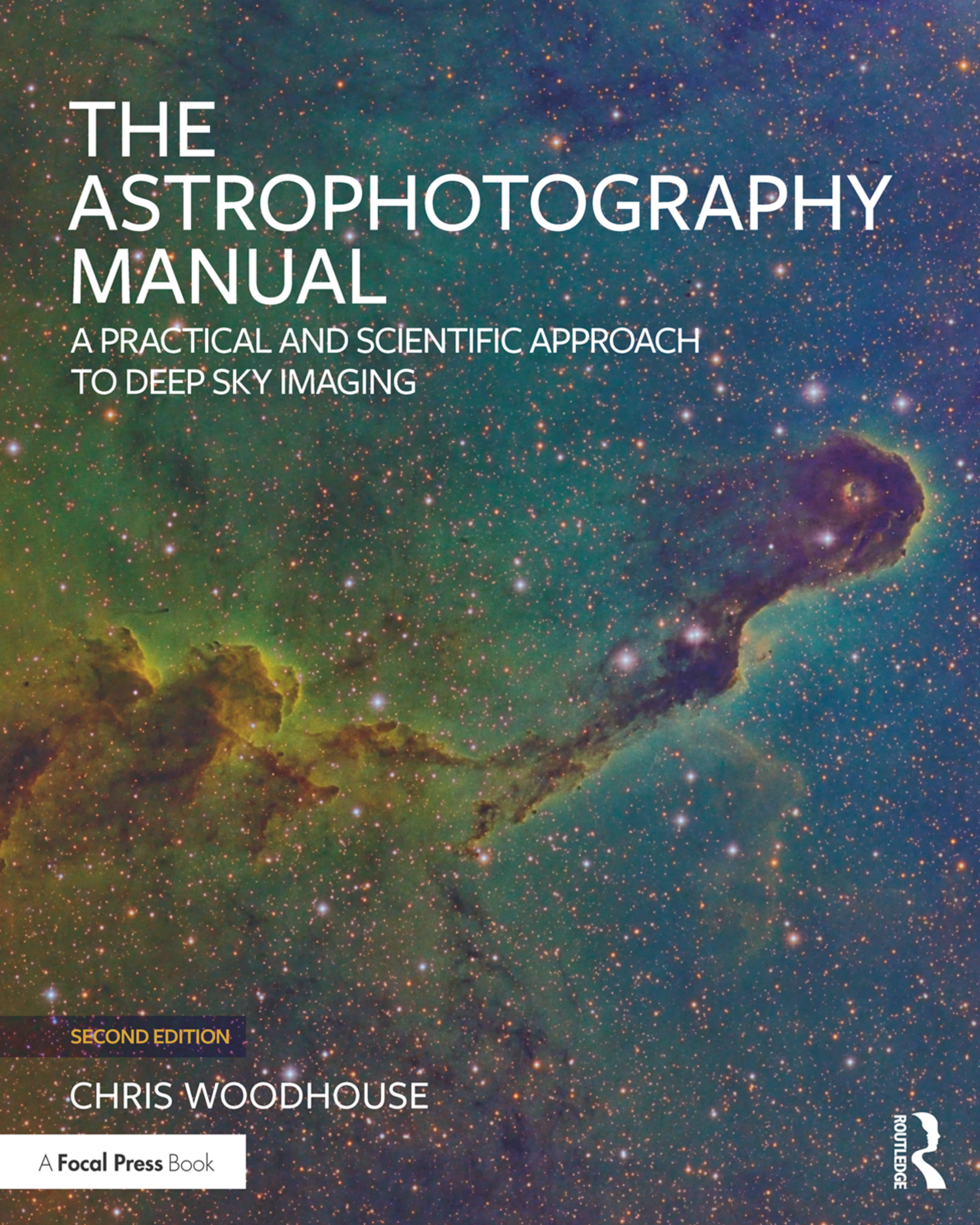

THE ASTROPHOTOGRAPHY MANUAL

A PRACTICAL AND SCIENTIFIC APPROACH TO DEEP SKY IMAGING

SECOND EDITION

CHRIS WOODHOUSE

A Focal Press Book

ROUTLEDGE

The Astrophotography Manual

A Practical and Scientific Approach to Deep Sky Imaging

2nd Edition

Chris Woodhouse

Routledge
Taylor & Francis Group
NEW YORK AND LONDON

First published 2017
by Routledge
711 3rd Avenue, New York, NY 10017

and by Routledge
2 Park Square, Milton Park, Abingdon, Oxon OX14 4RN

Routledge is an imprint of the Taylor & Francis Group, an informa business

Library of Congress in Publication Data
A catalog record for this book has been requested.

ISBN: 978-1-138-05536-0 (pbk)
ISBN: 978-1-138-06635-9 (hbk)
ISBN: 978-1-315-15922-5 (ebk)

Typeset in Adobe Garamond Pro and Myriad Pro by Chris Woodhouse
additional book resources: *http://www.digitalastrophotography.co.uk*

Publisher's Note
This book has been prepared from camera-ready copy provided by the author.

Contents

I was once asked by a 7-year old,
"Why do you take pictures of space"?

After a moment's reflection I replied,
"Because it is difficult."

Preface to the Second Edition

An edition with further refinement, insights and to expand the hobbyist's horizons.

The last four years have been a whirlwind of activity. From a complete newbie to a credible amateur has been both challenging and huge fun. The first edition was constrained by time and economics. I'm glad to say the feedback has been extremely encouraging; the pitch of the book was just right for the aspiring amateur and intermediate astrophotographer and in particular, readers liked the cogent write-ups on PixInsight, the fact it was up to date with the latest trends and, oh, by the way, please can we have some more? Some topics and imaging challenges were left untold in the first edition and since new developments continue to flourish in astrophotography, there is now sufficient content to fill an effectively "new" book.

When I authored my original photographic book ,*Way Beyond Monochrome*, it was already 350 pages long. The second edition, with considerable new content, pushed that to over 530 pages. That took 6 years to write, which was acceptable for the mature subject of classical monochrome photography. The same cannot be said of astrophotography and I thought it was essential to reduce the project time to a few years, in order to preserve its relevance.

I only write about things I have direct experience of; so time and money do limit that to some extent. Fortunately I have owned several systems, in addition to many astronomy applications for Mac OSX, Windows and Apple iOS. As time goes by, one slowly acquires or upgrades most of your equipment. There comes a point, after several years, that the cumulative outlay becomes daunting to a newcomer. As a result I have introduced some simpler, lower-cost and mobile elements into the hardware and software systems.

In the first edition, I deliberately dedicated the early chapters to the fundamentals. These included a brief astronomy primer, software and hardware essentials and some thought-provoking content on the practical limitations set by the environment, equipment and camera performance. I have not edited these out as these are still relevant. In the second edition, however, the new content concentrates on new developments; remote control, imaging techniques and an expanded section on PixInsight image processing.

Many readers of the first edition particularly liked the practical chapters and found the processing flow diagrams very useful. You should not be disappointed; in the second edition, after the new PixInsight tutorials, there are several case studies covering new techniques, again featuring PixInsight as the principal processing application. These illustrate the unique challenges posed by a particular image, with practical details on image acquisition, processing and from using a range of equipment.

Astrophotography still has plenty of opportunity for small home-made gizmos and there are additional practical projects too in this edition to stretch the user, including software and hardware development. After some further insights into diagnostics, there is an extensive index, glossary, bibliography and supporting resources. The website adds to the book's usefulness and progression to better things:

www.digitalastrophotography.co.uk

Clear skies.

chris@digitalastrophotography.co.uk

"Supermoon" Lunar eclipse, September 2015 (This is not a book on solar system astrophotography and any resemblance is purely coincidental.)

About the Author

My wife is resolved to the fact that I do not have "normal" hobbies.

Chris was born in England and from his teenage years was fascinated by the natural sciences, engineering and photography, all of which he found more interesting than football. At the weekend he could be found building or designing some gadget or other. At school he used a slide-rule and log books for his exams at 16. Two years later, scientific calculators had completely displaced them. He studied Electronics at Bath University and by the time he had completed his masters degree, the computer age was well under way and 8-bit home computers were common. After a period designing military communication and optical gauging equipment, as well as writing software in Forth, Occam, C++ and Assembler, he joined an automotive engineering company.

As a member of the Royal Photographic Society, he gained LRPS and ARPS distinctions and pursued a passion for all forms of photography, mostly using traditional monochrome techniques. Not surprisingly, this hobby, coupled with his professional experience led him to invent and patent several highly regarded f/stop darkroom meters and timers, still sold throughout the world. During that time digital cameras evolved rapidly and photo ink-jet printers slowly overcame their annoying limitations. Resisting the temptation of the early optimistic digital promises, he authored a book on traditional monochrome photography, *Way Beyond Monochrome*, to critical acclaim and followed with a second edition to satisfy the ongoing demand.

Digital monochrome appeared to be the likely next avenue for his energy, until an eye-opening presentation on astrophotography renewed a dormant interest in astronomy, enabled by the digital cameras. Astrophotography was the perfect fusion of science, electronics and photography. Like many before, his first attempts ended in frustration and disappointment, but he quickly realized the technical challenges of astrophotography responded well to a methodical and scientific approach. He found this, together with his photographic eye and decades of printing experience, was an excellent foundation to produce beautiful and fascinating images from a seemingly featureless sky. The outcome was *The Astrophotography Manual*, acclaimed by many readers as the best book on the subject in the last 15 years and he was accepted as a Fellow of the Royal Astronomical Society, founded in 1820.

Acknowledgements

This book and the intensive research that it demands would not have been possible without the ongoing support of my wife Carol (who even dug the footings for my observatory) and the wider on-line community. Special thanks go to Sam Anahory and Lawrence Dunn for contributing a guest chapter each on their respective specialty.

This edition is dedicated to Jacques Stiévenart, who piqued my interest in photography and astronomy. In the 1970s, he showed me how to silver a mirror and print a small black and white picture of the moon, taken through his home-made 6-inch Newtonian using a Zeiss Ikonta held up to the eyepiece. It was made all the more exotic since we only had a few words of each other's language. Such moments often inspire you when you are a kid.

It is one of the pleasures of this hobby to share problems and solutions with other hobbyists and this edition builds upon the knowledge and wisdom of many astrophotographers. This hobby is a never-ending journey of refinement, knowledge and development. It is a collaborative pursuit and I welcome any feedback or suggestions for this book or the next edition.

Chris Woodhouse ARPS, FRAS

Introduction

It is always humbling to consider the great achievements of the ancients, who made their discoveries without access to today's technology.

Astronomy is such a fascinating subject that I like to think that astrophotography is more than just making pretty pictures. For my own part, I started both at the same time and I quickly realized that my knowledge of astronomy was deficient in many areas. Reading up on the subject added to my sense of awe and also made me appreciate the dedication of astronomers and their patient achievements over thousands of years. A little history and science is not amiss in such a naturally technical hobby. Incredibly, the science is anything but static; in the intervening time since the last book, not only has the general quality of amateur astrophotography improved greatly, but we have sent a probe 6.5 billion km to land on a comet traveling at 65,000 km/h and found firm evidence of water on Mars. In July 2015 the New Horizons space probe, launched before Pluto was downgraded to a minor planet, grazed past the planet 12,000 km from its surface after a 9.5 year journey of 5 billion km. (It is amazing to think that its trajectory was calculated using Newton's law of universal gravitation, published in 1687.)

