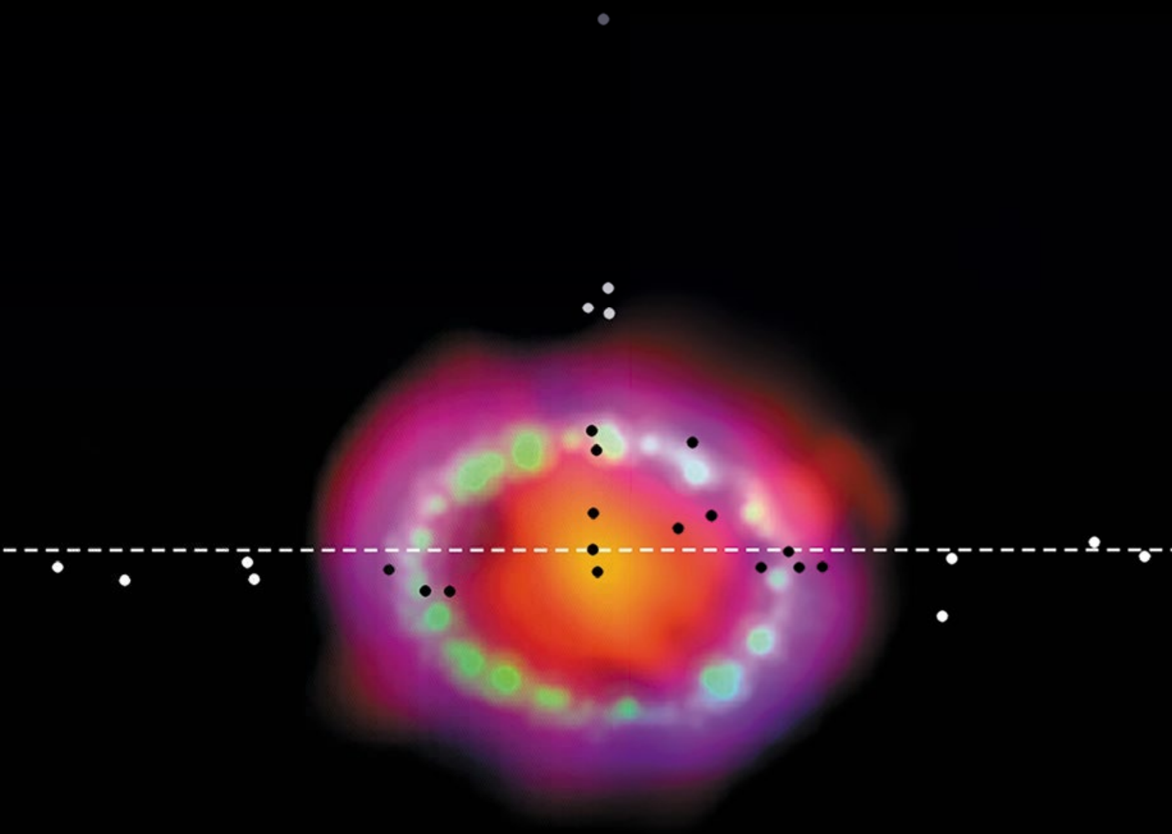
Astronomers' Universe

John Etienne Beckman

Multimessenger Astronomy



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Cover illustration: The remnant of Supernova 1987a in radiation at very different wavelengths: submillimetre wave data from ALMA (coded in red) shows newly formed dust in the centre of the remnant. Hubble Space Telescope visible image (coded in green) and Chandra Space Telescope X-ray image (coded in blue) show the expanding shock wave. Credits: HST and Chandra images: NASA, ALMA image: ESO/NSF/NINS.
Superposed graph: The detection of neutrinos from Supernova 1987a by the Kamiokande neutrino detector. Horizontally dispersed points show the background neutrino level, and the vertical pulse in the centre shows the clear detection of the neutrinos from the supernova. Credit: Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo Design: Inés Bonet/IAC/UC3

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Dedicated to Leocadia Pérez González and Jaime Beckman Pérez.

Foreword

John and I first met at the National Scientific Ballooning Facility in Palestine Texas. We were both trying to fly experiments that would measure the spectrum of the cosmic microwave background that had been discovered a few years before. The critical thing we both were anxious to establish was whether the spectrum was truly that of a black body at around 3 degrees Kelvin. In those days, the measurement was really difficult; the technology for observations at a wavelength around a millimetre was not well developed. You had to make your own instruments from scratch, and furthermore, the detectors as well as the instruments had to operate at cryogenic temperatures, comparable if not smaller than the temperature of the background radiation itself. The most serious enemy was the radiation from everything at room temperature (300 degrees Kelvin). Even a little hole or a sidelobe of the beam touching a warm surface was enough to wreck the measurement. You could not observe from the ground or even a high mountain so we both chose to fly our instruments on balloons that made it to an altitude of 40 km and gave typically 6 hours of night-time observing at the edge of the atmosphere.

