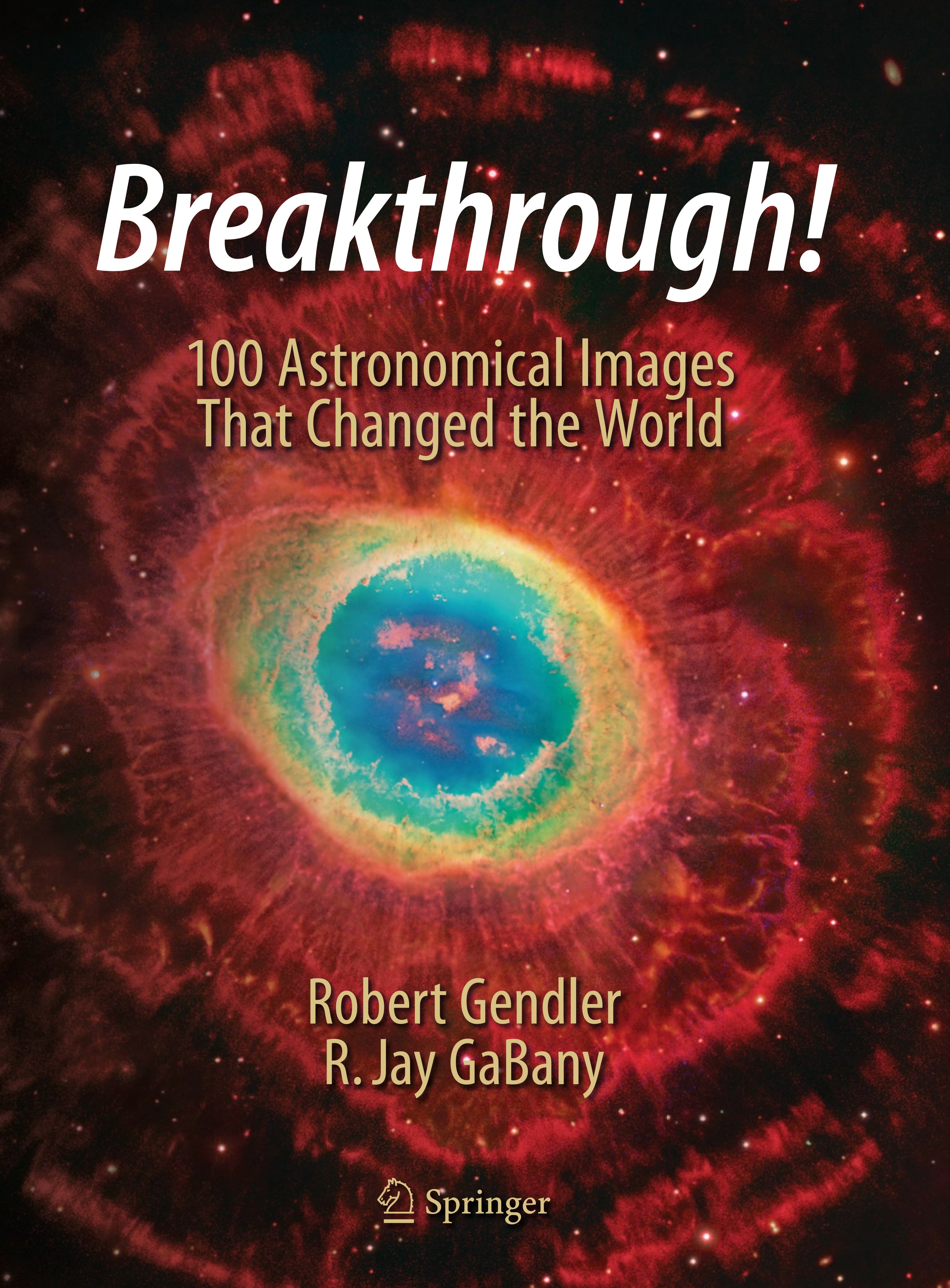

Breakthrough!