From the earliest days of human consciousness, mankind has studied the night sky and placed special significance on eclipses, comets and new appearances. With only primitive methods, they quickly realized that the position of the stars, the Moon and the Sun could tell them when to plant crops, navigate and keep the passage of time. Driven by a need for astrology as well as science, their study of the heavens and the belief of an Earth-centric universe was interwoven with religious doctrine. It took the Herculean efforts of Copernicus, Galileo and Tycho, not to mention Kepler, to wrest control from the Catholic Church in Europe and define the heliocentric solar system with elliptical orbits, anomalies and detailed stellar mapping.

Astronomers in the Middle East and in South America made careful observations and, without instruments, were able to determine the solar year with incredible accuracy. The Mayans even developed a sophisticated calendar that did not require adjustment for leap years. Centuries later, the Conquistadors all but obliterated these records at a time when ironically Western Europe was struggling to align their calendars with the seasons. (Pope Gregory XIII eventually proposed the month of

Year [Circa]	Place	Astronomy Event
2700 BC	England	Stonehenge, in common with other ancient archaeological sites around the world, is clearly aligned to celestial events.
2000 BC	Egypt	First Solar and Lunar calendars
1570 BC	Babylon	First evidence of recorded periodicity of planetary motion (Jupiter) over a 21-year period.
1600 BC	Germany	Nebra sky disk, a Bronze age artifact, which has astronomical significance.
280 BC	Greece	Aristarchus suggests the Earth travels around the Sun, clearly a man before his time!
240 BC	Libya	Eratosthenes calculates the circumference of the earth astronomically.
125 BC	Greece	Hipparchus calculates length of year precisely, notes Earth's rotational wobble.
87 BC	Greece	Antikythera mechanism, a clockwork planetarium showing planetary, solar and lunar events with extraordinary precision.
150 AD	Egypt	Ptolemy publishes *Almagest*; this was the astronomer's bible for the next 1,400 years. His model is an Earth-centered universe, with planet epicycles to account for strange observed motion.
1543 AD	Poland	Copernicus, after many years of patient measurement, realizes the Earth is a planet too and moves around the Sun in a circular orbit. Each planet's speed is dependent upon its distance from the Sun.
1570 AD	Denmark	Tycho Brahe establishes a dedicated observatory and generates first accurate star catalog to 1/60th degree. Develops complicated solar-system model combining Ptolemaic and Copernican systems.
1609 AD	Germany	Kepler works with Tycho Brahe's astronomical data and develops an elliptical-path model with planet speed based on its average distance from the Sun. Designs improvement to refractor telescope using dual convex elements.
1610 AD	Italy	Galileo uses an early telescope to discover that several moons orbit Jupiter and Venus and have phases. He is put under house arrest by the Inquisition for supporting Kepler's Sun-centered system to underpin his theory on tides.

fig.1a An abbreviated time-line of the advances in astronomy is shown above and is continued in fig.1b. The achievements of the early astronomers are wholly remarkable, especially when one considers not only their lack of precision optical equipment but also the most basic of requirements, an accurate timekeeper.

Year [Circa]	Place	Astronomy Event
1654 AD	Holland	Christiaan Huygens devises improved method for grinding and polishing lenses, invents the pendulum clock and the achromatic eye-piece lens.
1660 AD	Italy	Giovanni Cassini identifies 3 moons around Saturn and the gap between the rings that bear his name. He also calculates the deformation of Venus and its rotation.
1687 AD	England	Isaac Newton invents the reflector telescope, calculus and defines the laws of gravity and motion including planetary motion in *Principia*, which remained unchallenged until 1915.
1705 AD	England	Edmund Halley discovers the proper motion of stars and publishes a theoretical study of comets, which accurately predicts their periods.
1781 AD	England	William Herschel discovers Uranus and doubles the size of our solar system. Notable astronomers Flamsteed and Lemonnier had recorded it before but had not realized it was a planet. Using his 20-foot telescope, he went on to document 2,500 nebular objects.
1846 AD	Germany	Johann Galle discovers Neptune, predicted by mathematical modelling.
1850 AD	Germany	Kirchoff and Bunsell realize Fraunhofer lines identify elements in a hot body, leading to spectrographic analysis of stars.
1908 AD	U.S.A.	Edwin Hubble provides evidence that some "nebula" are made of stars and uses the term "extra-galactic nebula" or galaxies. He also realizes a galaxy's recessional velocity increases with its distance from Earth, or "Hubble's law", leading to expanding universe theories.
1916 AD	Germany	Albert Einstein publishes his *General Theory of Relativity* changing the course of modern astronomy.
1930 AD	U.S.A.	Clyde Tombaugh discovers planet Pluto. In 2006, Pluto was stripped of its title and relegated to the Kuiper belt.
1963 AD	U.S.A.	Maarten Schmidt links visible object with radio source. From spectra realizes quasars are energetic receding galactic nuclei.
1992 AD	U.S.A.	Space probes COBE and WMAP measure cosmic microwaves and determines the exact Hubble constant and predicts the universe is 13.7 billion years old.
2012 AD	U.S.A.	Mars rover *Curiosity* lands successfully and begins exploration of planet's surface.
2014 AD	ESA	*Rosetta* probe touches down on comet 67P after 12-year journey.
2015 AD	ESA	*New Horizons* probe flies past Pluto

fig.1b Astronomy accelerated once telescopes were in common use, although early discoveries were sometimes confused by the limitations of small aperture devices.

October be shortened by 10 days to re-align the religious and hence agricultural calendar with the solar (sidereal) year. The Catholic states complied in 1583 but others like Britain delayed until 1752, by which time the adjustment had increased to 11 days!)

The invention of the telescope propelled scholarly learning, and with better and larger designs, astronomers were able to identify other celestial bodies other than stars, namely nebula and much later, galaxies. These discoveries completely changed our appreciation of our own significance within the universe. Even though the first lunar explorations are over 45 years behind us, very few of us have looked at the heavens through a telescope and observed the faint fuzzy patches of a nebula, galaxy or the serene beauty of a star cluster. To otherwise educated people it is a revelation when they observe the colorful glow of the Orion nebula appearing on a computer screen or the fried-egg disk of the Andromeda Galaxy taken with a consumer digital camera and lens.

This amazement is even more surprising when one considers the extraordinary information presented on television shows, books and on the Internet. When I have shared back-yard images with work colleagues, their reaction highlights a view that astrophotography is the domain of large isolated observatories inhabited with nocturnal Physics students. This sense of wonderment is one of the reasons why astrophotographers pursue their quarry. It reminds me of the anticipation one gets as a black and white print emerges in a tray of developer. The challenges we overcome to make an image only increase our satisfaction and the admiration of others, especially those in the know. When you write down the numbers on the page, the exposure times, the pointing accuracy and the hours taken to capture and process an image, the outcome is all the more remarkable.

New Technology

The explosion of interest and amateur ability fuels the market place and supports an increasing number of astro-based companies. Five years on after writing the first edition, the innovation and value engineering continue to advance affordable technology in the form of mechanics, optics, computers, digital cameras and in no small way, software. The digital sensor was chiefly responsible for revolutionizing astrophotography but it itself is now at a crossroads. Dedicated imaging cameras piggy-back off the sensors from the digital camera market, typically DSLRs. At one time CCDs and CMOS sensors were both used in abundance. Today, CMOS sensors dominate the market place and are the primary focus of sensor development, increasing in size and pixel density. Their pixel size, linearity and noise performance are not necessarily ideal for astrophotography. New CCDs do emerge from Sony but these are a comparative rarity and are typically smaller than APS-C. It will be interesting to see what happens next; it may well drive a change in telescope optics to move to small field, shorter focal length and high resolution imaging. At the same time, the CCD sensor in my QSI camera has become a teenager.

It was not that long ago that a bulky Newtonian reflector was the most popular instrument and large aperture refractors were either expensive or of poor quality and computer control was but a distant dream. The increasing market helps to make advanced technology more affordable or downsize high-end features into smaller units, most noticeably in portable high-performance mounts and using the latest manufacturing techniques to produce large non-spherical mirrors for large reflector telescopes.

At the same time computers, especially laptops, continue to reduce in price and with increased performance and battery life. Laptops are not necessarily ideal for outdoor use; many are switching to miniature PCs (without displays or keyboards) as dedicated controllers, using remote desktop control via network technologies. New software required to plan, control, acquire and process images is now available from many companies at both amateur and professional levels. Quite a few are free, courtesy of generous individuals. At the same time, continued collaboration on interface standards (for instance ASCOM weather standards) encourages new product development, as it reduces software development costs and lead-times. If that was not enough, in the last few years, tablet computing and advanced smart phones have provided alternative platforms for controlling mounts and can display the sky with GPS-located and gyroscopically-pointed star maps. The universe is our oyster.

Year [Circa]	Astrophotography Event
1840	First successful daguerreotype of Moon
1850	First successful star picture
1852	First successful wet-plate process
1858	Application of photography to stellar photometry is realized
1871	Dry plate process on glass
1875	Spectra taken of all bright stars
1882	Spectra taken of nebula for first time
1883	First image to discover stars beyond human vision
1889	First plastic film base, nitro cellulose
1920	Cellulose acetate replaces nitro cellulose as film base
1935	Lowered temperature was found to improve film performance in astrophotography applications
1940	Mercury vapor film treatment used to boost sensitivity of emulsion for astrophotography purposes
1970	Nitrogen gas treatment used to temporarily boost emulsion sensitivity by 10x for long exposure use
1970	Nitrogen followed by Hydrogen gas treatment used as further improvement to increase film sensitivity
1974	First astrophotograph made with a digital sensor
1989	SBIG release ST4 dedicated astrophotography CCD camera
1995	By this time, digital cameras have arguably ousted film cameras for astrophotography.
2004	Meade Instruments Corp. release affordable USB controlled imaging camera. Digital SLRs used too.
2010	Dedicated cameras for astrophotography are widespread, with cooling, combined guiders; in monochrome and color versions. Consumer digital cameras too have improved and overcome initial long exposure issues.
2013	New low-noise CCDs commonly available with noise levels below 1 electron per square micron
2015-	Low-noise CMOS chips starting to make inroads into popular astrophotograhy cameras.

fig.2 A time-line for some of the key events in astrophotography. It is now 30 years since the first digital astrophotograph was taken and I would argue that it is only in the last 5 years that digital astrophotography has really grown exponentially, driven by affordable hardware and software. Public awareness has increased too, fuelled by recent events in space exploration, documentaries and astrophotography competitions.

Scope of Choice

Today's consumer choice is overwhelming. Judging from the current rate of change, I quickly realized that it is an impossible task to cover all equipment or avenues in detail without being variously out of date at publishing. Broad evaluations of the more popular alternatives are to be found in the text but with a practical emphasis and a process of rationalization; in the case of my own system, to deliver quick and reliable setups to maximize those brief opportunities that the English weather permits. My setup is not esoteric and serves as a popular example of its type, ideal for explaining the principles of astrophotography. Some things will be unique to one piece of equipment or another but the principles are common. In my case, after trying and using several types of telescope and mount, I settled on a hardware and software configuration that works as an affordable, portable solution for deep sky and occasional planetary imaging. By choosing equipment at the upper end of what can be termed "portable", when the exertion of continual lifting persuaded me to invest in a permanent observatory, I was able to redeploy all the equipment without the need for upgrading. Five years on, astronomy remains a fascinating subject; each image is more than a pretty picture as a little background research reveals yet more strange phenomena and at a scale that beggars the imagination.

About This Book

I wrote the first edition with the concept of being a fast track to intermediate astrophotography. This was an ambitious task and quite a challenge. Many astrophotographers start off with a conventional SLR camera and image processing software like Photoshop®. In the right conditions these provide good images. For those users there are several excellent on-line and published guides that I note in the bibliography. It was impossible to cover every aspect in detail, limited by time, page count and budget. My aim in this book is to continue where I left off: covering new ideas, advanced image processing, more advanced practical projects and fresh practical examples that cover new ground. This book is firmly focused on deep-sky imaging; my own situation is not ideal for high magnification work and any references to planetary imaging are made in passing.

