UNVEILING GALAXIES

The Role of Images in Astronomical Discovery

Galaxies are known as the building blocks of the universe, but arriving at this understanding has been a thousand-year odyssey. This journey is told through the lens of the evolving use of images as investigative tools. Initial chapters explore how early insights developed in line with new methods of scientific imaging, particularly photography. The volume then explores the impact of optical, radio, and X-ray imaging techniques. The final part of the story discusses the importance of atlases of galaxies; how astronomers organised images in ways that educated, promoted ideas, and pushed for new knowledge. Images that created confusion as well as advanced knowledge are included to demonstrate the challenges faced by astronomers and the long road to understanding galaxies. By examining developments in imaging, this text places the study of galaxies in its broader historical context, contributing to both astronomy and the history of science.

JEAN-RENÉ ROY is a retired astronomer who was a professor at Laval University, Québec, Canada from 1977 to 2000. Since then he has served as Deputy Director and Head of Science at the Gemini Observatory in Hawai'i and Chile and worked at the Large Facilities Office of the National Science Foundation and finally at the Space Telescope Science Institute. He has done research on the Sun, the interstellar medium, and the evolution of gas-rich galaxies. A new edition of his previous book, *A Question and Answer Guide to Astronomy*, was published in 2017.

"As one of the world's leading astronomers, Jean-René Roy provides us with an insightful and readable account of the use of images to distinguish between deep-sky objects, such as nebulae and galaxies. What makes this an exceptional work is the level to which Roy, as a practitioner, engages with historians of science in developing his rich account. This engagement leads to a unique book, one that will be indispensable to understanding the significant role played by images in the history of twentieth-century science."

Omar Nasim, *Universität Regensburg*

"Unveiling Galaxies examines the role of 'transformational images' in the history of astronomy. Images are a tool of discovery, and this book brings attention to the groundbreaking images behind some of the greatest discoveries in astronomy. The book also highlights the role of galaxy atlases in astronomy as well as the lives of the people who made these images and how their work impacted the progress of astronomy. I found that telling the story of the discovery of galaxies by focussing on iconic images is an excellent approach to the subject. *Unveiling Galaxies* is informative, well written, and well researched, and provides a superb read of the process of discovery in science."

Ronald J. Buta, *University of Alabama*

"In this beautifully clear, reflective, and almost non-mathematical book, Jean-René Roy explains how we came to understand that galaxies are the building blocks of the universe. Roy is an accomplished galaxy researcher who takes us on this long and fascinating journey with its many challenges, from the perspective of developments in scientific imaging of galaxies. The story is based on images, starting with sketches of galaxies made from visual observations in the 18th and 19th centuries. The book describes how the gradual improvement in the quality of the images led to the understanding that galaxies are very distant objects, lying far outside the Milky Way."

Kenneth Freeman, *The Australian National University*

"Roy's unique contribution goes beyond tracing the development of making images of galaxies to examine their compilation into atlases. Roy's underlying motivation for this work is personal; his own exploration of a gift of an atlas of galaxies sparked his interest in science and astronomy. With the descriptions of the characters who contributed to the progress of understanding galaxies, the author reminds us that science is a human activity. This book touches on the highlights of how images proceeded from eye and hand to photographic and lately electronic record."

Nancy Levenson, *Space Telescope Science Institute*

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We may, therefore, well hope that many excellent and useful matters are yet treasured up in the bosom of nature. Francis Bacon

To the memories of Allan Rex Sandage, Gérard de Vaucouleurs and Halton Christian Arp

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Preface

Galaxies are the building blocks of the universe. They have been and continue to be extraordinary objects for probing and understanding the universe, its origin and evolution. This book is about galaxies, and about how images led to their discovery and contributed to the understanding of their nature.

Held together by gravitation, galaxies are gigantic systems of stars and clouds of gas and dust. They populate the universe in the billions. Extrapolating counts from the deepest current observations by telescopes in space and on the ground, one estimates that there are more than 200 billion galaxies in the observable universe. We belong to one of them, the Milky Way, a typical large spiral galaxy: disk-shaped like a slightly inflated pizza, the Milky Way hosts about 200 billion stars and measures more than 100,000 light-years across. Our Sun is one of its numerous stars and is located at about 27,000 light-years from the center of the giant whirlpool of stars, interstellar gas and dust. We have only become aware of our cosmic geography in the last century.