100 Astronomical Images That Changed the World

Robert Gendler
R. Jay GaBany

Springer

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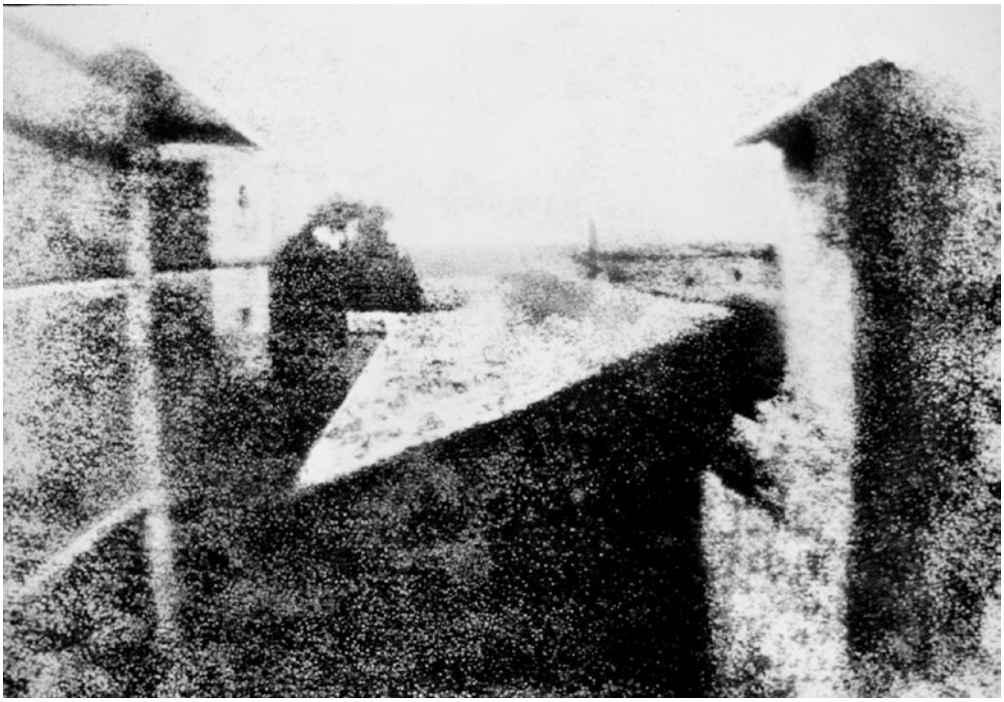

View from the Window at Le Gras, Joseph Nicéphore Niépce, the earliest known surviving photograph, Camera Obscura, 8 hours, 1826–1827.

Robert Gendler • R. Jay GaBany

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Cover image of M-57, the Ring Nebula, courtesy of Robert Gendler

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We dedicate this book to our wives, Joanne and Anne, for their patience and loving support while we pursued our passions.

Preface

Until the mid-nineteenth century, observational astronomy was the primary means of advancing our knowledge of the universe. Paper and a writing instrument were all that recorded the wonders revealed by looking through a telescope eyepiece. Although the first telescopes were in use by 1609, astrophotography had to wait until the invention of the camera in 1839.

The coupling of a camera to a telescope soon followed, and in 1840, with the awkward snap of a primitive shutter, the first image of the Moon heralded the birth of astrophotography. This event was shortly superseded by photographs of the Sun, planets, stars, and comets. But all of these were relatively easy subjects because of their brightness, which only required a relatively short exposure.

Photographs that peered deep into the heavens, revealing stars far fainter than those observed with the naked eye or through an eyepiece, had to wait for a number of frustrating technical issues to be solved. These issues included the advent of more sensitive photographic media, more efficient telescope optics, and the precision clock drives necessary to carry those instruments for extended exposures.

Hundreds of thousands of pictures have been produced since the first telescopic images were exposed. Occasionally, a single image or a group of images will stand out as a substantial milestone in our understanding of cosmic phenomena. These pictures are rare and often as inspirational as they are groundbreaking. They may provide the first glimpse of a new object or structure previously unsuspected, provide fresh insight into a natural process that was only partially understood, or capture a cosmic event that alters our perspective about humanity's place in the cosmos. They may also represent a technical breakthrough that opens a multitude of new opportunities for understanding fundamental concepts previously out of reach.

Fast-forwarding to the twenty-first century, we can now look back and confidently say that for over a century and a half astrophotography has revealed most of what we know about the universe.

The nature, origin, and human stories behind these pioneering images are varied and fascinating. Some are produced by ground-based observatories, others by orbiting telescopes, and still others by manned and unmanned space missions near our planet or deep into the Solar System. Some are recorded by professional astronomers operating large telescopes from mountaintop observatories, while others are the work of gifted and resourceful amateur astronomers using modest equipment.

Many are stunningly beautiful, although some may appear visually simple, abstract, or mundane at first glance. In all cases, however, each image was in fact a revelation because of its enormous impact on our perception of the universe and our place within it. The history of modern astronomy is chronicled by astrophotographic images containing this measure of significance.

This book pays homage to these groundbreaking milestones of imaging by presenting 100 of the most extraordinary examples with the unique human and scientific stories that accompany them. Many images included in this book were chosen for their historical scientific importance, but some were also selected because of their ability to convey the majesty and wonder of the cosmos and by virtue of that quality have been elevated to an iconic status embedded within the collective consciousness of the public. Of course, the selection process and the decision to elevate certain pictures above others was a subjective process that is open to contrary opinions.

Therefore, the authors sought suggestions from professional astronomers and astrophysicists plus trusted astronomical authors and leading publishers of astronomical print and web journals. We wish to extend our thanks to this esteemed group for their valued input.

However, the final choice of images was ultimately at the discretion of the authors. As such, we understand and accept the subjective nature of the selection process and we hope our list will stimulate not only enjoyable and educational discussions but also constructive disagreement.

This book is divided into chapters that include the major eras of astrophotography in a loose chronological sequence. Each chapter deals with either a specific era or category of astrophotography. These are segmented into subsections, each devoted to a single milestone of astrophotography accompanied by a description about the nature, relevance, and human story behind it. The pictures are diverse, and we think you will find many stunningly beautiful in addition to being significant milestones in humankind's understanding of nature.

It is our sincere hope and goal to provide the reader with a rich photographic anthology of modern astronomical achievement and history.