The book is divided into logical sections as before: The first section covers the basics of astronomy and the limitations of physics and the environment. The second section examines the tools of the trade, brought up to date with new developments in hardware and software, including remote control, automation and control theory. The third section continues with setting up and is revised to take advantage of the latest technology. In the following section we do the same for image capture, looking at developments in process automation, guiding, focusing and mosaics.

The PixInsight content in the first book was very well received and several readers suggested I write a PixInsight manual. I am not a guru by any means and it would take many years of work to be confident enough to deliver an authoritative tome. Writing for me is meant to be a pleasure and the prospect of a software manual is not terribly exciting to either write, or I suspect, to read. Bowing to this demand, however, the image calibration and processing section provides further in-depth guides to selected processes in PixInsight and additionally uses PixInsight to process the new practical imaging assignments.

The assignments section has been revised and expanded: A couple of case studies have been removed, including the solitary planetary example. Some specialize in this field and they are best suited to expand on the extreme techniques required to get the very best imaging quality at high magnifications. As before, each case study considers the conception, exposure and processing of a particular object that, at the same time, provides an opportunity to highlight various unique techniques.

A worked example is often a wonderful way to explain things and these case studies deliberately use a variety of equipment, techniques and software. More recently these use my software of choice, namely Sequence Generator Pro, PHD2, PixInsight and Photoshop. The subjects are typically deep-sky objects that present unique challenges in their acquisition and processing. Practical examples are even more valuable if they make mistakes and we learn from them. Some examples deliberately include warts and present an opportunity to discuss remedies.

On the same theme, things do not always go to plan and in the appendices before the index and resources, I have updated the chapter on diagnostics, with a small gallery of errors to help with your own troubleshooting. Fixing problems can be half the fun but when they resist several reasoned attempts, a helping hand is most welcome. In my full-time job I use specialized tools for root-cause analysis and I share some simple ideas to track down gremlins. Astrophotography and astronomy in general lends itself to practical invention and not everything is available off the shelf. To that end, new practical projects are included in the appendices as well as sprinkled throughout the book. These include a comprehensive evaluation of collimation techniques for a Ritchey Chrétien telescope and ground-breaking chapters on designing and implementing an observatory controller, its ASCOM driver and a Windows Observatory controller application. It also includes a chapter on setting up a miniature PC as an imaging hub, with full remote control.

As in the first edition, I have included a useful bibliography and a comprehensive index. For some reason bibliographies are a rarity in astrophotography books. As Sir Isaac Newton once wrote, “If I have seen further it is by standing on the shoulders of Giants.” The printed page is not necessarily the best medium for some of the resources and the supporting website has downloadable versions of spreadsheets, drawings, program code, videos and tables, as well as any errata that escaped the various editors. They can be found at:

www.digitalastrophotography.co.uk

Share and enjoy.

Astronomy Primer

M45 (Open Cluster) or Pleiades, showing reflection nebulosity of interstellar medium

The Diverse Universe of Astrophotography

A totally absorbing hobby, limited only by your imagination, patience and weather.

Amateur astrophotography can be an end in itself or a means of scientific research and in some cases, a bit of both. It might be a surprise for some, but amateur astronomers, with differing degrees of patronage, have significantly contributed to our understanding of the universe, in addition to that from the scientific institutions. As an example, Tom Boles in Suffolk, England has identified over 149 supernova with his private observatory; these brief stellar explosions are of scientific importance and their spectra help determine the size and expansion of the universe. The professional large observatories cannot cover the entire sky at any one time and so the contribution from thousands of amateurs is invaluable, especially when it comes to identifying transient events. I might chance upon something in my lifetime but I have less lofty goals in mind as I stand shivering under a mantle of stars.

fig.1 The lunar surface is best shown with oblique lighting, in the area between light and shadow. A different part of the Moon is revealed on subsequent nights. This picture and the one below were taken with a micro 4/3rds camera body, fitted to the end of a modest telescope.

Astrophotography is not one hobby but many: There are many specialities and individual circumstances, as well as purpose. Depending on viewing conditions, equipment, budget and available time, amateur astronomers can vary from occasional imagers using a portable setup, to those with a permanent installation capable of remote control and operational at a moment's notice. The subjects are just as numerous too; from high magnification planetary, and deep sky imaging, through medium and wide-field imaging in broad or selective wavelengths. Then there is lunar and solar photography as well as environmental astrophotography, which creates wonderful starry vistas. As with any hobby, there is a law of diminishing returns and once the fundamentals are in place, further enhancements often have more to do with convenience and reliability than raw performance. My own setup is fit for purpose and ultimately its limiting factor is my location. Any further purchase would do little to increase my enjoyment. Well, that is the official line I told my better half!

A Public Health Warning

The next few pages touch on some of the more common forms of astrophotography and the likely setups. Unlike digital photography, one-upmanship between astrophotographers is rare but even so, once you are hooked, it is tempting to pursue an obsessive frenzy of upgrades and continual tuning. It is important to realize that there is a weak link in the imaging chain and that is often your location, light pollution, weather, stable atmosphere, obscuration and family commitments. Suffice to say, I did warn you!

fig.2 A full moon has a serene beauty but the reflected illumination adds considerably to any light pollution. This is likely to restrict any other imaging to bright planets or clusters. I have a theory that full moons only occur on clear nights.

Lunar Imaging

The Moon is the most obvious feature of the night sky and easily passed over for more sexy objects. Several astronomers, including the late Sir Patrick Moore, specialized in lunar observation and photography. Being a large and bright object, it does not mandate extreme magnifications or an expensive cooled CCD camera. Many successful lunar photographs use a modest refractor telescope with a consumer CCD-based webcam adapted to fit into the eyepiece holder. The resultant video image jumps around the screen and

fig.3 The Rosette Nebula appears as a small cluster of stars when observed through a short telescope. The nebula is almost invisible, even in a dark sky. Our eyes are the limiting factor; at low intensities, we have monochromatic vision and in particular, our eyes are less sensitive to deep red wavelengths, which is the dominant color for many nebulae.

fig.4 By way of comparison, if a digital camera is substituted for the human eye, we are able to record faint details and in color too. The above image has been mildly processed with a boost in shadow detail to show the detailed deep red gas clouds in the nebula. This is a large object, approximately 3x wider than the Moon.

many frames are blurred. The resulting video is a starting point; subsequent processing discards the blurred frames and the remainder are aligned and combined to make a detailed image. Increasingly, digital SLRs are used for lunar photography, either in the increasingly popular video modes or take individual stills at high shutter speeds. The unique aspect of the Moon, and to some extent some planets too, is that their appearance changes from night to night. As the Moon waxes and wanes, the interesting boundary between light and shade, the terminator, moves and reveals the details of a different strip of the lunar surface. No two nights are precisely the same.

Planetary Imaging

The larger and brighter planets, Jupiter, Saturn, Venus and to a lesser extent Mars, have very similar challenges to that of lunar imaging. These bright objects require short exposures but with more magnification, often achieved with the telescope equivalent of a tele-converter lens. A converted or dedicated webcam is often the camera of choice in these situations since its small chip size is ideally matched to the image size. Some use digital SLRs but the larger sensors do create large video files and only at standard video frame rates between 24 frames per second (fps) and 60 fps. I have made pleasing images of Jupiter and Mars using just a refractor with a focal length of just over 900 mm combined with a high-quality 5x tele-converter and an adapted webcam.

These and the smaller planets pose unique challenges though and are not the primary focus of this book. Not only are they are more tricky to locate with portable setups but to show sufficient surface detail requires high magnification. At high magnification, every imperfection from vibration, tracking errors, focus errors and most significantly, atmospheric seeing is obvious. The work of Damian Peach sets the standard for amateur imaging. His astonishing images are the result of painstaking preparation and commitment and his website (*www.damianpeach.com*) is well worth a look.

Solar Imaging

Solar imaging is another rewarding activity, especially during the summer months, and provided it is practised with extreme care, conventional telescopes can be employed using a purpose-designed solar filter fitted to the main and guide scope. Specialist solar scopes are also available which feature fine-tuned filters to maximize the contrast of the Sun's surface features and prominences. The resulting bright image can be photographed with a high-speed video camera or a still camera.

Large Deep Sky Objects

One of the biggest surprises I had when I first started imaging was the enormous size of some of the galaxies and nebulae; I once thought the Moon was the biggest object in the night sky. Under a dark sky one may just discern the center of the Andromeda Galaxy with the naked eye but the entire object span is six times the width of our Moon. It is interesting to ponder what ancient civilizations would have made of it had they perceived its full extent. These objects are within the grasp of an affordable short focal-length lens in the range 350-500 mm. At lower image magnifications accurate star tracking is less critical and even in light polluted areas, it is possible to use special filters and reduce the effect of the ever-present sodium street light. Successful imagers use dedicated CCD cameras or digital SLRs, either coupled to the back of a short telescope or with a camera telephoto lens. Typically, the camera system fits to a motorized equatorial mount and individual exposures range from a few 10s of seconds to 20 minutes. Short focal length telescopes by their nature have short lengths and smaller diameters with correspondingly lightweight focus tubes. The technical challenges associated with this type of photography include achieving fore-aft balancing and the mechanical performance of the focus mechanism and tube as a result of a heavy camera hanging off its end. If you live under a regular flight path, a wide field brings with it the increased chance of aircraft trails across your images.

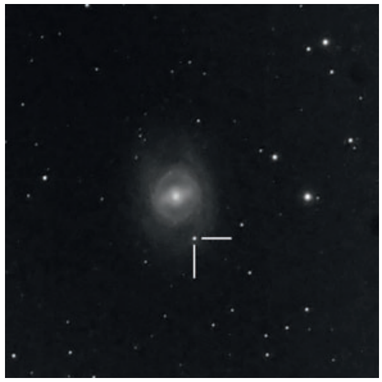

fig.5 A few months after I started using a CCD camera for astrophotography, a supernova was announced in the galaxy M95. I recorded an image of the dim galaxy (top) and used the Internet to identify the supernova position. The color image below was taken a few years later by which time the supernova has disappeared. I now have software that allows one to compare two images taken of the same object from different nights. This automatically identifies any "new" stars or, as in the case of a supernova in our own galaxy, a star that just becomes suddenly very much brighter. Galaxies are the favorite location for likely supernova, as they contain the most stars. A friend was imaging a galaxy as a supernova exploded. His series of unprocessed images proved useful to NASA since they showed the event unfolding between the separate image captures.

Small Deep Sky Objects

The smaller objects in the night sky require a longer focal length to make meaningful images, starting at around 800 mm. As the magnification increases, the image brightness reduces, unless the aperture increases at the same rate. This quickly becomes a lesson in practicality and economics. Affordable refractor telescopes at the time of writing have typically a 5-inch or smaller aperture and at the same time, reflector telescopes have between 6- and 10-inch apertures. Larger models do exist, to 16 inches and beyond, but come with the inherent risk of an overdraft and a hernia. The longer exposures required for these highly magnified objects benefit from patience, good tracking and a cooled CCD camera. At higher magnifications, the effect of atmospheric turbulence is noticeable and it is usually the weakest link in the imaging chain.

Environmental Imaging

I have coined this phrase for those shots that are astronomy-related but typically involve the surrounding landscape. Examples include images of the Northern Lights or a wide-field shot of the Milky Way overhead. Long exposures on a stationary tripod show the customary star trails, but shorter exposures (or slow tracking) with a wide-angle lens can render foreground and stars sharply at the same time. Digital SLRs and those compacts with larger sensors make ideal cameras for these applications and a great place to start with no additional cost. At a dark field site, a panorama of the Milky Way makes a fantastic image.