John and his group had made an elegant polarising interferometer based on a design by his colleague Derek Martin while my group used a simple set of bandpass filters; we both used the same kind of detector. John's first effort did not get any data due to a destructive balloon failure while our flight functioned but gave a spurious result due to high frequency leakage in the critical channel designed to measure the thermal peak of the 3 K background. Both of us continued with further flights. In a subsequent flight, John saw a peak in the CMB spectrum but was unsure of the calibration. In our case, we needed to subtract a significant amount of atmospheric radiation to show the peak. After several years of flights by many more groups and instruments with slowly improving results, the ground work had been set to convince NASA to actually carry out a dedicated space mission to measure the spectrum and angular distribution of the cosmic background as well as an assay of the sky in the infrared. This was the COBE mission first proposed in 1972 by John Mather but finally flown in 1989. The instrument used to measure the spectrum on that mission was derived from the interferometer John had flown.

John and I met again a few years ago when he invited me to come to the Almeria Astronomy Week held in Almeria, Spain, in June 2018 as part of a celebration of the first direct detection of gravitational waves. We gave a talk together to a group of amateur astronomers who were primarily Spanish and more comfortable with a talk in Spanish rather than English. I was a little wary of the idea, but it worked well. I would show a slide and describe its content in English for a few minutes after which John would translate with the proper emphasis and equivalent excitement including the ironic comments and asides. What impressed me most was his depth of understanding and ability to explain. It was during that visit John told me about his ambitious plan to write this book.

The reason I am telling you all of this is that what John learned through that experience with the 3 K background coupled with his breadth and knowledge is all over this book and is what makes it a unique book about astronomy. (If you are interested in his interferometer you will find it in the section on infrared astronomy where he used it on the Concorde supersonic aircraft to look at the solar chromosphere.) John tells you about the astronomy, but he also explains the physics and other sciences associated with the sources. You will also learn about the instruments used to make the observations and enough about the physics and engineering to appreciate how they work and some of the human ingenuity involved in their design.

I learned a lot from the book, especially about some of the major puzzles in current astronomy and astrophysics, enough so that you are well enough equipped, should you want, to launch into some of the technical papers about the topics in the literature. Above all John elegantly shows the extent of the science involved in understanding our universe and its contents. In the next edition of the book, there will probably be a chapter on biology and the possible evidence for life in many places in the universe. Enjoy the read.

Newton, Massachusetts, USA
November 2020

Rainer Weiss
Emeritus Professor of Physics, MIT
Nobel Laureate in Physics, 2017

Preface

Astronomy has the power to inspire science, art, religion, and popular culture. It is one of the few sciences where amateurs can and continually do make significant contributions, and it is the originator of citizen science, in which the general public can contribute to discoveries via computer-based techniques. It is one of the oldest and most traditional of the sciences but at the same time is continually pushing back the frontiers of new technology, due to the technical prowess required to detect the incredibly faint signals which reach us from around the universe. From when Galileo used the first modern astronomical instrument, the telescope, until almost half way through the twentieth century all our astronomical knowledge was acquired using visible light, even though the visible wavelength range occupies only a small fraction of the full gamut of the electromagnetic spectrum. During the nineteenth century, two powerful tools were added to the astronomers' kit: spectroscopy, which led to the exploration of the composition and the physical states of objects far from the Earth, and photography, which enabled astronomers to accumulate the photons from astronomical sources, allowing them to obtain images of objects much fainter than is ever possible with the naked eye, even through a telescope, and hence to penetrate more and more deeply into space. Within the first three decades of the twentieth century, astronomers, using only visible light, already knew that there are galaxies outside the Milky Way and that on the largest scales the universe is expanding.

Radioastronomy was the first of what came to be called the "new astronomies". In the United States in the 1930s, radio experts who were also amateur astronomers had detected radio waves from outside the Earth, and can be considered the founders of radioastronomy, but this science was really lifted into reality by the technical advances in radio made during the Second World

War to create radar. I was a boy in the 1940s and 1950s and interested in astronomy from an early age. Living in England in those years I learned about this new window on the universe, and visited the Jodrell Bank radio-observatory, which was not very far from Sheffield where I lived. The new generation of radioastronomers, together with a bright group of theorists, was setting the pace and regarded the optical astronomers as “old hat”. In many ways they were right, and their influence was the key to the subsequent resurgence of British optical astronomy, when important optical telescopes had been built on sites well away from cloudy British skies. In the meantime, radioastronomers in the Netherlands, the United States, Australia, and the United Kingdom were mapping large parts of the Milky Way for the first time in the radio emission from atomic hydrogen, penetrating not only the cloudy skies but also the dust which shrouds many of the most interesting astronomical sources in the Galactic plane. They were also making a series of major sky catalogues in radio. These included the famous series by the Cambridge group under Ryle, in a series which reached 7C but whose most famous 3C catalogue included many sources which did not correspond to anything known in the visible. In the early days of radioastronomy, in the early 1950s, these were often referred to as “radio stars”, but as time went on, and other techniques came into use, almost all of them were found to be quite different from stars.