Avon, CT, USA Robert Gendler
San Jose, CA, USA R. Jay GaBany

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About the Authors

Robert Gendler is a physician who began doing CCD astrophotography in the early 1990s. He spent his first decade imaging from his home using a portable setup. With advances in Internet accessibility and worsening light pollution at home, Gendler began imaging remotely in 2005 from observatories in the southwestern United States and later in Australia. Gendler now spends much of his time mining professional astronomical archives and assembling unique composite images from a wide variety of data sources, including the Hubble Space Telescope, Japan's 8.2 m Subaru Telescope, and various ground-based professional and amateur systems.

Gendler has published four books on astrophotography including *A Year in the Life of the Universe* (Voyageur Press, 2006), *Capturing the Stars: Astrophotography by the Masters* (Voyageur Press, 2009), *Treasures of the Southern Sky* (Springer, 2011) and most recently *Lessons from the Masters: Current Concepts in Astronomical Image Processing* (Springer, 2013).

In 2008, he was featured in the PBS documentary *Seeing in the Dark* by Timothy Ferris, who referred to Gendler as "one of the great astrophotographers in all of history." Gendler's images have been featured in two national stamp series (United Kingdom 2007, Germany 2011). In 2007, he was the recipient of the "Hubble Award" at Advanced Imaging Conference. His images have been featured by the NASA site "Astronomy Picture of the Day" over 100 times. This work has earned him international recognition and has led to professional collaborations with NASA's Hubble Heritage team on two Hubble Space Telescope projects (M106 in February 2013, and M31 in February 2015). Visit Gendler's web site at www.robgendlerastropics.com.

R. Jay GaBany, by profession, is an eCommerce product manager working in California and the recipient of five patents for innovations in his field. Over the last decade, he has earned a reputation as an elite astrophotographer. His work has been highly recognized internationally. He has also distinguished himself by his collaborations with professional astronomers such as his work with Dr. David Martinez-Delgado on tidal streams produced by galaxy mergers.

GaBany has coauthored several significant scientific papers on the subject. For his contributions at the professional level, he was given the Chambliss Award by the American Astronomical Society.

Among his many other accomplishments, GaBany's image of NGC 3521 was selected as the backdrop for the official crew portrait of Expedition 30 to the International Space Station. Incredibly, in 2012, he was selected by *Time* magazine as one of "The 25 Most Influential People in Space."

Pertinent to this book, GaBany has written numerous articles, blogs, and reviews for a variety of popular astronomy magazines such as *Sky & Telescope, Universe Today,* and *Astronomy Now*. Visit GaBany's website at www.cosmotography.com.

1 The Birth and Evolution of Astrophotography

Since the dawn of antiquity, humanity has relied on our understanding of the universe. In many ways, astronomy was the first science, and its roots can be found entangled throughout most cultures across the globe. This is because the changing nature of the sky has guided humanity through the cycle of the seasons.

For the first Neolithic farmers, it was important to know when to plant, when to harvest, and when to move their herds. Understanding the motions of the Sun during the day and the stars at night could guide the traveler on land and at sea where landmarks were absent.

Until the mid-nineteenth century, our notions about the cosmos were limited to only what our eyes could detect. For example, the first known star map, depicting the brighter stars in the constellation we now know as Orion, was carved on the ivory tusk of a mammoth about 32,000 years ago. As recently as 10,000 years ago, the Pleiades star cluster, a tight group of stars in the northern constellation of Taurus, was painted on a cave wall in France. By the year 430 B.C., the Chinese produced a star chart of the entire sky on a lacquer box.

Before his death in 120 B.C., Hipparchus of Nicaea, the Greek mathematician, geographer, and arguably the greatest ancient astronomical observer, compiled the first comprehensive star catalog of the western world that placed stars into six groups based on their apparent brightness and referred to these categories as magnitudes. He was the first to create accurate models explaining the motions of the Sun and Moon, and he produced a reliable method for predicting lunar and solar eclipses. His work was adapted three centuries later by the Greco-Roman astronomer Ptolemy, who placed Earth at the center of the universe and hung the Sun, Moon, stars, and planets on concentric crystal spheres that circled around it.

Our understanding of the universe did not much change until Copernicus who, shortly before his death in 1543, published a book representing one of the most significant accomplishments in the history of science that located the Sun at the center of the universe and Earth as one of its orbiting planets. In the early seventeenth century, Galileo Galilei, the Italian astronomer, physicist, mathematician, and philosopher, turned his small refracting telescope to the sky and ushered in the era of modern science with his observations of the Moon's craters, solar sunspots, the large moons of Jupiter, the phases of Venus, and his discovery of the vast star fields filling the Milky Way.

However, for the next 200 years generations of astronomical observers continued relying on manual notations to log the mountains of information and telescopic drawings they collected in meticulously maintained journals. Not only was this a laborious task, it was also incomplete because no individual could hope or aspire to catalog the characteristics of every star seen through a telescope.

Then came photography.

The Astrophotography Pioneers

Almost from its inception in the mid-nineteenth century, photography offered the tantalizing prospect that it could serve as a tool to document or even discover phenomena of the natural world hitherto unseen. As photographic techniques improved over time, photography offered a method of recording more information with far greater accuracy than would ever be captured by manually transcribing what the eye observed. Even more significantly, because photographic exposures worked by accumulating light, photography had the potential of capturing astronomical features too faint to be seen by the human eye.