About a hundred years ago, in the late 1910s and through the 1920s – a remarkable decade – astronomers proved beyond doubt that our Milky Way was one of numerous giant stellar systems, and that a multitude of similar "island-universes" were scattered at colossal distances from each other. "Nebulae," noticed by sharp eye telescope viewing all over the sky during previous centuries, were found to be extremely numerous, at least millions in number, and complex in their appearances, from mottled disk-shaped pinwheels to soft spheroidals. The diversity of silhouettes and forms turned out to be a key to understand the formation and evolution of galaxies. Probed by inquisitive astronomers with the modern photographic equipment of the twentieth century, "nebulae" became galaxies and literally opened the door to grasping the whole universe. Some say, we then found the universe.[1] Getting there was a fascinating story.

From the first viewing of a "nebula" in the tenth century to the time these foamy patches in the sky were explained and understood, it took more than a thousand years. Why did it take so long? Discovering galaxies and determining their nature was indeed a long path full of obstacles, confusion, debates, conflicts and finally convergence. In this book I will re-tell this arduous road and exhilarating venture. To do so, I will employ a specific perspective:

[1] M. Bartusiak, *The Day We Found the Universe*, New York: Vintage Books, 2010.

the role of viewing, drawing and photographing in figuring out the nature of nebulae, and I will show how this long and time-honored imaging process has helped to bring out the world of galaxies.

Why Images?

An image allows us to see things, to record and describe them, to prove that they exist and to reflect on them. Images can bring irrefutable pieces of evidence for a concept or proof of the reality of a "thing." One can count objects on an image, measure their shapes, identify features and establish if they contain structures, then describe these. When images are digitized, mathematical operations can be executed and quantitative information can be extracted from them. With a large number of images at hand, one can compare and recognize variations between objects. In some cases, such as it was with "nebulae" over the centuries, we might not have a clue about what the "thing" is. Once it is understood, common trends can be traced, "peculiar cases" can be identified and orderly behavior inferred.

Scientists are illustrators. They learn by juxtaposing objects and images. Images then provide an empirical basis for classification, often a critical pre-discovery step, to understand the nature of objects, "nebulae" and galaxies, in our case.[2] Atlases are the juxtaposition of images. Scientific atlases with their rich compendia of images become the pictorial beacons helping us to navigate the natural world. I will explore why and how the great atlases of galaxies of the past decades were put together. I will explain how these image galleries helped to broaden our knowledge of the world of galaxies, how they influenced research programs and drove the design and construction of new telescopes and cameras.

We read text; we read images. Scientific images are not only powerful conveyors of information but also a tool to share complex knowledge.[3] Images also carry esthetic value. They help to create enthusiasm and understanding. Images of astronomical objects can be truly beautiful, esthetically abstract and amazingly representational.[4] The popularity of the Hubble Space Telescope is in great part due to an outstanding and successful educational effort to explain and share particularly significant astronomical images with an audience broader than the astronomer specialist using the facility.[5,6]

My approach and perspective in writing this book are those of a practitioner: it is the viewpoint of someone who has observed and studied galaxies, taught and trained students into learning what they are, helped in building instruments to image galaxies and, finally, run a large observatory where major programs were conducted to explore these prodigious sidereal objects. My career was ignited by a spark. As a teenager, I was

[2] S. J. Dick, *Discovery and Classification in Astronomy, Controversy and Consensus*, Cambridge: Cambridge University Press, 2013, pp. 233–276.
[3] M. Lynch and S. Y. Edgerton Jr., Aesthetic and digital image processing: representational craft in contemporary astronomy, *The Sociological Review*, 1987, Vol. 35, pp. 184–220.
[4] M. Benson, *Cosmigraphics, Picturing the Universe Through Time*, New York: Abrams, 2014.
[5] E. Snider, The Eye of Hubble, Framing Astronomical Images, *Frame: A Journal of Visual and Material Culture*, Issue One, Spring 2011, pp. 3–21.
[6] For example, see Z. Levay, *Hubble Space Telescope: Re-imagining the Universe*, TEDxKC, 2015, www.youtube.com/watch?v=JDJsiEI_0gE

dazzled and inspired by *The Hubble Atlas of Galaxies* by Allan Rex Sandage, a giant of twentieth-century astronomy.

To ground my story on a broad foothold, I also borrow the works of scholars who have disentangled the scientific discovery process: historians, sociologists and epistemologists. Their perspicuous investigations have explored the minds of scientists and dissected their products. These scholars have helped us understand why it took 1,000 years from the first viewing of nebulae to the final unveiling of the world of galaxies in the initial part of the twentieth century. Thus, I encapsulate the works of many. Ambitiously, I am striving to build a bridge between the genre of science writing typical of scientists and the history of science literature.