For two decades, radioastronomy and optical astronomy were the main agents of advance in the field. During this period, two striking discoveries were made by the radioastronomers: quasars and pulsars. Quasars were “quasi-stars” bright point sources of radio energy which did not correspond in position to any known stars, even faint stars. At radio wavelengths, it was difficult to pinpoint the position of any source, because the angular resolution of single radiotelescope was nowhere near good enough. A breakthrough came when, in 1962, one of the strong sources 3C273 (number 273 in the third Cambridge calalogue) could be observed when occulted by the Moon, and by careful timing of the moment when the source disappeared and reappeared its position could be measured with only a small area of uncertainty on the sky. The optical observers could then identify this source with a quite faint starlike object, but whose velocity of recession from us placed it at a redshift of 0.16; it was apparently receding from us at 16% of the velocity of light. This was an astonishing result, because from this value of redshift using the Hubble–Lemaître law of the expanding universe, its distance was over 2000 million light years, and the power it was emitting had to be similar to that of a galaxy rather than of a star. We are now accustomed to thinking of these objects as the supermassive black holes which are at the centres of galaxies, and which produce colossal energies in a compact volume due to the conversion of gravitational energy into other types of energy. But this was one of the signs that opening a new window on the universe, in this case the radio window, would lead to important discoveries. Five years later, another new type of astronomical objects, the pulsars, was discovered by the radioastronomers, and these rapidly spinning, highly compact stars turned out to be neutron stars, the central cores of much more massive stars which have exploded as supernovae. Pulsars have played a special role in showing that general relativity is, so far, the best description of gravity, and they remained the best demonstrations of general relativity in action until gravitational waves were first measured in 2015.

After radioastronomy the electromagnetic windows on the universe began to open one after another. As the Earth's atmosphere is fully or partly opaque to radiation in all the wavelength ranges except the narrow optical waveband, and a large fraction of the wider radio waveband, many of the advances were made when it became possible to escape from the effects of the atmosphere (it is, of course, no coincidence that the atmosphere is transparent in the optical, i.e. the visible, wavelength range; evolution has ensured that animals' eyes are most sensitive in this range). This was done by using balloons, aircraft, rockets, and above all satellites as observatories. The era of astronomy from space beginning in the second half of the twentieth century is by any standards the golden age of astronomy. The new opportunities stimulated the invention of new techniques, covering notably the infrared, X-rays, and gamma-rays. The visible and the ultraviolet also benefitted from the development of electronic detectors which substituted the photographic plate, yielding orders of magnitude in improved sensitivity. By the turn of the century, astronomy and astrophysics were technically capable of tackling some of the most interesting problems in the whole of physics, combining information about the universe, its initial phases, and its evolution, with the puzzles intriguing particle physicists. The cosmic microwave background radiation, discovered in 1964 at short radio wavelengths, had been shown to be the most directly observable relic of the Big Bang, and its study, combined with optical and infrared studies of stars, galaxies, and the intergalactic medium on the largest scales, put cosmology on a scientific basis, as opposed to the largely speculative models relying on good theory (general relativity) but with limited types of observations that had prevailed for the previous half century. Even so, all the information gathered from the cosmos was via electromagnetic waves, albeit over a range of more than 20 orders of magnitude in wavelength (also in frequency, and in energy). In one sense, we were still relying almost entirely on a single type of messenger to deliver the information about the universe. Much of this book is aimed at describing the practical ways in which these new astronomies worked.

There was in fact one other stream of information from outside the Earth which had been actively observed since the first decade of the twentieth century. These were the cosmic rays, which was a misnomer for the high energy particles which impinge on the Earth from space. These particles were first detected using relatively simple equipment which had been developed during the beginnings of the new science of radioactivity, which would become nuclear physics. These particles have energies ranging well above those which can be produced even in the biggest particle accelerators, and until the mid-1950s they were used to make new discoveries in particle physics rather than to explore astronomical objects. They were much cheaper to use than to build accelerators, hence of great interest to particle physicists, but their sources could not be easily identified, hence of less direct interest to astrophysicists. Particles such as protons (hydrogen nuclei), electrons, and alpha particles (helium nuclei) have their trajectories interfered with by magnetic fields as they pass through interstellar and intergalactic space, so it is almost impossible to discover their sources directly. These particles make up most of the cosmic rays, and as we will see, they originate in some of the most energetic processes in the universe, giving us unique insights into those processes. They also make up a large part of what is found as radioactivity on Earth, and their names, alpha particles, beta particles, (which are electrons), and gamma-rays reflect experimental discovery and classification in the late nineteenth century prior to the understanding of their nature and detailed properties. We now know that gamma-rays are the highest frequency, highest energy form of electromagnetic radiation. This means that they travel through space just as light does, with no deviation by magnetic fields, for example. We also know that they are produced in similar processes to those which produce cosmic rays, and indeed in one sense they are the only true cosmic rays, while the other types should really be called cosmic particles. So we can combine detections of gamma-rays and cosmic rays to find out about high energy processes, such as supernova explosions, and accretion onto black holes, because the gamma-rays allow us to detect the position of the source in the sky.