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Astrophotography by definition is the act of capturing radiation released by or reflected from a celestial object with a light-sensitive medium that results in an accurate facsimile or graphic representation of the subject. The light-sensitive material can be a chemical-based emulsion, a vidicon tube, an electronic chip, or any number of other sensors including radio receivers. The history of astrophotography is intertwined with advancements in telescope design, photography and, more recently, electronics and rocketry. Despite humble beginnings, improvements in each of these technologies gradually established astrophotography as the dominant means of improving our view of the heavens and gathering new information about the cosmos. Today astrophotography remains our greatest hope to better understand humankind's place in the universe.

The road leading to the production of astrophotographs began when the French inventor, Nicéphore Niépce, applied silver chloride to paper and succeeded in producing the first photographic negative images, where bright areas appear dark and vice versa, using a pinhole camera based on the ancient camera obscura. Unfortunately, these first pictures could not be preserved and slowly darkened over time. However, by the mid-1820s Niépce produced the oldest surviving crude photograph requiring an exposure that lasted several days to complete.

Niépce began working with Louis Daguerre, a French physicist and occasional scenery painter for the opera, to refine his process, and their collaboration produced higher quality pictures with exposure times reduced to hours. Following Niépce's sudden death in 1838, Daguerre began experimenting with producing photographs directly onto plates coated with light-sensitive silver iodide.

The official birth of photography occurred on January 7, 1839, when the French Academy of Sciences announced Daguerre's photographic process. Although the news spread quickly, the processes' details were withheld until the French government bought the rights in return for providing a pension to Daguerre and the son of his late partner, Niépce. Thus, complete instructions were made public on August 19, 1839 as a gift to the world.

Within a year of the processes' release, Daguerre attempted to produce the first image of the Moon through a telescope. Unfortunately, his attempts resulted in a fuzzy picture with less detail than is visible with the unaided eye. During the same year, John William Draper, an English-born American scientist, was more successful when he captured the first clear image of the Moon with his 5-inch (13 cm) reflecting telescope using the daguerreotype process. His 20-minute exposure produced a picture with sufficient clarity to display the cratered lunar surface. This picture, as humble and simple as it was, signaled the birth of astrophotography.

Although the daguerreotype method caught on enthusiastically and spread rapidly around the world, its use for photographing celestial objects proved difficult, and progress was painfully slow. For example, it wasn't until 1851 that bright celestial objects such as the Sun, Moon, Jupiter, the bright star 'Vega,' and a solar eclipse were successfully exposed using Daguerre's method.

In the same year, Frederick Scott Archer, an English sculptor, dramatically shortened exposure times by inventing the wet collodion process. The wet process was less expensive than the daguerreotype because the image was produced on glass spread with a solution containing potassium iodide. When the glass was dipped into a bath of silver nitrate, the silver and potassium compounds reacted to form silver iodide, the same light-sensitive silver salt used by Daguerre. The plate was then exposed while moist. Within a decade Archer's new process replaced the daguerreotype.

With this innovation came more firsts in astrophotography. For example, in 1854 Joseph Bancroft Reade, an English clergyman and amateur scientist, produced the first images of the Sun's photosphere, the outer shell that radiates light. Then, in 1858 the first image of a comet was taken by William Usherwood, an English miniature artist and commercial photographer. During the same year stellar photometry, the science of measuring the intensity of a star's electromagnetic radiation, was born when George Phillips Bond, an American astronomer, demonstrated that the brightness of stars could be accurately measured with photographs. Finally, Warren de la Rue, a British astronomer and chemist, exposed almost 2,800 photographs of the Sun between 1862 and 1872, including the total solar eclipse of July 18, 1860.

The wet process was very inconvenient because it required the photographic material to be prepared, exposed, and developed within the span of between 10 and 15 minutes. Similar to Daguerre's process, it also necessitated a portable darkroom for use in the field. The extreme inconvenience of shooting wet collodion stimulated the need to develop a dry process that could be coated in advance for later exposure and development at the photographer's convenience. In 1864 W. B. Bolton and B. J. Sayce published an idea that would revolutionize photography by proposing the use of an emulsion containing light-sensitive silver salts that could be spread across the surface of a glass plate.

Their idea soon bore fruit, and by the early 1870s the gelatin dry plate supplanted the wet process. This innovation used glass plates with a photographic emulsion of silver halides suspended in hardened gelatin. With this new method the photographer no longer needed chemicals on site but could expose the plates in the field then develop them later in a dark room. The dry gelatin emulsion was not only more convenient but could be made considerably more sensitive, greatly reducing exposure times. This improvement emboldened early astrophotographic pioneers to attempt more difficult and challenging targets.

In 1872 photographic stellar spectroscopy, the science of identifying the chemical components of stars by analyzing dark lines appearing in their spectra using photographs, originated when Henry Draper, an American physician and amateur astronomer, recorded the spectrum of the star Vega using the dry method, a 28-inch (72 cm) telescope, and a quartz prism.