Other Activities

Spectroscopic analysis, supernova hunting, asteroid, minor planet, exoplanet, comet and satellite tracking are further specializations for some astrophotographers. Supernova hunting requires a computer-controlled mount directing a telescope to briefly image multiple galaxies each night, following a programmed sequence. Each image in turn is compared with prior images of the same object. The prize is not a pretty image but the identification of an exploding star. Each of these specialities have interesting technical challenges associated with object location, tracking and imaging. For instance, on *Atlantis*' last flight it docked with the International Space Station. Thierry Legault imaged it with a mobile telescope as it transited the Sun. The transit time was less than a second and he used a digital SLR, operating at its top shutter speed and frame rate to capture a sequence of incredible images, paparazzi-style. His amazing images can be seen at *www.astrophoto.fr*.

Space

The thing about space is when you think you have seen it all, something truly bizarre shows up.

Astrophotographers have many specialities to pursue but in the main, the images that adorn the multitudinous websites consist of stars, special events, planets and deep sky objects. This chapter and the next few give an astronomical grounding in the various objects in space and the systems we use to characterize, locate and measure them. It is not essential to understand astronomy to obtain good pictures, but I think it helps to decipher the lingo and adds to the enjoyment and appreciation of our own and others' efforts.

Stars

The points of light that we see in the night sky are stars, well, almost. Our own Sun is a star, but the planets of our solar system are not, they merely reflect our own Sun's light. Every star is a gravitationally bound luminous sphere of plasma; a thermonuclear light bulb. With the naked eye, on a dark night, you might see up to 3,000 after a period of dark adaptation. That number decreases rapidly as light pollution increases. A star may have its own solar system, but its distance and brightness is such that we cannot directly observe any orbiting planets, even with the help of space-borne telescopes. In recent years in the never-ending search for extraterrestrial life, the presence of planets has been detected outside our own solar system but only by the effect of their gravitational pull on their home star's position. Not all stars are equal; they can be a range of masses, temperatures and brightnesses. Stars have a sequence of formation, life and decay, starting in a nebula and subsequently converting their mass into electromagnetic radiation, through a mechanism governed by their mass, composition and density. Hertzsprung and Russell realized that the color and intensity of stars were related and the diagram named after them shows this pictorially (fig.1). Most stars comply with the "main sequence" on the diagram, including our own Sun. Notable exceptions are the intensely dense white dwarfs and the huge red giants, some of which are so large, we could fit our entire solar system within their boundary. There are countless stars in a galaxy but at the end of a star's life, if it explodes and briefly becomes a supernova, it can outshine its entire parent galaxy. In our own Milky Way galaxy, documentary evidence suggests on average, there are about three supernova events per century.

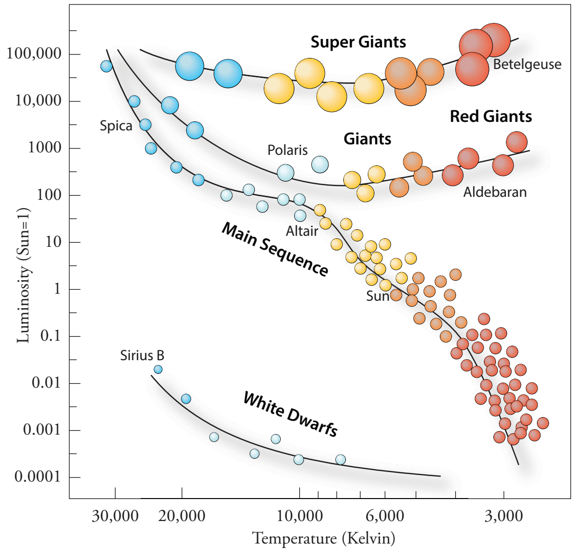

fig.1 The Hertzsprung-Russell diagram, named after its developers, shows the relationship and observed trend between the brightness and color of stars. The color is directly related to temperature. Ninety percent of stars lie on a diagonal trend known as the main sequence. Other groups and some familiar stars are also shown. At one time, scientists thought that stars migrated along the main sequence as they age. More recent study suggests a number of different scenarios, depending on the makeup, mass and size of the star.

From a visual standpoint, although stars may be different physical sizes, they are so distant from Earth, they become singular points of light. The only star to be resolved as something other than a point of light, and only by the largest telescopes, is the red giant Betelgeuse in the constellation Orion. It is puzzling then that stars appear in photographs and through the eyepiece in varying sizes, in relation to their visual intensity. This is an optical effect which arises from light scatter and diffraction along the optical path through our atmosphere, telescope optics and the sensitivity cut-off of our eyes or imaging sensor. Stars as single objects are perhaps not the most interesting objects to photograph, although there is satisfaction from photographing double stars and specific colored stars, such as the beautiful Albireo double. Resolving double stars has a certain kudos; it is a classical test of your optics, seeing conditions, focus and tracking ability of your setup.

When imaging stars, the main consideration is to ensure that they all are circular points of light, all the way into the corners of the image, sharply focused and with good color. This is quite a challenge since the brightness range between the brightest and dimmest stars in the field of view may be several orders of magnitude. In these cases, the astrophotographer has to make a conscious decision on which stars will over-saturate the sensor and render as pure white blobs and whether to make a second, or even third reduced exposure set, for later selective combination. Very few images are "straight".

Constellations

Since ancient times, astronomers have grouped the brighter stars as a means of identification and order. In nontechnical terms, we refer to them as constellations but strictly speaking, these star patterns are asterisms and the term constellation defines the bounded area around the asterism. These are irregular in shape and size and together they form a U.S. state-like jigsaw of the entire celestial sphere. This provides a convenient way of dividing the sky and referring to the general position of an object. The 12 constellations that lay on the path of our companion planets' orbits (the ecliptic) have astrological significance and we know them as the constellations of the Zodiac.

Star Names

Over thousands of years, each culture has created its own version of the constellations and formed convenient join-the-dot depictions of animals, gods and sacred objects. It has to be said that some stretch the imagination more than others. Through international collaboration there are now 88 official constellations. The brightest stars have been named for nearly as long. Many, for instance "Arcturus" and "Algol", are ancient Arabic in origin.

For some time a simple naming system has been used to label the bright stars in a constellation: This comprises of two elements, a consecutive letter of the Greek alphabet and the possessive name of the constellation or its abbreviation. Each star, in order of brightness, takes the next letter of the alphabet: For instance, in the constellation Centaurus, the brightest star is Alpha Centauri or αCen, the next is Beta Centauri or βCen and so on. Beyond the limits of the Greek alphabet, the most reliable way to define a star is to use its coordinates. As the number of identifiable stars increases, various catalog systems are used to identify over 1 billion objects in the night sky.

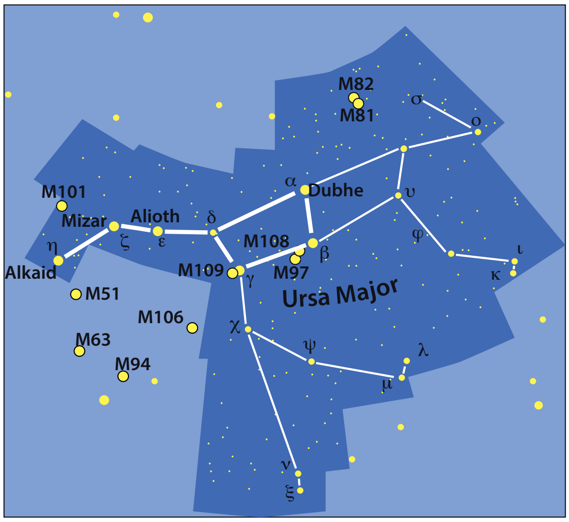

fig.2 The above illustration shows the constellation Ursa Major, of which the main asterism is commonly known as the Big Dipper, The Great Bear, The Plough and others. Many stars are named and take the successive letters of the Greek alphabet to designate their order of brightness. Several galaxies lie within or close to this constellation; the M-designation is an entry in the famous Messier catalog.

Deep Sky Objects

A deep sky object is a broad term referring to anything in the sky apart from singular stars and solar system objects. They form the basis of most astrophotography subjects and include nebulae, clusters and supernova remnants.

Star Clusters

As stars appear to be randomly scattered over the night sky, one would expect there to be groups of apparently closely packed stars. Clusters are strictly groups of stars in close proximity in three dimensions. They are characterized into two groups: Those with a loose sprinkling of approximately 100 to 1,000 younger stars, such as Pleiades, are termed an open cluster and often have ionized gas and dust associated with them. Those with 10,000 or more densely packed stars are older are referred to as globular clusters of which, in the Northern Hemisphere, M13 in the constellation Hercules is a wonderful example.

Although we can detect clusters in neighboring galaxies, they are too distant to resolve as individual stars. The clusters we commonly image are located in our own Milky Way galaxy. As well as being beautiful objects, clusters contain some of the oldest stars in the galaxy and are subject to intense scientific study too.

An image of star cluster is a showcase for good technique. It should have good star resolution and separation, extended to the dimmer stars at the periphery but without highlight clipping at the core. The stars should show good color too. This requires a combination of good tracking, focus, exposure and resolution and is the subject of one of the later case studies.

Star vistas can be wide-angle shots showing thousands of stars, the Milky Way or a landscape picture where the night sky plays an important part of the image. By their nature, they require lower magnifications and less demanding on pointing and tracking accuracy. They do, however, highlight any focus, vignetting or resolution issues, especially at the edges of an image.

Double and Binary Stars

A double star describes a distinguishable pair of stars that appear visually close to one another. In some cases they really are, with gravitational attraction, and these are termed visual binaries. Binary stars are one stage on, a pair of stars revolving around a common center of gravity but appear as one star. Amazingly, scientists believe that over 50% of Sun-like stars have orbiting companions. Most binary stars are indistinguishable but sometimes with eclipsing binaries the light output is variable, with defined periodicity.

Variable Stars

Variable stars have more scientific significance than pictorial. A class of variable star, the Cepheid Variables, unlocked a cosmic ruler through a chance discovery: In the early 20th century, scientists realized that the period of the pulsating light from many Cepheid Variables in our neighboring galaxy, the Small Magellanic Cloud, showed a strong correlation to their individual average brightness. By measuring other variable stars' period and intensity in another galaxy, scientists can ascertain it's relative distance. Supernova hunting and measuring variable stars require calibrated camera images rather than those manipulated for pictorial effect.

Nebula

A nebula is an interstellar cloud of dust, hydrogen, helium, oxygen, sulfur, cobalt or other ionized gas. In the beginning, before Edwin Hubble's discovery, galaxies beyond the Milky Way were called nebulae. In older texts, the Andromeda Galaxy is referred to as the Andromeda Nebula. Nebulae are classified into several types; diffuse nebulae and planetary nebulae.

Diffuse Nebulae

Diffuse nebulae are the most common and have no distinct boundaries. They can emit, reflect or absorb light. Those that emit light are formed from ionized gas, which as we know from sodium, neon and xenon lamps radiate distinct colors. This is particularly significant for astrophotographers, since the common hydrogen, oxygen, sulfur and nitrogen emissions do not overlap with the common sodium and mercury vapor lamps used in city lighting. As a result, even in heavily light-polluted areas, it is possible to image a faint nebula through tuned narrowband filters with little interference. Diffuse nebula can also be very large and many fantastic images are possible with short focal-length optics. The Hubble Space Telescope has made many iconic false color images using "The Hubble Palette", comprising narrowband filters tuned to ionized hydrogen, oxygen and sulfur emissions which are assigned to green, blue and red image channels.