Among the most elusive sub-atomic particles are the neutrinos. They were first predicted to exist in the 1930s in order to explain the missing energy and momentum in certain nuclear reactions, but their interaction with matter in general is so weak that it was very difficult to find them. They were not detected until the 1950s as products of a nuclear reactor which was producing neutrinos in such huge quantities that a few of them interacted with the apparatus of the physicists who were looking for them. It was during the same period that nuclear physics was able to give a detailed explanation of the processes which produce the energy of the stars. For stable stars such as the Sun the process is the fusion of four hydrogen nuclei to produce one helium nucleus. This releases energy in the Sun's core in the form of gamma-rays and also neutrinos; two neutrinos are produced for every helium nucleus formed. These escape easily from the Sun and travel towards Earth at almost the speed of light. The number of fusions per second in the centre of the Sun is close to 10^{38} which means that the number of neutrinos passing through a square metre at the Earth is some is 10^{15} per second. It is fortunate for us that neutrinos interact so weakly with all other particles because this number is close to the number of neutrinos which pass through your body every second. The first step in neutrino astronomy was taken in the 1960s when a small number of solar neutrinos were detected with a "neutrino telescope" down a deep mine. Since then, the study of solar neutrinos has told us a lot about neutrinos, and something about the Sun's interior. In this way, another type of messenger has been established. High energy neutrinos from supernova explosions have also been detected, and neutrino telescopes are now present deep in the Mediterranean and under the Antarctic ice sheet.

The event which brought the phrase "multimessenger astronomy" to the attention of the media was the detection of gravitational waves in 2015. In the nineteenth century, Maxwell had formulated the theory of electromagnetism which associated the movement of electric charge (later shown to consist of electrons) with waves of energy transmitted through space by radiation. Oscillating electrons produce electromagnetic waves, and it is these waves which astronomers use, in their wide variety of forms from radio waves to gamma-rays, to study the phenomena in the universe. By analogy Einstein's theory of gravitation associates mass in motion with the emission of gravitational waves. But the gravitational force is very weak compared to the electromagnetic force, and to produce detectable gravitational waves requires huge masses in rapid motion. Einstein himself, after first doubting his own prediction, eventually came to believe that gravitational waves should be a real phenomenon, but too tiny compared to electromagnetic and nuclear phenomena to be ever detectable. But in the decades which have passed since his death decisive steps have been made to show that gravitational waves are a reality and not a mere theoretical construct. Some of these steps are observational: the detection by conventional techniques of very compact objects with large gravitational fields such a neutron stars and black holes. The other step is technical, the construction of detectors sensitive enough to respond to the tiny signals emitted when such compact objects merge, at which event they emit a large pulse of gravitational waves. I think that the technical achievement which enabled gravitational waves to be detected is fully up to the level of the intellectual achievement which produced general relativity. Once the first detection was made, gravitational wave astronomy has taken its place as a powerful exploration method to deepen our understanding of the zones in the universe where extreme gravitational fields produce extremely energetic phenomena.

But in the general and fully justified excitement about the new ways of probing the universe embodied in neutrinos and gravitational waves, most people have forgotten another way we have to examine the universe, and to do so directly in the laboratory. This is the use of meteoritic material. Meteorites are mostly the dusty and rocky remains of comets which have been pushed into interplanetary space from the surface of a comet when it heats up as it approaches the Sun. These remains are left in the comets' orbits, and if the Earth's annual path around the Sun cuts one of these orbits, the particles fall through the atmosphere and the larger ones land on the ground. The light trails caused by the burning up of the particles are meteors, and the rocks which reach the ground are meteorites. In the past fifty years, nuclear chemistry has been applied to meteorites to derive their ages, and conventional chemistry has analysed their compositions. The information gained tells us a great deal about the history of the solar system, including material which formed the disc of particles which gave rise to the planets, and even particles whose ages predate that of the Sun. More recently space missions have allowed scientists to collect similar samples directly from the Moon, from comets, and from asteroids. Meteorites have been found on Earth which are clearly of Martian origin, and NASA's Mars rover series has enabled *in situ* analysis of Martian rock and soil. I have put all of these techniques into one basket, labelled "hands-on astronomy", and this is surely a very effective messenger from outside the Earth, and from the past.

When I was considering writing this book I wanted to give a wide meaning to the term "multimessenger" which meant including not only the methods of astronomy which do not use electromagnetic radiation, but also the full range of those that do. The initial idea was to place emphasis on the techniques, on how the measurements were made, and the second idea was to present some brief historical lines of development. But I quickly realised that a complete book based on these two principles would be encyclopaedic, and well beyond my scope. So I had to find criteria for choosing only a small fraction of what could have been included. I am afraid to say that I adopted the criterion of including themes and details that I find of personal interest. This means leaving out large swathes of information which are very interesting too. This way of choosing also meant that I have done less than justice to those areas where my own knowledge is least. Even though I have an eclectic interest in astronomy, it would be absurd to claim that I have more than a thin veneer of knowledge in certain areas. This is particularly the case for three of the chapters in the book, on ultraviolet (UV) astronomy, on gamma-ray astronomy, and on "hands-on" astronomy. I have based two of these chapters on specific review articles, whose authors I have recognised in the acknowledgements. For the third, I was fortunate enough to find an expert willing to give me detailed help, which I have also acknowledged.