Until this time, no photograph produced with a telescope had captured anything that had not already been observed visually through an eyepiece. So it was a revelation when, on January 30, 1883, Andrew Ainslie Common, an English amateur astronomer, trained his 36-inch (91 cm) telescope on the Orion Nebula for a 37-minute exposure and revealed stars within the cloud of gas and dust that had not been visually seen through the world's largest telescopes. Within a month, Henry Draper produced an even longer 60-minute exposure of the nebula, thus confirming the value of astrophotography to reveal previously unsuspected objects that had essentially been invisible. The potential for this new and powerful tool to expand our knowledge of the universe was being realized.

On November 16, 1885, two French astronomers and brothers, Paul and Prosper Henry, ended a long running debate within the scientific community about whether the Pleiades, a small bright grouping of stars visible during winter, was enveloped by a nebula when they photographed thin wispy clouds surrounding one of the bright stars in the star cluster using a 13-inch (33 cm) refractor. Around the same time, the Henrys realized photographs might make it easier to identify asteroids. Because they move quickly against the background of more distant stars, asteroids would appear as easily identifiable short streaks. They used this technique to eventually discover 14 of these small worlds.

The achievements by Common, Draper, and the Henrys were pivotal because they helped establish astrophotography as a legitimate research tool. Until the late 1880s, astrophotographic innovation was largely accomplished by non-professional astronomers using their own telescopes and equipment. This began to change as the accomplishments of these pioneering astrophotographers captured the attention of professional astronomers who quickly embraced and began to drive the future of the fledgling field.

The next 30 years, from about 1890 to 1920, saw an emerging generation of professional and non-professional practitioners aligned with and supported by institutional observatories. These new alliances gave these astronomers freedom to concentrate their efforts on specific projects and consequently push the boundaries of what had previously been accomplished.

For example, in 1887, the success of the Henry brothers inspired Edward Barnard, a self-taught astronomer working at California's Lick Observatory, to begin one of the first comprehensive photographic maps of the sky. Over a period of 40 years, Barnard produced hundreds of images, some requiring up to 7 hours exposure time. Fifty of these pictures were published in 1927, 5 years following his death, as *The Atlas of Selected Regions of the Milky Way*.

The Telescopic Leap

The next great leap in astrophotography was made possible through the expansion of telescopic light-gathering power and their evolution to acting primarily as large cameras. Astronomical telescopes serve two primary functions: to collect faint starlight and to resolve closely placed objects. Telescopes with larger diameters, or apertures, collect more light and provide greater resolution than smaller instruments of the same optical quality. From Galileo's first telescope until the close of the nineteenth century, telescopes were designed to be used visually by observing through an eyepiece. The increasing role of photography inspired mechanical adaptations that enabled astronomers to remove the eyepiece and insert a photographic plate holder.

Until early in the twentieth century, refracting telescopes were the scientific instrument of choice. At that time, the world's largest astronomical instrument was the 40-inch (1 m) refractor telescope at the Yerkes Observatory in northern Wisconsin. It was comprised of two 40-inch diameter lenses with a focal length extending 62 feet.

The 40-inch would remain the largest refractor ever built because the enormous weight of its lenses, which had to be supported at their edges, caused the optics to sag and lose focus. For example, a 49-inch (1.25 m) lens was displayed at the Great 1900 Paris Telescope Exhibition, but it was scrapped because its mount proved too impractical for use as a serious research tool. Thus, the Yerkes telescope remains the largest refracting telescope in the world to this day.

With the increasing role of professional observatories came the push to probe deeper into the known universe. The photographic exploration of fainter and more distant objects would necessitate telescope designs that could collect light more efficiently. The long focal length refractors of the late nineteenth century proved inadequate to the task, so astronomers turned their attention to reflecting telescopes. These instruments operated with a primary, slightly concave, mirror that collected and reflected light onto a smaller secondary, slightly convex, mirror that was usually placed directly in front of the primary. The secondary mirror bounced the light from the primary and focused it into an eyepiece or onto a photographic plate.

Reflecting telescopes did not have the size limitations of refractors because the primary mirror could be supported from behind. In addition, reflectors were lighter, more compact instruments than the larger, more cumbersome refractors and were therefore more suitable for the longer exposure times needed to achieve deep space photography. So, the beginning of the twentieth century saw the introduction of much larger and more powerful telescopes that reflected light instead of refracting it.

As photography was assuming greater importance it was replacing visual observation as the principal method of investigating the heavens. This transition accelerated during the closing decade of the nineteenth century. Simultaneously, as designs for larger instruments were evolving in the early twentieth century, their dual role as light collector and camera assumed greater significance, and the eyepiece became a secondary consideration that eventually was removed altogether.

Located on a 5,700-foot (1,737 m) peak in the San Gabriel Mountains northeast of Los Angeles overlooking Pasadena, the Mount Wilson Observatory became the home of two historically significant instruments: the 60-inch (1.5 m) Hale telescope, built in 1908, and the 100-inch (2.5 m) Hooker telescope, completed in 1917. The 60-inch Hale was the largest telescope in the world until it was superseded by the 100-inch Hooker instrument, which remained the world's most powerful telescope for the next 31 years.