Planetary Nebulae

These amazing objects are expanding glowing shells of ionized gas emitted from a dying star. They are faint and tiny in comparison to diffuse nebula and require high magnifications for satisfactory images. They are not visible to the naked eye and the most intricate details require space-telescopes operating in visible and non-visible electromagnetic spectrums. The first planetary nebula to be discovered was the Dumbbell Nebula in 1764 and its comparative brightness and large 1/8th degree diameter render it visible through binoculars. Only the Helix Nebula is bigger or brighter.

Supernova Remnants

One other fascinating nebula type forms when a star collapses and explodes at the end of its life. The subsequent outburst of ionized gas into the surrounding vacuum, emits highly energetic radiation including X-rays, gamma waves, radio waves, visible light and infrared. The Crab Nebula is a notable example, originating from a stellar explosion (supernova), recorded by astronomers around the world in 1054. Amazingly, by comparing recent images with photographic evidence from the last century, astronomers have shown the nebula is expanding at the rate of about 1,500 kilometers per second. After certain classes of supernova events there is a gravitational collapse into an extremely dense, hot neutron star. Astronomers have detected a neutron star at the heart of the Crab Nebula. They often give off gamma and radio waves but also have been detected visibly too.

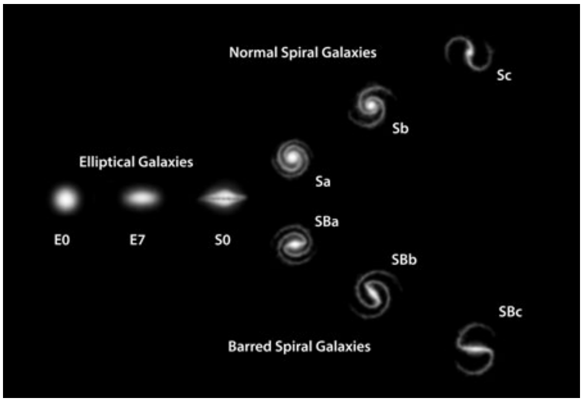

fig.3 When Edwin Hubble discovered that galaxies exist outside our own, he went about classifying their types from their appearance. The original scheme above is the most famous, the "Hubble Sequence" and was added to later by other astronomers. The elliptical galaxies are designated with an "E" followed by an index x, spiral galaxies normally with a central bulge and two or more arms are designated "Sx" of which some have a center barred structure , designated "SBx". The remaining class ("S0") is known as lenticular *and although they feature a central bulge in the middle of a disk-like shape, they have no observable spiral structure.*

Galaxies

As mentioned already, the existence of other galaxies outside our own was a late realization in 1925 that fundamentally changed our view of the universe. Galaxies are gravitationally bound collections of millions or trillions of stars, planets, dust and gas and other particles. At the center of most galaxies, scientists believe there is a super massive black hole. There are billions of galaxies in the observable universe but terrestrial astrophotography concerns itself with the brighter ones. There are approximately 200 brighter than magnitude 12, but at magnitude 14 the number rises to over 10,000. The brightest is the Large Magellanic Cloud, a neighbor to our Milky Way and easily visible to the naked eye by observers in the Southern Hemisphere. Charles Messier in the 18th century cataloged many other notable examples and are a ready-made who's who.

Galaxies come in all shapes and sizes, making them beautiful and fascinating. Many common types are classified in fig.3. Most of the imaging light from galaxies comes from their stars, though there is some contribution from ionized gases too, as in nebulae. Imaging galaxies requires good seeing conditions and low light pollution since they are in general, less luminous than stars or clusters and have less distinct boundaries. In general, a good quality image of a galaxy is a balance of good surrounding star color, galaxy color and extension of the faint galaxy periphery, without sharp cut-offs into the background or over exposing the brighter core. This requires careful exposure and sensitive manipulation and quite possibly an additional shorter exposure sequence for the surrounding brighter stars. Supplementary exposures through narrowband filters (tuned to ionized gases, or infrared) can enhance and image but in general, since these filters pass very little light, the exposure times quickly become inconveniently long and only practical when applied to the brightest galaxies.

Quasars may appear as stars, but in fact are the bright cores of very distant galaxies and are the most luminous things in the universe. They were first identified through their radio wave emissions and only later linked to a faint, visible, heavily red-shifted dot. The extreme energies involved with their emissions is linked to the interaction of gas and dust spiralling into a black hole. A few quasars are visible from Earth and within the reach of amateur astrophotographer's equipment.

Solar System Objects

The prominent planets in our solar system were identified thousands of years ago. The clue to how is in the name. Derived from the ancient Greek, "planet" means wanderer, and in relation to the background of wheeling stars, Mercury, Venus, Mars, Jupiter, and Saturn appeared in different positions each night. Unlike the continual annual stately cycle of star movement, these planets performed U-turns at certain times in the calendar. Those planets closer to the Sun than the Earth are called inferior planets (Venus and Mercury) and correspondingly Mars, Jupiter, Saturn, Uranus and Neptune are called superior planets. By definition, planets orbit a sun and need to be a significant distinct ball-like shape of rock, ice and gas. The definition is a bit hazy and as such Pluto was demoted in the 20th century, after much debate, to a minor planet (of which there are many).

The Keplerian and Newtonian laws of motion amazingly predict the precise position of our planets in the night sky. Within planetarium programs, their position has to be individually calculated but from an imaging standpoint, for the short duration of an exposure, their overriding apparent motion is from the earth's rotation, which is adjusted for by the standard (sidereal) tracking rate of a telescope.

From Earth, some planets change appearance: Planets appear larger when they are close to "opposition" and closest to Earth. Mercury and Venus, being closer to the

Sun than the Earth, show phases just as our Moon does, and Jupiter, Saturn and Mars change their appearance from planet rotation and tilt.

The massive Jupiter spins very quickly and completes a revolution in about 10 hours. This sets a limit on the exposure time of a photograph to about 90 seconds at medium magnifications and less with more. Above this time, its moons and the surface features, most notable of which is the giant red spot, may become blurred.

Saturn, whose iconic ring structure has inspired astronomers since the first telescopic examination, has an interesting cycle of activity. These rings, which in cosmic terms are unbelievably thin at less than 1 kilometer, have an inclination that changes over a 30-year cycle. In 2009, the rings were edge-on and were almost invisible to Earth but will reach a maximum 30° inclination during 2016-17.

Mars rotates at a similar rate to Earth. Terrestrial photographs of Mars show some surface details as it rotates. In addition, there are seasonal changes caused by the axial tilt and its highly eccentric orbit. From an imaging standpoint, this affects the size of its white polar ice cap of frozen carbon dioxide during the Martian year (lasting about two Earth-years). Its size is under 1/120th degree and requires a high magnification and stable atmospherics for good results. It is a challenging object to image well.

When we observe a distant galaxy, we are only seeing the stars and none of the planets. Even taking into consideration the extra mass of planets, dust and space debris, the rotational speed of the observed galaxies can only be explained if their overall mass is considerably higher. The hypothesized solution is to include "dark matter" into the mass calculation. Dark matter defies detection but its presence is inferred from its gravitational effect. In 2012 the Hadron particle collider in Switzerland identified a new elementary particle, the Higgs Boson, with a mass 125x that of a proton. It is an important step along the way to explaining where the missing mass is in the observable universe.

Asteroids, Satellites and Meteorites

At various times, these too become subject to photographic record. Of these, asteroids are perhaps the least interesting to the pictorialist until they fall to Earth. These lumps of rock or ice are normally confined to one of our solar system's asteroid belts, but in our prehistory, may have been knocked out of orbit by collisions or gravitational interactions of the planets. One of the largest, Vesta, has been subject to special up-close scrutiny by the Dawn spacecraft. Indeed, debris from a Vesta collision in space fell to Earth as meteorites. On rare occasions asteroids pass closer to Earth than the Moon.

Satellites, especially when they pass in front of the Moon or Sun in silhouette, are visually interesting and require forward planning. More commonly, satellite images are indistinct reflections of sunlight against a dark sky. There are thousands of man-made satellites circling the Earth. The most well known have published orbital data which can be used within planetarium programs to indicate their position or line up a computer-controlled telescope. They orbit from 180 km or more away at a variety of speeds, depending on their altitude and purpose.

Meteorites are not in themselves special objects, merely the name we give natural objects when they make it to the Earth's crust. They are mostly comprised of rock, silicates or iron. Specimens are of important scientific value, for locked inside, there can be traces of organic material or of their source atmosphere. During their entry into our atmosphere, their extreme speed and the friction with the air heats them to extreme temperatures, leading to their characteristic blazing light trail and occasional mid-air explosions. The larger ones are random events, but there are regular occurrences of meteor showers that beckon to the astrophotographer.

Meteor showers occur when the Earth interacts with a stream of debris from a comet. This debris is usually very fine, smaller than a grain of sand and burns up in our atmosphere. These events are regular and predictable and produce a celestial firework display for a few successive nights each year. The events are named after the constellation from which the streaks appear to emanate. Famous meteor showers are the Perseids in August and the Leonids in November, which produce many streaks per hour. Often the most spectacular photographs make use of a wide-angle lens on a static camera and repeated exposures on a time-lapse for later selection of the best ones.

Special Events

Over thousands of years, astrologers have attached significance to special astronomical events. The most well known, yet strangely unproven, is the "Star of Bethlehem" announcing Jesus' birth, which may have been a supernova explosion. These events include special causes, like supernova, where an individual star can achieve sufficient short-lived intensity to be visible during the day, or the sudden appearance of a bright comet. Many other events consider the relative positions of a planet and the Sun, the Moon and the Sun, the phases of the Moon or the longest day or night. Modern society has disassociated itself from Astrology, but the rarity of some events encourages astronomers and physicists to travel the world to study eclipses, transits or another one-off event. The good news for astronomers is that, apart from supernova, everything else is predictable. (Edmond Halley realized that most comets too have a predictable orbit and appearance.) For an imaging standpoint, the luck and skill of capturing a rare event adds to the satisfaction of the image. As they say, "chance favors the prepared mind" and astrophotography is no different.

Exoplanets

In recent years, amateurs have joined in the search for exoplanets, made feasible by low-noise CCD cameras and high quality equipment. With care, one can not only detect known exoplanets through their momentary lowering of their host star's flux but potentially find new ones too by the same means. A highly specialized area but one which is introduced in a later chapter. The image in this case is not of the planet itself (it is too dim) but a graph of the host star's light output with a characteristic and regular dip.

Comets

Comets become interesting when they pass close to the Sun. In space, they are lumps of ice and rock circling in enormous orbits. As their orbit passes close to the Sun, the characteristic tail and tiny atmosphere (coma) develops. The tail points away from the Sun and arises from the effect of solar radiation and wind on the comet's volatile contents. Short-period comets, with orbits of less than 200 years, are widely predicted, and with a little luck, can be photographed in good conditions. More occasional visitors are often detected by the various near-earth object telescopes long before they become more readily visible. A bright comet discovered in September 2012, name ISON, passed close to the Sun in January 2014 and many hoped it would provide an opportunity for unique images. A photograph of a comet is a wonderful thing, but to image it as it passes through another landmark site, such as a star cluster, makes it memorable. Since the stars and comet are moving in different directions and speed, one must decide whether to track the stars or not during the brief exposure. However, ISON was imaged by Damian Peach and others as it approached the Sun but it never made it past perihelion and the solar radiation was too much for the muddy snowball. It should have been renamed comet Icarus!