On Nebulae

"Nebulae" are far away, and most are astonishingly distant. The concept of "nebulae" has been at times very confusing, even chaotic, as successive attempts were made to distinguish the categories of these elusive cosmic objects. It took a long time to figure out the diversity of "nebulae" and to understand them. For a long time, astronomers were unable to determine their distances, which many thought implausible. Moreover, the puzzling objects could not be related to anything familiar. The nature of "nebulae" was considered to be out of the ordinary: were they made of a mysterious cosmic fluid, a bunch of unresolved stars or just illusions in the mind of imaginative observers?

To assist you in navigating through this long and foggy history, I give here the gist of the different classes of "nebulae" as we now know them. This will help you to stay the course through the maze of the long-lasting unraveling of their nature.

There are two main classes of "nebulae": (i) diffuse nebulae (clouds of gas and dust) and (ii) extragalactic "nebulae" or galaxies (huge assemblies of stars). Diffuse nebulae are members of our Milky Way; they also exist in other galaxies as components of the interstellar medium – the space between stars. Diffuse nebulae can be divided further into two broad categories, (a) emission nebulae where the atoms of the cosmic gas are stripped of their electrons and made fluorescent by the ultraviolet light of hot massive stars, and (b) reflection nebulae whose dust reflects the light of stars in their vicinity.

By far the largest category of "nebulae" are the non-galactic or extragalactic "nebulae," now called galaxies. Much larger physical entities than emission and reflection nebulae, they are totally different from diffuse nebulae. Galaxies are made of billions of stars and contain huge quantities of interstellar matter often seen as diffuse nebulae and dust clouds. They form two main categories, ellipticals and spirals.

A major epistemological stumbling block was the following: for centuries, most researchers tried to bring all nebulae under one umbrella, making them a single class of physical objects. This is not an uncommon approach in the development of science. The long quest is not without parallel to Plato's allegory of the cave, where people try to understand the world by watching shadows on the walls from the things passing in front of the

fire behind them. For centuries, astronomers, like the prisoners of Plato's cave, puzzled over "nebulae." The challenge and key to a successful epistemic exit were to distinguish the different categories of "nebulae," and, as a critical step, to establish their distances. Key breakthroughs came with reliable distance determinations and from spectroscopy. The latter technique revealed the physical nature of sidereal matter in its various states, providing the tool to distinguish stars from true nebular material.

Throughout the initial chapters of the book, I will use the word "nebula" in quotes since historically the object discussed could be either a cloud of gas and dust, an unresolved cluster of stars or a distant galaxy, the observers not knowing or being unable to make the distinction. When unquoted, nebula refers to diffuse or reflection nebulae. More confusing for the unfamiliar reader, galaxies were initially called "non-galactic nebulae," "extragalactic nebulae," or "anagalactic nebulae." After the death of Edwin Hubble in 1953, they became simply galaxies. Just watch for the shifting of names, especially when I cite original material.

Plan of the Book

The book is divided in three parts. In the introduction, I deal with the challenges of images and their role in scientific discovery. I discuss the issue of images not being self-evident. Part I deals with the specificity of astronomical imaging and its challenges at finding and revealing galaxies: the long path from the visual discovery of fuzzy celestial clouds to the photography of multitudes of spirals, a long quest that lighted the path to our finding of the universe. I show how images provided the exacting and essential steps for unveiling the world of galaxies: first from written descriptions of what was seen through the telescope (Chapter 1), then sketched in the drawings of nineteenth-century visual observers (Chapter 2), later photographed by the pioneers of the end of the nineteenth century and early twentieth century (Chapter 3), then abstracted as images for the mind (Chapter 4). Chapter 5 acts as a gateway. It is a transition chapter: I recap the whole story in a more traditional way, bringing together the names of the key actors, their places and dates, as well as the ideas that contributed to the unveiling of the world of galaxies. I describe how galaxies became stepping stones for measuring the size and the age of the universe, and not least can be used to determine the exact position of the Sun and solar system in cosmic space and time. I chronicle the crucial decade of 1915–1925, where reliable distances to galaxies were established. I refer extensively to the works of astronomers, both professionals and amateurs, as the latter often contributed in most innovative ways. For example, the early recognition that imaging techniques (photography and spectroscopy) could be valuable to study nebulae and galaxies came from amateur astronomers. It took decades for the professionals, who initially mistrusted photography, to be convinced.[7]

[7] See A. Hirshfeld, *Starlight Detectives: How Astronomers, Inventors and Eccentrics Discovered the Modern Universe*, New York: Bellevue Literary Press, 2014.