Edwin Hubble's 1919 arrival at the Mount Wilson Observatory coincided with the completion of the Hooker telescope. Using the new instrument from 1922 to 1923 he exposed photographic plates of several 'spiral nebulae.' Astronomers had discovered dozens of nebulae with spiral shapes. But, because scientists believed the Milky Way represented the limits of the universe, the spiral nebulae were thought to be located within our home galaxy.

One of the spirals photographed by Hubble was the great spiral nebula in Andromeda. Upon analysis of his images, Hubble identified several variable stars known as Cepheids. Variable stars are those that go through a periodic cycle of brightening and dimming.

Hubble measured the brightness of Cepheid variable stars in the Andromeda Nebula from his photographs, and based on the previous groundbreaking work of Harriet Leavitt, he knew the amount of time required to complete their cycle. He was finally ready to determine the distance of the Andromeda Nebula from Earth.

His calculations shattered the existing model of the universe by placing the Andromeda Nebula well beyond the known limits of the Milky Way. Hubble's discovery of Cepheid variables in the Great Spiral Nebula of Andromeda conclusively proved that spiral nebulae were indeed other galaxies located at vast distances from our own, and the Milky Way was just one of countless galaxies filling the universe.

Just 400 years earlier, Galileo proved that Earth was not the center of the universe and humankind was not the center of all things. In 1925, using the new science of astrophotography, Edwin Hubble no less profoundly changed our understanding of the universe and our place within it by demonstrating the existence of other galaxies. Thus, he enlarged our understanding of the size and scale of the cosmos. This would have been sufficient to cement Hubble as a giant in the annals of science, but he had one more significant contribution yet to make using astrophotography.

In 1927 Georges Lemaître, a Belgium Catholic priest, astronomer, and physics professor, theorized Einstein's work predicted the universe was growing larger. But Einstein did not accept Lemaître's idea, saying "Your calculations are correct, but your physics is atrocious." Therefore, Lemaître's theory did not receive much scientific attention.

Then, in 1929, Edwin Hubble, utilizing redshift analysis of other galaxies, announced photographic proof that the universe was expanding in every direction – each galaxy in the universe was rushing away from all the others. Although Lemaître made other important scientific contributions, including the theory now known as the *Big Bang*, it was Hubble and his interpretation of the photographic analysis that is still credited with the discovery of universal expansion of the cosmos. Thus, with these shining achievements, the contributions of astrophotography took on monumental proportions.

From 1940 to the mid-1970s advances in optical design and engineering enabled the construction of even larger and more powerful instruments that were specifically optimized for astrophotographic use. In the northern hemisphere, the 200-inch (5 m) Hale telescope was constructed at the Palomar Observatory, northeast of San Diego, California. In the southern hemisphere, the 153-inch (3.9 m) Anglo-Australian telescope was built at Siding Spring Observatory in Australia. These instruments enabled astronomers to probe more deeply into the depths of space than ever before, and their combined locations afforded a collective view of the entire sky.

However, they shared one limitation. Because of their enormous size, their view of the sky was limited to only a fraction of the full Moon. This made them perfect for examining the small structure of faint distant galaxies or closely spaced stars but incapable of investigating large swaths of the night sky without the need to take hundreds of pictures and assemble them into a mosaic.

The large reflecting telescopes that had come into operation after the beginning of the 1900s were capable of producing much sharper images than the refractors favored by astronomer until the turn of the twentieth century. But their sharpness was limited to objects placed near the center of the mirror. Objects that fell more than a fraction of an inch from the telescope's optical axis, a line perpendicular to the center of the instrument's mirrors, were blurred by the mirror's curvature. For example, the sharply focused area of the 200-inch Hale telescope is only about 60 arcseconds in diameter, or about the size of a bean.

A solution to this problem came in 1929 at the hands of Norwegian lens crafter Bernhard Schmidt when he proposed to build a combination reflecting telescope and camera that would be capable of producing sharp images of broad sky expanses. His concept had two parts. First it used a special lens that would be placed in front of the mirror to slightly bend the incoming light and correct the mirror's tendency to blur objects that lay too far from its optical axis. Next, Schmidt's telescope would use a holder that would bend the photographic plate slightly toward the mirror so it had a subtle convex curve. With these improvements, Schmidt proposed to capture images spanning up to 10 degrees, or 20 times the Moon's diameter, with the sharpness of the best reflecting telescopes.

In 1936, a Schmidt telescope was installed at Palomar Observatory. It featured an 18-inch (45 cm) correcting lens and a 26-inch (.6 m) mirror. It was used to prove that supernovae were the final cataclysm of massive stars.

With further innovations in design, a new generation of meter-class Schmidt cameras began to probe the skies above and below the equator. In 1948 the Oschin Schmidt telescope opened its eye at Palomar with a 48-inch (1.2 m) correcting lens and a 72-inch (1.8 m) mirror. Its lens was larger than the 40-inch maximum established by the refractor at Yerkes Observatory because, being only a correcting lens, it was considerably thinner and weighed considerably less.

In 1973, the UK Schmidt telescope was installed at Siding Spring Observatory in Australia. Similar in design to the Oschin Schmidt at Palomar, it also had a 48-inch (1.2 m) corrector and 72-inch (1.8 m) mirror. Combined, these two instruments enabled astronomers to probe huge areas of both the northern and southern sky using photographs filled edge to edge with pinpoint stars.