It would not have made sense to write only about the techniques and their development without including some of the discoveries. As I went along writing each chapter and finding illustrations of the objects observed, I realised that many of the objects brought into focus by the new messengers are not "normal" stars or planets, and many of them are not even galaxies. The tendency is to highlight very energetic objects which show up especially in the interstellar medium. These can be supernova remnants, the zones where supernovae have exploded in the recent past, leaving luminous gas expanding at hundreds, even thousands of kilometres per second. This gas can be detected in the optical range, by the emission lines from its ionised elements, but it also emits strong radio waves, due to a process called synchrotron emission, involving magnetic fields, also X-rays and gamma-rays, and the dust made by the heavy elements created in the supernova emits in the infrared. The Milky Way has considerable numbers of these supernova remnants, but also regions of active star formation which glow over a wide wavelength range, notably over the full infrared and submillimetre ranges, also due to the interstellar dust produced in the regions. The Milky Way is in many ways the star performer here, matched in number and variety of images by the Sun, which over the years has served as a test-bed object for high energy imaging in astrophysics. It is my hope that some of the objects imaged in the different chapters of the book will be useful as links to show unity in variety. Not all of astronomy lends itself to beautiful photographs, of the sort regularly presented in NASA's Astronomy Picture of the Day (APOD) and I have not held back in the use of graphs, some fairly technical, to explain the meaning of results, notably in the chapter on cosmology, but in general throughout the book. However, I have not included any dreaded equations and relatively few symbols, in the hope that interested non-science readers will be able to maintain their interest.

During my scientific lifetime I have been an active witness to the opening up of many of the new pathways through the universe described here. This book can be an initial guide, and for those readers who are young and want to take up the challenge, I hope that they will be able to venture along some of the pathways, intellectually or even physically, and discover the immense territories awaiting humanity in space.

San Cristóbal de la Laguna,
Sta. Cruz de Tenerife
December 2020

John Etienne Beckman

Acknowledgements

I have used many sources of information and images while preparing this book, and the respective attributions are given in the figure captions. The figures which have been taken from the major journals: *The Astrophysical Journal*, *Astronomy & Astrophysics*, and *Monthly Notices of the Royal Astronomical Society* all are used with explicit permission from those journals and their governing entities, as well as their authors. But some of the help merits special thanks to individuals. Firstly, I would like to thank the LIGO collaboration for permission to use figures from their work, Martin Hendry for helping me to find good quality figures from their archive, and above all Rainer Weiss for helping me with both the historical and the technical content.

For the chapter dealing with the analysis of meteoritic material I am very pleased to acknowledge the help of Larry Nittler, who supplemented my quite thin previous knowledge with the benefit of his deep and wide experience, as well as providing me with figures. I have to thank the Antares, Ice Cube, Kamiokande, SNOLab, the AMS experiment, the MAGIC telescopes, the CTA observatories, and the Pierre Auger observatory for permission to use images. I have turned to two review articles for the chapters where my previous knowledge needed a boost, and I am grateful to the authors of these for generously allowing me to learn from, and use, their material. The articles are: for chapter 4 on UV astronomy, the review by Jeffrey Linsky "*UV astronomy throughout the ages: a historical perspective*" published in *Astronomy and Space Science*, Volume 363, page 101, in 2018, and for chapter 6 on gamma-ray astronomy, the review by Stefan Funk, "*Ground- and Space-based Gamma-Ray Astronomy*" published in *Annual Reviews of Nuclear and Particle Science*, Volume 65, page 245, 2015. In both cases, there is much more in the reviews than I have been able to select for the chapter in this book, so they are recommended reading for those interested.

I benefitted from the help in drawing figures by Inés Bonet, of the Unit for Science Culture and Outreach at the Instituto de Astrofísica de Canarias (IAC). My friend and colleague Terry Mahoney, also of the IAC, gave me much useful guidance from his wise publishing experience, and helped me considerably in stitching the book together. I would also like to thank Rebecca Roth, Image Coordinator and Social Media Specialist at NASA's Goddard Space Flight Center, for her help with all of the NASA material needed to illustrate the book. I am also grateful for permission to use the ESA Image Gallery photo archive to contribute to the illustrations. At Springer I received constant help and encouragement from the Editors, Ramon Khanna, Rebecca Sauter, and Christina Fehling, while from Straive in Chennai I was given the needed technical help in publishing by DhivyaGeno Savariraj.

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Finally, I have to thank Leo, my wife, for her patience in realising that although astronomy has always competed for her affections, without her constant support I would be lost, and Jaime my son, for making my life interesting when I might have lapsed into complacency.

Contents

1

Optical Astronomy

1.1 The Instruments of Optical Astronomy

1.1.1 Telescopes

Optical astronomy, or astronomy in the visible wavelength range, is the original form of the science, which is a paradigm for all observational astronomy using electromagnetic waves. Although people had been observing and interpreting the sky for millennia, the change to modern science came with the invention of the telescope. The concept of an instrument for improving our sight over long distances was first put into practical form by the German-Dutch lens maker Hans Lippershey who in 1608 requested a patent for his combination of a converging and a diverging lens in a pair of sliding concentric tubes which produced an image of distant objects, bringing them apparently much closer to the eye. A description of this instrument reached Galileo Galilei, then a professor at the University of Pisa, who quickly made his own, and went on to build telescopes of increasing power. He used them to observe the Moon, discovering its mountains, craters, and plains, Jupiter, whose four major satellites, the Galilean moons, he observed and recognised as such, Venus, whose phases he also discovered, and the Sun, where he confirmed the presence of sunspots previously noted by Christoph Scheiner. Figure 1.1 is an optical diagram of a Galilean telescope.