A photograph of stars close to the Sun, taken by Arthur Eddington during a total solar eclipse in 1919, when compared to a photograph of the same stars with the Sun not present, showed a tiny deflection. It was the first measurement to substantiate that light-beams could be bent by gravity, predicted in Einstein's general theory of relativity.

Lunar Eclipses

A lunar eclipse occurs when the Moon, Earth and Sun are in a direct line and the Moon is in Earth's shadow. We can still see the Moon, which is illuminated from scattered light through our atmosphere, and it often takes on a reddish appearance. A time sequence of a lunar eclipse from 2007 is shown in fig.4.

Solar Eclipses

A solar eclipse occurs when the Earth, Moon and Sun are in a direct line and the Moon blocks our view of the Sun. By amazing coincidence, the Moon and Sun have the same apparent size, and eclipses may be partial, where the Moon clips the Sun, or total, which provides a unique opportunity to image the solar corona safely. A total solar eclipse will only be visible from a select 100-kilometer wide tract of the Earth's surface, and avid observers will travel to far flung corners of the world to get the best view of a "totality".

fig.4 This lunar eclipse was captured in March 2007 and assembled from a sequence of still photographs, taken with a consumer digital SLR mounted on a tripod and fitted with a 210 mm zoom lens.

Planetary Transits

Mercury and Venus, the "inferior" planets, lie closer to the Sun than the Earth. On the rare occasions that they pass in front of the Sun, they are in transit. Man-made satellites also transit the Moon and Sun for a few seconds. Photographing the Sun during a transit requires the same mandatory precautions as any other form of solar photography. Transits occur when the nearer object is smaller than the more distant object. (Occultations occur when it is the other way around and it is possible to get transits and occultations between planets too.) In 2065, Venus transits Jupiter and in 2067, Mercury occults Neptune. I'll pass on that one.

Superior and Inferior Conjunctions

These are general terms for line-ups of astronomical bodies from an observer's standpoint. These may be between planets, a planet and the Moon or Sun or other combinations. From an imaging standpoint it is interesting when one can make an image of two close important bodies, though the brightness difference often makes it a challenge. Planetarium programs are very adept at predicting these events and can produce timetables for their occurrence.

Opposition

Another particular event, opposition, occurs when two bodies are on opposite sides of the sky from an observed position. This is of most significance to astrophotographers since when a superior planet is in opposition, it generally is at its closest point to earth and hence its apparent size will be a maximum. Jupiter increases its apparent size by 66%. Mars' change is more extreme and its apparent diameter increases by more than 600%. It is good practice to image planets when they are close to their opposition.

Equinoxes and Solstices

These regular events occur when the Earth is at a specific point in its orbit around the Sun. In the case of the equinox, the tilt of the earth's axis is tangential to the Sun and it has the unique characteristic that night and day are of equal length. It does not have any significant imaging significance, but it does for our celestial coordinate system. There are two equinoxes per year (spring and autumn) and the celestial coordinate system uses the Sun's position at the spring equinox to define an absolute reference point for measuring right ascension. (We will discuss coordinate systems in more detail later on.) There are also two solstices each year, in winter and summer. These mark the shortest and longest day and occur when the tilt of the Earth's axis is in line with the Sun. Their significance for photography mostly relates to the number of available hours for imaging!

Catalogs

It is easy to forget that the availability of detailed planetarium and catalog data on personal devices was only made possible by the patient and astonishing dedication of generations of astronomers.

Astronomical catalogs are an invaluable resource to the astrophotographer. They are the à la Carte menu of the cosmos. One can easily imagine, although the first astronomers recorded the very brightest stars onto fanciful charts, as soon as telescopes were used to methodically survey the heavens, the number of objects increased exponentially. This created the need for systematic catalogs by type, position and brightness. One of the earliest catalogs dates from the first millennia and lists more than 1,000 stars in detail, and interestingly includes the fuzzy outlines of the Andromeda Galaxy and the Large Magellanic Cloud.

Classification

As observations became more sophisticated, it was necessary to find ways of classifying stars and organizing them in logical ways. Johann Bayer started the convention of prefixing the constellation name with a letter from the Greek alphabet in the order of their brightness, a system that is still in use today. John Flamsteed, in his star atlas of 1725, listed stars using numbers combined with the constellation in the order of their right ascension. (John Flamsteed was the first Astronomer Royal at the Greenwich Observatory. The observatory was built on the meridian and his telescopes pivoted in altitude only and so it was convenient for him to label stars in the order they crossed the line of sight.)

In 1781 the French astronomer Charles Messier published "Nebulae and Star Clusters". Crucially, this was not a star catalog but one of deep sky objects. He used a simple index, prefixed with "M" to identify these objects; for example, M31 is the Andromeda Galaxy. Since observations with a telescope at that time only showed the most discernible deep sky objects, it follows that these objects in turn are prime subjects for amateur astrophotography. The Messier catalog is very convenient and arguably the backbone of amateur astrophotography. Indeed, at star parties "The Messier Marathon" is a challenge to see how many of his catalog items (there are 110) you can view in one night.

One hundred years on another significant catalog, the New General Catalog (NGC), compiled by J. Dreyer, listed about 8,000 objects, stars and deep sky objects and remains a useful comprehensive catalog, in use today. It is astonishing to realize that these early catalogs were compiled by hand, without the help of computers or photographic records, but by patient observation and often in poor conditions.

The "Guide Star Catalog" (GSC) is another important catalog, initially compiled to support the Hubble Space Telescope and now also used by amateurs with plate-solving software. (Plate-solving is a technique that recognizes the relative positions and brightness of stars in an image against a catalog database and derives the actual image scale, position and rotation to incredible accuracy.)

In the following century, as telescopes continued to improve and crucially photography allowed astronomers to see fainter objects, the catalogs expanded exponentially. In the early 20th century the Henry Draper Catalog listed more than a quarter of million stars, and later still, using satellite imagery, the Tycho-2 catalog identifies positions and color information of 2.5 million stars in the Milky Way.

In practice, many common objects have several names, corresponding to their listing in each of the popular catalogs, and in addition, descriptive names based on their appearance. Thankfully, we do not need to pore over large books of numbers but can use planetarium programs on computers, smart phones or tablets to select objects for viewing or imaging, display its image and display its relative size and brightness. Many planetarium programs can also command a telescope to point to an object via a number of connections, from external RS232 serial, through Bluetooth and WiFi, wired Ethernet and remotely over the Internet.

Today the main catalogs are available in digital formats and are freely available; for example from U.S. and European Space Agency websites. Clearly in the early days, as new objects were identified, the catalogs expanded and overlapped previous editions. Subsequently, as measurement techniques improved, those with more accurate measurements of position, brightness and color replaced earlier surveys. Even so, stars and galaxies are on the move, relative to Earth and to each other and so any catalog's accuracy will change in time. This perhaps has less significance for the amateur but for scientific use, renewed surveys are required to update their databases.

Too Much Data?

Several commonly available catalogs are compiled, employing filters to generate data sub-sets for specific purposes, for instance, all stars brighter than a certain magnitude. Even with digital computers, too much data can obscure or slow down the search and display for what you want to view, the proverbial needle in a haystack. It is sobering to realize that the Hubble Space Telescope was *upgraded* to a ruggedized 486-based PCs running at 25 MHz clock speed and the Chandra X-Ray space observatory, with a VAX computer, is roughly equivalent to a 386-based PC. Hubble's main computer has just 10 GB of drive space, less than 1/200th of the capacity or speed of the computer writing this! Robustness in this extreme environment is more important than speed.

Catalogs for Astrophotographers

There are two main types of catalog today, the detailed star-based measurement intensive astrometric databases and catalogs of interesting objects. The second form is the most useful for astrophotographers. For deep sky objects, subsequent to the ubiquitous Messier catalog, Sir Patrick Moore generated a supplementary hit list of 109 objects in his Caldwell Catalog. He noticed that Messier had excluded objects that were only visible in the southern hemisphere and had missed quite a few interesting bright deep sky objects too. Since Messier had already taken the "M" prefix, Moore used his middle name Caldwell and used "C" instead. His catalog is listed in numerical order of degrees away from Polaris (declination).

In addition to these two, a group of astronomers selected 400 deep sky objects from the 5,000 listed in John Herschel's Catalog of 1864, all of which are observable from mid northern latitudes and with a modest telescope. It is called the Herschel 400. About 60 objects in the Herschel 400 also occur in the Messier or Caldwell catalogs.

The astrophotographer has more objects to photograph than a lifetime of clear nights. The choice is bewildering and thankfully many planetarium programs offer recommendations for a given night. The huge astrometric databases are of more importance to the scientific community but can be used for plate solving and supernova detection in amateur systems. Most are available as free downloads from the Internet and most planetarium programs are able to load and access them selectively. If too many are enabled at the same time, the star map is cluttered with multiple names for each object. To add to the fun, several popular objects have multiple common names and their catalog number is useful to remove ambiguity.

Catalog	Date	Objects	Notes
Messier "M"	1771	110	Deep space objects, including galaxies, nebulae and clusters, visible from Northern Hemisphere
Herschel "H"	1786 1864	2,500 5,000	Deep space objects, including galaxies, nebulae and clusters, visible from Northern Hemisphere. Later revision by son doubled object count
NGC/IC	1888	5,386	Revised Herschel Catalog but had errors that evaded several attempts to correct. Extensively used.
BSC or YBS	1908	9,110	Bright star catalog, brighter than magnitude 6.5
Melotte	1915	245	Open and Globular clusters
Barnard	~1923	370	Dark Nebulae
Collinder	1931	471	Open Star clusters
ADS	1932	17,000	Aitkin Double Star Catalog
Abell	1958-89	4073	Galaxy Clusters
Sharpless	1953-59	312	HII and planetary nebula and supernova remnants
Herschel 400	1980	400	400 deep space items from the Herschel Catalog - use "NGC"
GSC1 GSC2	1989	20M 1B	Catalog to magnitude 15 and 21 for space telescope navigation. (Stars)
Hipparcos "HIP"	1993	120,000	Extremely accurate positional and motion star data
Caldwell "C"	1995	109	109 deep space bright objects missed by Messier or in Southern Hemisphere, by Sir Patrick Caldwell Moore
Tycho-2	1997	2.5M	Star catalog with revised proper motion, brightness and color data
USNO-B1	2003	1B	Stars and galaxies, over 80 GBytes of data
NOMAD	2005	1.1B	Merged data from HIP, Tycho-2, USNO-B1
RNGC/IC	2009	5,000	Revised and corrected Herschel Catalog

fig.1 The table above lists some of the more common catalogs that one finds in planetarium programs, books and references. Some of these are included since they are used, not necessarily to identify objects to image, but in support of plate-solving software. This accurately locates an image's center by comparing the star positions and intensities with the catalog database. There are many more specialist catalogs, which can be found on the Internet and imported into planetarium programs, such as comet, satellite and asteroid databases.

Four Dimensions and Counting

Locating an object in 3-D space from a spinning and wobbling planet, which orbits a star, which orbits its galactic center that itself is receding from most other galaxies is ... interesting.

I have to admit that when I first started astronomy I found the multiple references to time and coordinate systems extremely confusing. It took some time, helped by the research for this book, to fully appreciate and understand these terms. As the famous quote goes, "time is an illusion" and as it happens, so too are coordinate systems.

Consider the lonely astronomer, sitting on his planet observing billions of stars and galaxies floating around in space, all in constant motion with respect to each other and his own planet, which is spinning and rotating around its solar system in turn rotating around its host galaxy. One can start to appreciate the dilemma that faces anyone who wants to make a definitive time and coordinate-based system.