Beginning in 1949, the 48-inch Oschin Schmidt telescope at Mount Palomar was assigned to complete the first massive all-sky survey by accurately recording the positions of every star and galaxy in the northern sky down to the 22nd magnitude – a million times dimmer than the unaided human eye can see. Completed in 1958, the First Palomar Sky Survey (POSS I) filled 1,870 plates.

During the 1970s, the UK Schmidt telescope completed the Southern Sky Survey. However, due to progress in the construction of telescopes and sensitivity of film emulsions, the Southern Sky Survey was able to capture fainter objects than the original Palomar Sky Survey of the northern sky. So, in the early 1980s, Palomar's Oschin Schmidt was upgraded and set out to compile a second northern sky survey, called POSS II, which would match the sensitivity of the Australian catalog. POSS II is now available in digital format on the web as the Digitized Sky Survey.

Film Developments

By the late 1950s, astrophotography had reached a plateau. Even though photographic emulsions were capable of translating thousands of brightness levels into their corresponding tones, the relation between stellar brilliance and the gray tones in a photograph were not linear – one star twice as bright as another did not produce an image with twice its density. This major limitation of photographic emulsion is known as reciprocity failure. Despite many innovations in the photographic process reciprocity failure persisted as an impediment to progress in deep space astrophotography. In addition, emulsion sensitivity to light and the ability for photographs to capture fine details had only marginally improved since the beginning of the twentieth century.

For example, even the most sensitive photographic emulsion only captured about 1 % of the light it received. Even if a plate were exposed over a longer period of time, the faintest stars would be lost behind a layer of haze caused by nighttime emissions in the upper atmosphere called airglow. This was a particular challenge for spectroscopy, where significant activity had been taking place since the 1930s.

To create the spectrum of a star, the light had to be spread out into its constituent of colors. Doing this significantly reduces the intensity of the light falling onto a photographic plate, thus limiting the number of stars that could be studied. For example, the faintest stars suitable for spectroscopic photography with the 200-inch Hale telescope were 16 times brighter than the dimmest objects detected by its photographs.

Little progress in resolving these challenges was made until the 1970s when several new emulsions came onto the market. Some responded more strongly to red light wavelengths so they would capture faint stars and avoid the green wavelengths associated with airglow. Others offered higher resolution using smaller grains of silver salts, but these required longer exposures because the small silver grains had less light sensitivity than larger ones.

To overcome this challenge, astronomers developed techniques to hypersensitize these emulsions by boosting their responsiveness between 5 and sometimes as much as 2,000 times. This involved various approaches, such as baking plates while exposing them to a mixture of gases. This process was known as gas *hypersensitization* or *hypering* for short.

Even while emulsions were improving, David Malin of Australia's Anglo-Australian Observatory began experimenting with darkroom procedures to counteract airglow, producing high-fidelity color images and extracting as much information as possible from each plate. For example, photographic plates produced a poor print when transferred to photographic paper. A photographic plate can exhibit 100,000 shades of gray between pure white and total black whereas photographic papers usually only exhibit a range of 50 brightness levels.

So, based on the exposure time, a print of an astrophotograph on paper could be made to exhibit bright details, dim structures, some in the middle range, but not everything at the same time. Thus, the cores of bright nebulae would appear featureless if the faint outer reaches were also exhibited.

Malin solved this problem by adopting a lithographic technique called unsharp masking. This darkroom technique enabled the production of prints in which the brightest details are only about 30 times brighter than the faint ones. This was a tonal range photographic paper could accommodate. Using this procedure, Malin was able to reveal information from older plates that had been previously unseen. For example, he applied his expertise to photographs produced with the UK Schmidt telescope and discovered a galaxy, previously unsuspected, lying in the direction of the constellation Virgo. Estimated to be almost 1 billion light-years from Earth, astronomers determined it was one of the most massive and luminous galaxies ever detected.

Although color emulsion astrophotography made its entrance in the 1950s, when William C. Miller produced color images with the Mount Wilson and Palomar Observatory instruments, Malin is credited with the first true-color astronomical pictures by assembling three separate monochromatic photographs exposed through red, green, and blue filters. This tricolor process was originally introduced in 1861 by James Clerk Maxwell, but more than a century passed before it was applied astrophotographically by Malin.

Photoelectronics

Early work on the use of an alternative to emulsion-based astrophotography began in the 1940s and 1950s with the introduction of photomultiplier tubes originally developed during the 1930s to detect radiation and measure very faint light. When light strikes certain metallic elements and compounds, it creates an electric current; this is called the photoelectric effect. Photomultiplier tubes intensify this current up to 100 million times, enabling the detection of individual photons. Thus, they are light amplifiers.

Photomultipliers offered several advantages over photographic emulsions. First, they could accurately measure the value of tones in an image over a wide range. Next, by amplifying the light it received, photomultipliers could detect faint objects in space, such as new stars, and enable the spectroscopic analysis of stars that were too dim to be captured photographically. Finally, photomultipliers could detect objects up to 100,000 times fainter than the brightest ones captured in a picture. Emulsion photographs could only accommodate a brightness range of about 10,000 to 1.