A design change introduced by Johannes Kepler in 1611 was to replace the concave eyepiece by a second convex lens. This widened the field and produced an image outside the telescope which could be focused onto a plane for inspection. The drawback of these telescopes was the inversion of their images,

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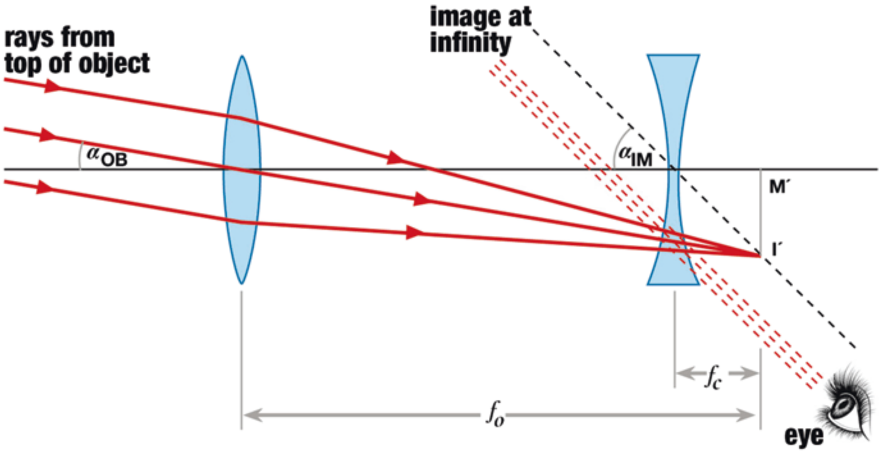

Fig. 1.1 Diagram of Galilean Telescope optics. The convex objective lens would produce an inverted image M′-I′ but the concave eyepiece lens produces a virtual image which is erect, "at infinity" and magnified compared to the object, by the ratio α_{IM}/α_{OB}. It could not be used to take photographs! Credit: The Open University/IAC-UC3

which made it less desirable for terrestrial use, but is no real problem for astronomy.

Refracting telescopes, those using lenses, played a key role in astronomy for two centuries, and many small refractors are in use around the world. But they have several drawbacks. Firstly the glass has a different refractive index for different wavelengths of light, so a simple lens brings light of different colours to different foci. This defect has been partly overcome by making "achromatic" lenses of at least two different types of glass (the same problem in cameras has been overcome in a similar way). Secondly a lens in a telescope must be supported around its edges, so a large lens will tend to deform as the telescope changes its pointing on the sky. This sets a limit to the sizes of refractors. The largest refractor ever built for professional use is at the Yerkes Observatory of the University of Chicago. It was put into operation in the early years of the twentieth century, and ceased operations in October 2018. Many of the world's greatest astronomers based their early researches on this telescope, including Edwin Hubble, Subrahmanyan Chandrasekhar, Nobel Laureate whose name was given to the major X-ray satellite Chandra, the Dutch-American astronomer Gerard Kuiper, and the outstanding populariser of astronomy Carl Sagan. Figure 1.2 shows the Yerkes refractor in 1921.

Reflecting telescopes, or reflectors, have now replaced refractors in all professional observatories, and virtually all amateur astronomers now use them. The first reflector was designed and built by Isaac Newton. The main focusing element, the primary mirror, is concave and brings the light to a focus

Fig. 1.2 The 40 in. refracting telescope at the Yerkes Observatory, U. Chicago with staff and visitor Albert Einstein in 1921 Credit: University of Chicago Photographic Archive, [apf 6-00415], Special Collections Research Center, University of Chicago Library

on the central axis of the telescope tube. Newton placed a small flat secondary mirror inside the tube, which diverts the beam and brings the focus out at the side of the tube. The scheme of a Newtonian reflector is shown in Fig. 1.3.

This works very well for a fairly small telescope where the observer can stand beside the instrument and look into the side tube. But for larger telescopes, and above all for observing with instruments, it is much more convenient to have the optics all aligned along the central axis. The basic design for this was suggested by Laurent Cassegrain in 1672, although as with all ideas, previous scientists had similar suggestions. In its most simple form a Cassegrain reflector has a concave primary mirror which sends the light to a focus back along the axis of the telescope tube, but before it reaches this focus it is intercepted by a small convex mirror which sends the light back towards the primary. A circular hole in the primary allows the light to go through to a focus just behind it, where on a modern professional telescope an instrument is placed, although for smaller telescopes an eyepiece can be put there for direct viewing. A scheme for a Cassegrain reflector is shown in Fig. 1.4. To minimise the aberrations in the image, the primary is normally a parábola and the