The solution is to agree a suitable space and time as a reference. Even something as simple as the length of an Earth day is complicated by the fact that although our Earth spins on its axis at a particular rate, since we are simultaneously moving around the Sun, the length of a day, as measured by the Sun's position, is different by about 4 minutes. An Earth-based coordinate system for measuring a star's position is flawed since the Earth is spinning, oscillating and orbiting its solar system, galaxy and so on. In fact, one has to make first-order assumptions and make corrections for second-order effects. Our Earth's daily rotation is almost constant and the tilt of the axis about which it rotates varies very slowly over 26,000 years (over an angular radius of 23°). Incredibly, this slow shift was detected and measured by Hipparchus in 125 BC. The name given to the change in the orientation of the Earth's axis is "precession" and the position of the North Celestial Pole (NCP) moves against the background of stars. Currently Polaris is a good approximation (about 45 arc minutes away) but in 3,200 years, Gamma Cephei will be closer to the NCP.

The upshot of all this is that there are several coordinate and time systems, each optimized for a purpose. The accuracy requirements will be different for science-based study, versus more humble, down-to-earth systems employed by amateur astronomers. Even so, we are impacted by the small changes in our reference systems, for instance a polar scope, designed to align a telescope to the NCP has a reticle engraved to show the position of Polaris (fig.1). Ideally, a polar reticle requires an update every 10 years to accommodate the Earth's precession and indicate the revised position of Polaris with respect to the NCP.

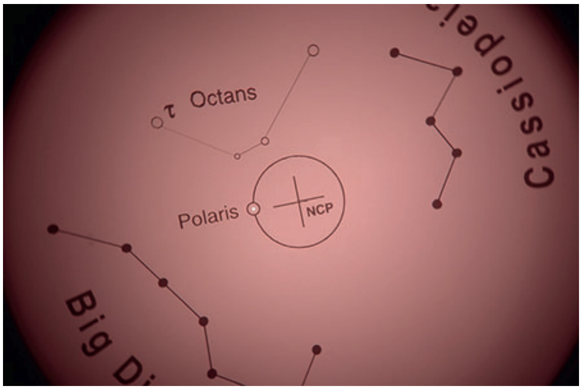

fig.1 This view through a polar scope shows a typical reticle that indicates the relative position of Polaris with the North Celestial Pole (NCP). This reticle was accurate in the epoch J2000 and but in 2013 it is necessary to place Polaris a little off-center in the bubble and closer to the NCP by about 10%.

Time Systems

Local Time (LT)

This is the time on our watch, designed for convenience. Most countries make an hour correction twice a year (daylight saving) to make the daylight hours fit in with sunrise and sunset. As one travels around the Earth, the local time in each country is designed to ensure that the daylight hours and the Sun's position are aligned.

Universal Time (UT)

Perhaps the most common time system used by amateur astronomers is Universal Time. This is the local time on the north-south Meridian, which passes through Greenwich, London. It has a number of different names, including Greenwich Mean Time (GMT), Zulu Time and Coordinated Universal Time (UTC). It is synchronized with the Earth's rotation and orbit and is accurate enough for practical purposes. Each night at a given time, however, a star's position will change. This is attributable to the 4-minute time difference between a 24-hour day and a sidereal day.

Atomic Time

Time systems based on astronomical events are ultimately flawed. The most stable time systems are those based on atomic clocks; over the course of a decade, small changes in the Earth's rotational speed add up. Atomic clocks use the ultra stable property of Cesium or Rubidium electronic transitions. If one uses Global Positioning Satellite (GPS) signals to locate and set your time, one is also benefitting from the stability of atomic clocks.

Barycentric or Heliocentric systems

Rather than use the Earth as a reference, this time system uses the Sun as the reference point for observation. This removes the sub-second errors incurred by the change in Earth's orbit between measurements. One use of this system is for the timing of eclipsing binary stars.

Local Sidereal Time

Local sidereal time is a system designed for use by astronomers. It is based on the Earth's rotation and does not account for its orbit around the Sun. Its "day" is 23 hours, 56 minutes and 4.1 seconds and allows one to form an accurate star clock. If you look at the night sky at a given LST each night, the stars appear in the same position. It is the basis of the Equatorial Coordinate system described later on.

Other Time References

Julian Dates (JD)

Julian dates are a day-number system that allows users to calculate the elapsed time between two dates. The formula converts dates into an integer that allows one to quickly work out the interval. For example, the 22nd January 2013 is JD 2456315. (A similar idea is used by spread-sheet programs to encode dates.) An example of an on-line calculator can be found at:
http://aa.usno.navy.mil/faq/index.php

Epoch

An epoch is a moment in time used as a reference point for a time-changing attribute, for instance, the coordinate of a star. Astrometric data often references the epoch of the measurement or coordinate system. One common instance, often as a check-box in planetarium and telescope control software, is the choice between J2000 and JNow, that is the coordinate system as defined in 2000 AD and today. As the years progress, the difference and selection will become more significant. In many cases, the underlying software translates coordinates between epochs and is transparent to the practical user.

Coordinate Systems

Horizontal Coordinates

There are several fundamental coordinate systems, each with a unique frame of reference. Perhaps the most well known is that which uses the astronomer's time and position on earth, with a localized horizon and the zenith directly above. The position of an object is measured with a bearing from north (azimuth) and its elevation (altitude) from the horizon, as shown in fig.2. This system is embodied in altazimuth telescope mounts, which are the astronomy equivalent of a pan and tilt tripod head, also abbreviated to "alt-az mounts".

There are pros and cons with all coordinate systems; in the case of horizontal coordinates, it is very easy to judge the position of an object in the night sky but this information is only relevant to a singular location and time. In the image-planning stage, horizontal coordinates, say from a planetarium program, are an easily understood reference for determining the rough position of the subject, if it crosses the north-south divide (meridian) and if it moves too close to the horizon during an imaging session.

Equatorial Coordinates

Unlike horizontal coordinates, a star's position, as defined by equatorial coordinates, is a constant for any place and time on the Earth's surface. (Well, as constant as it can be in the context of star's relative motion and Earth's motion within its galaxy.) For a given epoch,

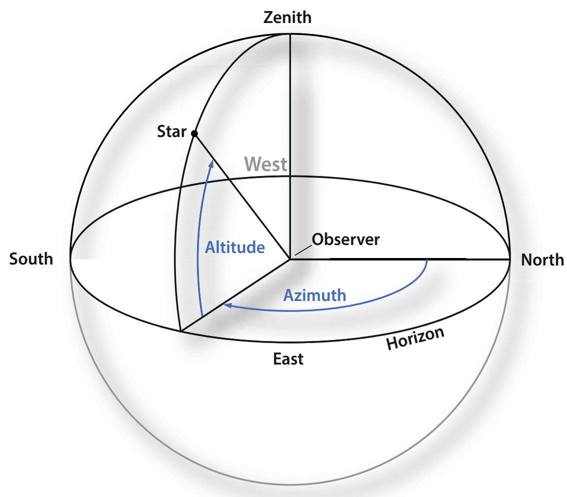

fig.2 This schematic shows the normal horizontal coordinate scheme, with local horizon and true north references. The zenith is directly overhead. Celestial coordinates in this system are only relevant to your precise location and time.

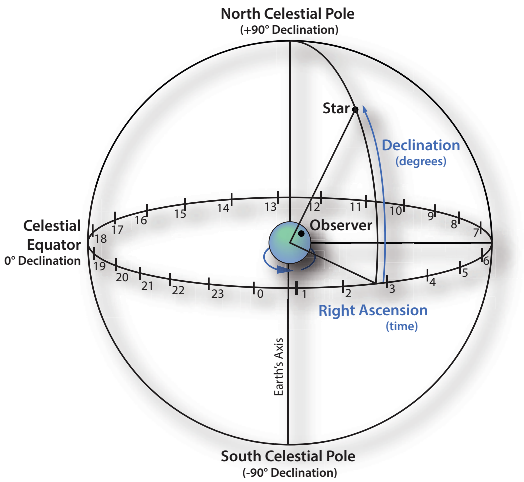

fig.3 This schematic shows the equatorial coordinate scheme, with celestial horizon and celestial pole references. Celestial coordinates in this system relate to the Earth and can be shared with users in other locations and at other times. Right ascension is measured counter-clockwise; a full circle is just less than 24 hours.

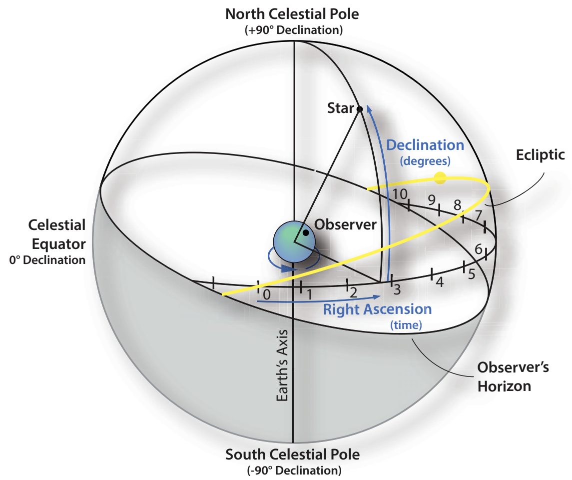

fig.4 This schematic expands on that in fig.3. It shows how the celestial horizon and the observer's horizon can be inclined to one another. In one direction the observer can view objects beneath the celestial equator. The ecliptic is shown crossing the celestial equator at the Vernal Equinox, defining 0 hour's right ascension reference point.

planetarium programs or the handset with a programmable telescope mount will store the equatorial coordinates for many thousands of stars. It is a simple matter with the additional information of local time and location on the Earth for a computer to convert any star's position into horizontal coordinates or display on a computer screen.

Equatorial coordinates are a little hard to explain, but as with horizontal coordinates, they have two reference points. The first reference point is the North Celestial Pole, as shown in fig.3, located on the imaginary line of the Earth's axis of rotation. A star's declination is the angular measure from the celestial equator. For instance, the polestar (Polaris) is very close to the North Celestial Pole and has a declination of 89.5°. If one observes the stars from the North Pole, one would see a fixed set of stars endlessly going around in a circle and parallel to your local horizon. In this special case a star's declination is equal to its altitude.

The second reference point lies on the celestial equator, from which the stars bearing is measured in hours, minutes and seconds (for historical reasons) rather than degrees. Unlike the azimuth value in horizontal coordinates, which is measured clockwise from true north, the star's bearing (right ascension) is measured counter-clockwise from the zero-hour reference point. This reference point is explained in fig.4 and corresponds to a special event, on the occasion of the Spring Equinox, where the Sun, moving along the ecliptic, crosses the celestial equator. (The ecliptic can conversely be thought of as the plane of the Earth's rotation as it orbits the the Sun. It moves with the seasons and is higher in the sky during the summer and lower in the winter.)

From an observer's standpoint, say at the latitude of the UK or north America, the North Celestial Pole is not at the zenith but some 30–40° away, and the stars wheel around, with many appearing and disappearing across the observer's horizon. (The North Celestial Pole is directly above the North Pole and hence Polaris has been used as a night-time compass for thousands of years.)

The equatorial coordinate system is quite confusing for an observer unless they are equipped with an aligned telescope to the NCP; unlike horizontal coordinates, the right ascension for any given direction is continually changing. Even at the same time each night, the right ascension changes by 4 minutes, the difference between a day measured in universal and sidereal time. (If you look very closely at the right ascension scale of a telescope, fig.5, you will notice a small anomaly, accounting for the time difference, between 23 and 0 hours.) Unlike the horizontal coordinate system, an astronomer armed with just a compass and equatorial coordinates would be unable to locate the general direction of an object.