However, photomultipliers were based on vacuum tube technology and did not have a panoramic field of view, like a camera. This restricted their use to a very small piece of the sky. Therefore, they supplemented rather than replaced astronomical photographic plates.

Each image produced with either Schmidt telescope (the one at Palomar or the other in Australia) might contain up to one million stars. Therefore, the amount of information quickly became overwhelming when manually searching through a sky survey to gather examples of a particular type of star. The solution to this problem required the plates to be digitized.

In the late 1960s, the digitization of astronomical images was performed with photomultipliers. Digitization required each plate to be divided into a fine grid containing thousands of squares called picture elements, or pixels. A beam of light was then passed through each pixel and the intensity of the beam was measured. Each grid was assigned a number, consisting of eight 1s and 0s, called bits. The brightness of each pixel was then assigned a value of between 0 and 255.

Once the images were turned into numbers they could be manipulated by computer software. During the 1970s algorithms were developed that could compare brightness between objects and distinguish stars, galaxies, comets, and nebulae from one another. During the mid-1980s, image processing software was developed that could extract information about the object's size and shape, thus revitalizing astrophotography as a useful tool in a manner few would have dreamed possible less than 25 years earlier.

At the same time photomultiplier tubes were being developed, work on electronic television cameras and image intensifiers for use in very low light situations was underway. The goal was to combine the accuracy, sensitivity, and unlimited exposure time of a photomultiplier with the television camera's field of view. Much of this development was motivated by the military for low light applications, but during the 1960s and 1970s image intensified devices were applied to astronomy. The most successful image intensifiers digitized each frame from the television camera and sent it to a computer where its photons were counted.

For example, in 1969 it was suggested that image intensifiers be used to produce short pictures of bright objects rather than taking long exposures in search of faint ones. The proposal was made by French physicist Antoine Labeyrie as a solution for poor seeing conditions. Seeing refers to the blurring and twinkling of astronomical objects caused by thermal variations in the atmosphere. Seeing can reduce the practical resolution of an astronomical instrument by a factor of 100 and lead astronomers to draw the wrong conclusions. For example, poor seeing contributed to the belief in canals on Mars.

Labeyrie compared the effect of poor seeing to the common everyday experience of noticing a shiny penny at the bottom of a sun-lit fountain. The penny will seem to flicker and appear as multiple objects when viewed from above the water's wave disturbed surface. This would make it impossible to identify which penny was real. However, a short exposure photograph could freeze the flickering. Similarly, Labeyrie proposed that a very short exposure of a star could capture its twinkling as bits, or speckles, of light, with each speckle representing a distorted image of the star. Therefore, he concluded, it should be possible to use a computer to combine each speckle and produce a single image without the distortions introduced by atmospheric turbulence.

Labeyrie thought it would require an exposure that was far quicker than the best photographic emulsions could muster. So, he suggested using an image intensifier.

In 1970, Labeyrie's theory was validated when the 200-inch Hale telescope captured the first speckle images. Soon after, computer programs that combined the information were developed. Speckle photography enabled astronomers to accurately measure the diameters of many large stars for the first time. From this information, their mass could be obtained with great precision. Soon afterward, other astronomers produced images of stars, the Sun, asteroids, and the outer planets and their satellites with unprecedented clarity.

Pixels in Space

A monumental advance occurred in 1969 when Willard Boyle and George Smith, two researchers working at Bell Laboratories, started investigating a new way to add more data onto computer memory chips. Their solution was the charged coupled device, or CCD. Like other chips in a computer, the CCD was made from silicon. However, instead of giving the chip a separate microscopic circuit for each of its memory cells, their system would contain electrical charges in 'potential wells.' Each potential well was a holding area for electrons. By removing the barrier between wells, each charge could be moved off the chip sequentially and into the computer's processing area.

Among the potential applications for the CCD was its use as a light detector. Since silicon exhibits a photoelectrical effect, photons of light falling on the chip could be transformed into electrons and placed into a potential well. Like photomultipliers, CCDs were also capable of recording over 100,000 variances in brightness between the faintest and most brilliant parts of an object, but they were ten times more sensitive to light. This would make it possible to capture both the dazzling cores of galaxies and the extremely faint outer arms that surround it without overexposing the bright central region.

Compared to film, CCDs are about 70 times more efficient at collecting light than the best photographic emulsions. This would enable a reduction in exposure times from hours to minutes. Just as importantly, the brightness information gathered by a CCD could be analyzed by image processing techniques.

Fundamentally, a CCD measures light intensity that falls onto each distinct picture element, or pixel, in an approach similar to that used in digitization with photomultipliers. The size of each pixel determines its sensitivity – larger pixels collect more light than smaller ones. Each picture element represents a small part of the celestial object. The first CCD cameras had thousands of pixels. Today, even the smallest handheld cameras contain millions of picture elements. The pixels are located on a wafer-thin chip that has been treated so different areas of the surface have different electrical properties.

When a pixel is struck by a photon of light it generates an electrical charge that is proportional to the brightness of the light that hit it. This is known as a "linear response" and represents a fundamental advantage of the CCD detector over film emulsion. Finally the problem of reciprocity failure was solved. The linear response of the CCD would offer tremendous advantages in many aspects of astrophotography.