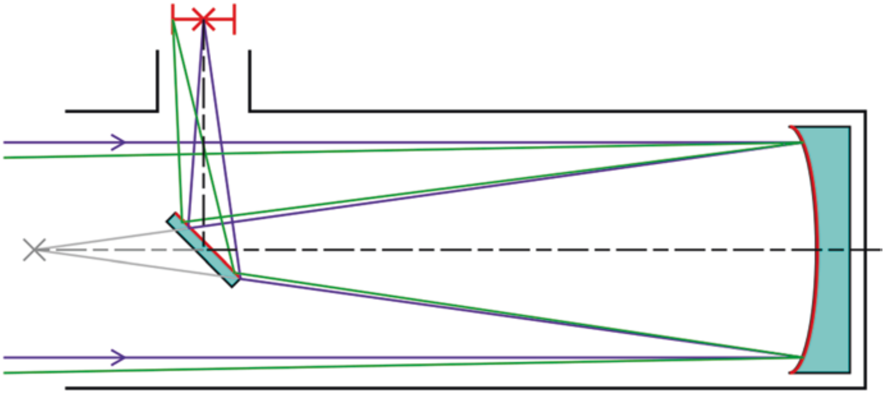

Fig. 1.3 Optical scheme of a Newtonian reflecting telescope. Light enters down the main tube, and is brought to a focus at one side, by the combined parabolic primary mirror to the right, and the small flat mirror in the centre. Credit: Newton-Teleskop. svg: Kizar derivative work: Kizar, CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0/), via Wikimedia Commons

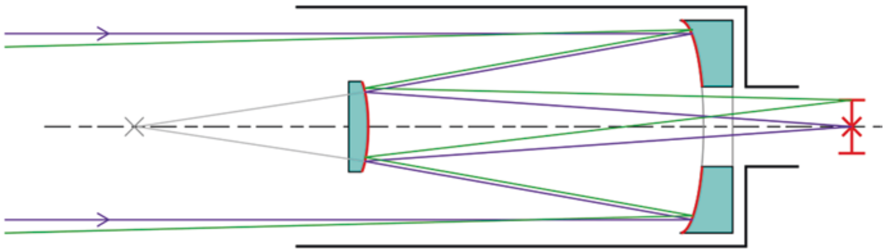

Fig. 1.4 Optical scheme of a Cassegrain reflecting telescope. Light enters from the left and first meets the primary mirror at the end of the tube. It is then focused back towards the secondary mirror, which reflects it again, to a focus behind the primary, where instruments can be placed. Credit: Upload: Wikibob, Original: ArtMechanic on de.wikipedia, CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0/), via Wikimedia Commons

secondary a hyperbola, neither of them differing greatly from simple spherical surfaces. Since the original Cassegrain design there have been a number of refinements introduced, among which the most widely used professionally is the Ritchey-Chrétien format, invented in the early twentieth century, where both primary and secondary mirrors are hyperbolic.

Reflecting telescopes were limited in their early days by the need to make the mirrors of speculum metal, an alloy of two parts copper to one part tin, which takes a reasonable reflecting surface, but tarnishes easily. Among the earliest large telescopes using speculum metal was that made in 1749 by

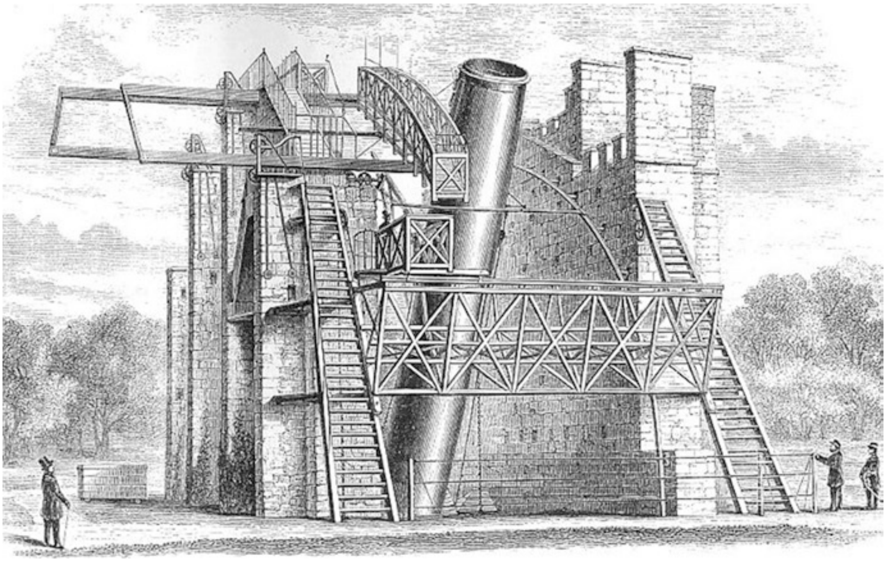

Fig. 1.5 The 72 in. telescope made by Lord Rosse, in Parsonstown, Ireland. He discovered the Whirlpool galaxy, M51, with this telescope. Copperplate engraving c. 1860

William Herschel, the discoverer of the planet Uranus, which had a 49.5 in. diameter primary, and a famous telescope of this type was the 72 in. telescope made by Lord Rosse, in 1845, shown in Fig. 1.5.

