsewhere… or had it?

Actually, Klondike prospectors could not survive without corn, and, similarly, Astrophysics needed astrometric data to feed and sustain its wild development. Soon, it became clear that Astrophysicists without good astrometric data were like a swarm of explorers without a good map. Surely, each of them could keep up exploration at an impressive speed, but the farther one moves, the larger the unexplored territory, and the longer it takes to find the right direction if one does not have the right tools.

This comparison is more literal than it might seem, since it was a matter of maps, indeed. At the very end, one of the most fundamental pieces of information needed to answer the uncountable questions raised by astronomical research is the distance of the objects under investigation. There are several techniques for estimating astronomical distances, each with its own range of validity. Moreover, they depend on each other with a general schema. Those applicable to smaller distances fail when the object is too far away, but, on the other hand, you need to finely tune the large-distance techniques to make them useful; otherwise, their accuracy is too poor. This fine-tuning is provided by each previous method in the series; therefore, you need to build this so-called cosmic distance ladder step by step to reach the farthest objects in the universe. And guess what the first of these rungs is: the parallax determination, which is the classical astrometric technique for measuring distances!

In principle, this is a purely geometric method, and it is self-consistent, but the parallax, which relies on the measurement of angle differences, is also extremely difficult to estimate. Moreover, there are two types of parallax, relative and absolute, and, although both are useful, the latter is the "philosopher's stone" of the cosmic distance ladder. You can bet that it is thus also the most difficult to obtain.

Determining the absolute parallax is an endeavor that deals with the realization of maps of the entire sky, something that astrometrists call "global catalogues," which is the most difficult of their endeavors. In fact, as late as the second half of the last century, the best global catalogues counted a few thousand objects, and only a handful of the nearest stars had a reliable relative parallax.

A large share of the difficulties came from the fact that, for various reasons, the necessity of observing from the ground limited the accuracy and speed of these measurements, which is why Hipparcos came into play. As a space-based measuring instrument, it made possible the realization of a catalogue 100 times larger and more accurate than its most recent predecessors, and it did it in about thirty years (a period that goes from the initial idea to the release of the final catalogue, and includes just 2.5 years of measurements).

Nevertheless, Hipparcos' horizon was limited to a small region around the Sun, some 100 times smaller than our Galaxy, in linear distance. During the last years of this mission, like a symbolic handover, a more ambitious program was conceived, that of another satellite that would have been able to measure a far greater number of stars and with much better accuracy. Something that could allow, for the first time in history, the realization of a three-dimensional map (actually, five-dimensional, but this will be revealed later) of practically the entire Milky Way. Its name was Gaia, and its promise is doing nothing less than revolutionizing our astronomical knowledge and keeping astronomers busy with its data for the next several decades.

Like all bird's-eye views, this can give us more or less of a general picture, but leaves most questions unanswered. Why, precisely, have hundreds of astronomers planned to work so hard for decades (Gaia will last for about thirty years, like Hipparcos) to realize a map of the sky? Who made the first star chart? How are astronomical satellites built and operated? How do they communicate with us, and how are their data processed to produce the final map? What will happen afterward? And, last, but not least … what the heck is the Milky Way?!

Gaia was launched in 2013 and, to date, the European Space Agency and the consortium of scientists that was established to process its data has released the second in the series of its catalogues, while the final one is not expected before 2023. The goal of this book is to try to answer these and other questions, and to show and explain the initial results of the mission. In a certain sense, the satellite itself, with its name, will guide us on this route, which could therefore rightly be called "The Spelling of Gaia."