In Part II, I summarize the current knowledge about galaxies, emphasizing the role of several imaging techniques that helped to unravel the complexities and extraordinary properties of galaxies: galaxies as viewed in the optical/infrared domain (Chapter 6), and at radio and X-ray wavelengths (Chapter 7). A particularly gripping story is how dark matter was discovered and inferred by what I call "imaging the invisible" (Chapter 8).

Part III of the book is my most original contribution. It is about atlases of galaxies. The scientific atlas is a standard tool to share and disseminate knowledge using carefully selected sets of images. "Scientific atlas images are images at work, and they have been at work for centuries in all the sciences of the eye, from anatomy to physics, from meteorology to embryology."[8] Astronomy is no exception. Atlases of galaxies have been trailblazers in the development and sharing of new knowledge about these great assemblies of stars. Classification of objects is the foundation of any scientific atlas. Chapter 9 tells the fascinating story of the building up of a classification system of galaxies and what role images played in the controversial process, and how morphology became a fundamental criterion to classify galaxies. In Chapter 10, I discuss and review all the major galaxy atlases that are published and used by astronomers and their students. In Chapter 11, using specific examples, I illustrate the impact of these atlases on the way research programs were proposed and conducted, and their role in the design and building of new astronomical cameras and telescopes. I conclude the book with some personal reflections on how images are helping us to understand the universe better, and what great tools they are for sharing that knowledge more broadly. Finally, I reflect on the changing role and future of galaxy atlases in the digital age.

From the very beginning, I wish to highlight the cumulative approach I will take you through as we move along. The main thesis (why it took so long) and theme (images as discovery tools) will gradually bulk up over the course of the book. Concepts, ideas, theories, observations, objects and historical actors will occur in different ways as we progress from one chapter to another. There will be repetitions. As we come back to these notions over and over again, we will build a fuller picture. My goal is that by the end of the book, you will appreciate these things in a more rounded fashion and be able to embrace a deeper perspective than provided by the standard astronomy textbook.

The research for this book is based on a mix of primary and secondary sources. Primary sources include research works published in observatory reports, in journals of professional societies, conference proceedings and galaxy atlases. Secondary sources are other scientific atlases, books and articles by researchers in history, sociology and epistemology of astronomy and natural sciences. The *Biographical Encyclopedia of Astronomers* was a rich source of information and provided many hints for further search. The Smithsonian Astrophysical Observatory/NASA Astrophysics Data System Bibliographic Services has been an inestimable resource. Several Wikipedia articles provided useful content and were indicators for other material.

[8] L. Daston and P. Galison, *Objectivity*, New York: Zone Books, 2007, p. 19.

This work was inspired and completed with the help of many individuals with whom I interacted during my career. I owe enormously to colleagues who read the evolving versions of the manuscript and provided most helpful comments, criticisms and suggestions.

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Zoltan Levy (STScI) instructed me on the subtle art and science of making "portraits" from the images obtained with the Hubble Space Telescope. Lars Lindberg Christensen of European Southern Observatory provided provocative insights on the future of imaging in the evolving world of interactive archives and the challenge of creating "ethically correct colour imagery" with raw data from telescopes.

In my exploration of the impact of atlases of galaxies, I interacted with several people by e-mail and telephone. I am most grateful to Alar Toomre (MIT) and François Schweizer (Carnegie Observatories) for their wonderful recollections on the development of the concept of interacting galaxies and of the impact of Halton Arp's *Atlas of Peculiar Galaxies* on their own thinking. I also extend my thanks to Wendy Freedman of the University of Chicago, Kenneth Freeman of the Australian National University, Marshall McCall of York University, Preethi Nair of the University of Alabama, Robert J. Hanisch of the National Institute of Standards and Technology, Eduardo Hardy of Associated Universities, Inc. and Harold G. Corwin, Jr. for sharing on how galaxy atlases did influence their work.

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professional assistance in identifying images for digitization. Loma Karklins of Caltech, Lianne Smith of King's College London and Janet Laidla of University of Tartu Museum came up with notable illustrations. Several librarians helped me to identify sources of images and to clarify ownership of material. Some individuals provided me with hints for other images or different versions, and help in identifying the exact sources. I am most grateful to Mark Bailey of Armagh Observatory and Planetarium, Jaan Pelt of Tartu Observatory, and Harold G. Corwin Jr.

I am in unbounded debt to Matt Mountain for inviting me to spend a year working in the Science Mission Office of the Space Telescope Science Institute, Baltimore, MD. This opportunity and multiple exchanges with STScI colleagues led me to reflect about scientific images and their function in astronomical discovery. My stay at the institute launched me into a small project on the role and impact of atlases of galaxies and that ultimately evolved into this book.

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