The process of silvering the front surface of a glass mirror, developed by von Steinheil and also by Foucault in the 1850s made reflectors more efficient, as silver reflects 90% of the incident light, compared with 65% for speculum metal. But also glass mirrors are much easier to figure, to give them the required precise shape. This was the trigger which led to the universal use of mirrors in large telescopes, although since the 1930s silver was generally replaced by aluminium, which is less subject to tarnishing in contact with the air. Even so, most major astronomical observatories re-aluminize their mirrors regularly, and have a specialised vacuum chamber on site for doing so. From the late nineteenth century to the late twentieth century single mirror reflectors of increasing size were made for telescopes, progressing from the 1.5 m ("60 in.") and 2.5 m ("100 in.") telescopes on Mount Wilson to the 5 m ("200 in.") Hale telescope on Mount Palomar in California, which was the largest telescope in the world for nearly 30 years after its inauguration in 1948. There are currently 27 single mirror reflectors working in the optical and near infrared range around the world with primary mirrors larger than 3 m in diameter, among the largest being the four telescopes of 8.2 m in diameter which make up the Very Large Telescope of the European Southern

Observatory in Chile, and Japan's 8.2 m Subaru telescope in Hawaii. But the largest optical telescopes in the world now have segmented primaries, composed of smaller mirrors combined into a single effective large mirror. This is easier to handle mechanically for the largest sizes, but requires continuous sophisticated electronic control to maintain optical perfection as the telescope pointing moves around the sky. We cannot give a list of these largest telescopes, but mention only the two US telescopes, the Kecks, on Hawaii since 1993 and 1996 respectively, each with 10 m diameter primaries made up of 36 segments, and the largest current optical/infrared telescope in the world, the 10.4 m Spanish GRANTECAN on the Canary Island of La Palma, operational since 2009, which also has a primary composed of 36 segments. Figure 1.6 shows two large optical telescopes: the equatorially mounted Hale Telescope, and the altazimuthally mounted GRANTECAN.

The advent of computer chips brought about various advances in the design of telescopes but one basic contribution is worth explaining here. Until the 1970s all telescopes, including the largest, were mounted equatorially, but the incorporation of computer control allowed the basic way of mounting telescopes to be changed to altazimuth. The difference has made it possible to build the modern super-telescopes. To point a telescope to any position on the sky and then keep it locked onto an object, it needs two axes of rotation. From the middle of the nineteenth century the best way to organise this was the equatorial mount, invented by Joseph von Fraunhofer in Germany. In this mount one of the axes, the polar axis, is parallel to the Earth's axis of rotation, and the other is perpendicular to it. To follow a star, or other celestial object, the telescope is rotated about these two axes until the object is found, then the perpendicular axis is held fixed, and the telescope is rotated about the polar axis at a steady rate to counteract the Earth's rotation. The system needs only a single driver, in modern times an electric motor, to follow the object. There are several ways to arrange the two axes; one of these is the way Fraunhofer did it, with the telescope on one arm of the perpendicular axis, counterbalanced by a weight on the other arm, which can be varied to suit the weights of the instruments placed at the telescope focus; this is best suited to small telescopes. There are half a dozen variants of equatorial mounts, each with its advantages and inconveniences. The 200 in. Telescope on Mount Palomar was one of the last generation of large telescopes using an equatorial mount, and because of its weight it used a fork mount The reason why equatorial mounts were universal in their time is that the telescope can be driven with a single motor at constant rate, which simplifies most of the design. On the contrary an altazimuth mount, where the two axes are locally vertical and horizontal, needs two motors, both driven at variable rates, to follow an object.

Incorporating computer technology into the drives solves this difficulty, and allows most other features of the telescope to be simplified. Equatorially mounted telescopes are on inclined axes, leading to awkward imbalance, and entailing a much larger telescope dome. The weight of a large telescope, tens of tons, bears down vertically on an altazimuth mount, which allows much bigger telescopes to be built. The first major altazimuth telescope was the Russian 6 m telescope in the Caucasus, operational since 1975, and all subsequent large telescopes, including the GRANTECAN featured in Fig. 1.6 have this design. Nowadays even small portable amateur telescopes are made altazimuth, as this allows them to be transported and used at different latitudes. At the other end of the size range the astronomical communities are now well advanced in the process leading to the construction of telescopes of new giant dimensions: the Extremely Large Telescope, ELT, of the European Southern Observatory, ESO, with a 39 m primary, planned for Chile in the coming decade, and the Thirty Metre Telescope, TMT, to be built by a consortium including institutions from the United States, Japan, China, India, and Canada, planned for Hawaii in a similar time-frame.

We can round off this piece on telescopes by adding that the optical telescope is still the most direct way to have access to astronomical knowledge and beauty, and as an illustration you have, in Fig. 1.7, an image of the neighbouring galaxy in our local group, the Andromeda Galaxy, (M31) taken by an amateur astronomer, Ivan Bok, who specialises in astrophotography of the highest class, with his own equipment and from within a city. This photograph in visible light over a full wavelength range shows the stars in white through orange, the interstellar dust in dark and patchy lanes, and scattered light in blue in the outskirts. The concentration of stars in the central spheroidal bulge is well presented, as is also the major part of the stellar distribution in a characteristic disc. The disc is warped at its edges, as we will see more clearly when the Andromeda nebula appears again at selected wavelengths in later chapters.

1.1.2 Spectrographs

Much quantitative astronomical information can be obtained from images, and we will see more on this later, but a large part of our understanding of astronomical systems and processes is obtained via spectroscopy. This tells us about the physical and chemical composition of stars, planets, and all distant objects in space. It also allows us to infer physical parameters such as the density and temperature of objects and of the planetary, interstellar, and