The beauty, however, of the equatorial system is that any star has a fixed declination and right ascension and an equatorial mounted and aligned telescope only needs to rotate counter-clockwise on its right ascension axis in order to follow the star as the Earth spins on its axis. In addition, since all the stars move together along this axis, an image taken with an aligned system does not require a camera rotator to resolve every star as a pinprick of light.

Equatorial coordinates are not a constant, however, even if one discounts star movements: a comparison of the readouts of a star position for successive years show a small change, due to the Earth's precession mentioned earlier, and serves as a reminder that the absolute position of a star requires its coordinates and epoch. In practice, the alignment routine of a computerized telescope mount or as part of the imaging software soon identify the initial offset and make adjustments to their pointing model. Linked planetarium programs accomplish the same correction through a "synch" command that correlates the theoretical and actual target and compensates for the manual adjustment.

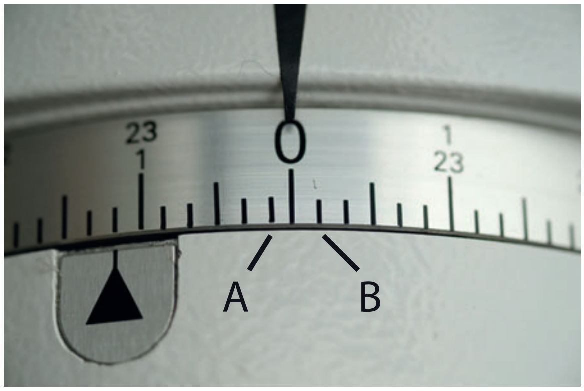

fig.5 This close up shows the right ascension scale from an equatorial telescope mount. Each tick-mark is 10 minutes and upon closer inspection one notices that the tick mark, labelled A is slightly closer to 0 than the one labelled B. This accounts for the fact that the right ascension scale is based on sidereal time, whose day is about 4 minutes short of the normal 24 hours in universal time.

Other Terms

Galactic Coordinates

Galactic coordinates are used for scientific purposes and remove the effect of the Earth's orbit by using a Sun-centered system, with a reference line pointing towards the center of the Milky Way. By removing the effect of Earth's orbit, this system improves the accuracy of measurements within our galaxy.

Ecliptic, Meridian and Celestial Equator

There are a couple of other terms that are worth explaining since they come up regularly in astronomy and astrophotography. The ecliptic is the apparent path of the Sun across the sky, essentially the plane of our solar system. The planets follow this path closely too and planetarium programs have a view option to display the ecliptic as an arc across the sky chart. It is a useful aid to locate planets and plan the best time to image them.

The meridian is an imaginary north-south divide that passes through the North Celestial Pole, the zenith and the north and south points on the observer's horizon. This has a special significance for astrophotographers since with many telescope mounts, as a star passes across the meridian, the telescope mount has to stop tracking and perform a "meridian flip". (This flips the telescope end-to-end and side-to-side on the mount so that it can continue to track the star without the telescope colliding with the mount's support. At the same time, the image turns upside down and any guiding software has to change its polarity too.) During the planning stage it is useful to display the meridian on the planetarium chart and check to see if your object is going to cross the meridian during your imaging session so that you can intervene at the right time, perform a meridian flip and reset the exposures and guiding to continue with the exposure sequence.

The celestial equator has been mentioned briefly before in the discussion on equatorial coordinates. The plane of the celestial equator and our Earth's equator are the same, just as the North Celestial Pole is directly above the North Pole. The effect of precession, however, means that as the tilt of the Earth's axis changes, so does the projection of the celestial equator and the stars will appear to shift in relation to this reference plane.

Degrees, Minutes and Seconds

Most software accepts and outputs angular measures for longitude and latitude, arc measurements and declination. This may be in decimal degrees (DDD.DDD) or in degrees, minutes and seconds. I have encountered several formats for entering data and it is worthwhile to check the format being assumed. Common formats might be DDDMMSS, DDD° MM' SS" or DDD:MM:SS.

In each case a minute is 1/60th degree and a second is 1/60th of a minute. In astrophotography the resolution of an image or sensor (the arc subtended by one pixel) is measured in arc seconds per pixel and the tracking error of a telescope may be similarly measured in arc seconds. For instance, a typical tracking error over 10 minutes, without guiding, may be ± 15 arc seconds but a sensor will have a much finer resolution of 1 to 2 arc seconds per pixel.

Distance

The fourth dimension in this case is distance. Again, several units of measure are commonly in use, with scientific and historical origins. The vastness of space is such that it is cumbersome to work with normal measures in meters or miles. Larger units are required, of which there are several.

Light-Years

Light-years are a common measure of stellar distances and as the name suggests, is the distance travelled by light in one year, approximately 9 x 10^{15} meters. Conversely, when we know the distance of some cosmic event, such as a supernova explosion, we also know how long ago it occurred. Distances in light-years use the symbol "ly".

Astronomical Unit

The astronomical unit or AU for short is also used. An AU is the mean Earth-Sun distance at about 150 x 10^{9} meters. It is most useful when used in the context of the measurement of stellar distances in parsecs.

Parsecs

A distance in parsecs is determined by the change in a star's angular position from two positions 1 AU apart. It is a convenient practical measure used by astronomers. In practice, a star's position is measured twice, 6 months apart. A star 1 parsec away would appear to shift by 1 arc second. It has a value of approximately 3.3 light-years. The parsec symbol is "pc". The further the star's distance, the smaller the shift in position. The Hipparcos satellite has sufficient resolution to determine stars up to 1,000 pc away.

All these measures of large distances require magnitude uplifts; hence kiloparsec, megaparsec, gigaparsec and the same for light-years.

Cosmic Distance Ladders

I have always wondered how some of the mind-numbing distances are determined with any certainty. The answer lies in a technique that uses cosmic distance ladders. Astronomers can only directly measure objects close to Earth (in cosmic terms). Using a succession of techniques, more distant objects can be estimated by their emission spectra, light intensity and statistics.

In these techniques, the red-shift of a distant star's spectrum indicates its speed and hence distance from Earth using the Hubble Constant equation, whereas closer to home, the period and brightness of a variable star is a good indicator of its distance. These techniques overlap in distance terms and allow one to multiply up the shorter measures to reach the far-flung galaxies.

distance	km	AU	ly	pc
Earth to Moon	3.8 x 10^{5}	2.5 x 10^{-3}	1.2 lsec	1.2 x 10^{-8}
Earth to Sun	1.5 x 10^{8}	1	8.3 lmin	4.8 x 10^{-6}
Sun to nearest star	4.0 x 10^{13}	2.7 x 10^{5}	4.2 ly	1.3
Sun to center of Milky Way	2.6 x 10^{17}	1.7 x 10^{9}	2.8 x 10^{4} ly	8.2 x 10^{3}
nearest galaxy	2.1 x 10^{19}	1.4 x 10^{11}	2.2 x 10^{6} ly	6.8 x 10^{5}
furthest we can see	1.2 x 10^{23}	8.0 x 10^{14}	1.3 x 10^{10} ly	3.8 x 10^{9}

fig.6 Some example distances in alternative units; kilometers, astronomical units, light-years and parsecs. Note the vast range of distances favors different practical units. Parsec distances over 1,000 pc cannot be measured in the classical way from two observations.

Limits of Perception

In the UK, if I had known how many clear nights there would be in the year, I would have taken up fishing.

The chance of success from a night's imaging improves with a little planning. Before committing to hours of exposure and precious clear skies, it pays to consider a few preliminaries, the most basic of which is frame size. The combination of telescope and camera should give the object the right emphasis within the frame. There are simple calculations that give the field of view in arc minutes, which you can compare with the object's size listed in a planetarium program. I have two refractors and two field flatteners, which in combination give four different fields of view (FOV). High quality imaging takes time and the next thing is to check if there is sufficient opportunity to deliver the required imaging time. There are several considerations: the object's declination, the season, the brightness of the object over the background illumination, sky quality and in part the resolution of the optical / imaging system.

Magnitude

A number of terms loosely describe brightness in many texts, namely, luminosity, flux and magnitude. Luminosity relates to the total light energy output from a star; flux is a surface intensity, which, like an incident light reading in photography, falls off with distance. The brightness or magnitude of a star is its apparent intensity from an observed position. The magnitude of a star or galaxy in relation to the sky background and the sensitivity of the sensor are the key factors that affect the required exposure. Most planetarium programs indicate the magnitude information for any given galaxy and most stars using a simple scale. This will be its "apparent" magnitude.

Apparent Visual Magnitude

Simply put, this is the luminosity of a star as it appears to an observer on Earth. Just as with light measurements in photography, astronomical magnitudes are a logarithmic measure, which provide a convenient numerical index. Astronomy magnitudes employ a scale where an increase of one unit decreases the intensity by 2.5x, and five units by 2.5^5 or 100x. At one time, the magnitude scale definition assigned Polaris with a magnitude of +2.0 until the discovery that it was actually a variable star! The brightest star (apart from our own sun) is Sirius at -1.47 and the faintest object observable from the Hubble Space Telescope is about +31, or about 2.4×10^{13} dimmer.

A mathematical simplification arises from using logarithmic figures; adding the logarithms of two values ***a*** and ***b*** is identical to the log of (***a*** x ***b***). This is the principle behind a slide-rule (for the younger readers, as seen in the movie *Apollo 13* when they calculate its emergency re-entry). In astronomy, any pair of similarly sized objects with a similar difference in magnitude value have the same brightness ratio. Similarly, if the magnitude limit for visual observation is magnitude 4 and a telescope boosts that by a factor, expressed in magnitude terms, say 5, the new magnitude limit is 9. A visually large object, such as a galaxy, will not appear as intense as a star of the same magnitude, as the same light output is spread over a larger field of view.

The table in fig.1 sets out the apparent magnitude scale and some example objects with the number of stars that reach that magnitude. At the same time, it indicates the limitations imposed by the sensitivity of the human eye under typical light pollution as well as the exponential number of stars at lower magnitudes. Further down the table, at the lowest magnitudes, the practical benefit of using a telescope for visual use can be seen, and that improves even further when a modest exposure onto a CCD sensor replaces the human eye. At the bottom of the table, the limit imposed by light pollution is removed by space-borne telescopes, whose sensors can see to the limits of their electronic noise.

The Advantage of Telescopes

A telescope has a light-gathering advantage over the eye, easily imagined if we think of all the light pouring into the front of a telescope compared to that of the human iris. The advantage, for a typical human eye with a pupil size of 6 mm, in units of magnitude is:

$$gain\ (magnitude) = 2.5 \cdot \log\left(\frac{aperture\ (mm)}{6}\right)^2$$

In the conditions that allow one to see magnitude 5 stars, a 6-inch (15 cm) telescope will pick out magnitude 12 stars, and with an exposure of less than 1 hour, imaged with a cooled CCD, stars 250x fainter still, at magnitude 18 in typical suburban light pollution.

visibility	apparent magnitude	# objects brighter	example / notes
human eye urban sky	-1	1	Sirius (-1.5)
	0	4	Vega
	1	15	Saturn (1.5)
	2	50	Jupiter (-2.9 to -1.6)
	3	<200	Andromeda Galaxy (3.4)
human eye dark sky	4	500	Orion Nebula (M42)
	5	1,600	Uranus (5.5-6.0)
	6	4,800	Eagle Nebula (M16)
binoculars with 50-mm aperture	7	14,000	Bode's Nebula (M81)
	8	42,000	Crab Nebula (M1)
	9	121,000	M43 Nebula in Orion
typical visual 8-cm aperture	10	340,000	NGC4244 Galaxy
	11	-	Little dumbbell (M76)
typical visual 15-cm aperture	12	-	beyond Messier Catalog
	13	-	Quasar 3C 273
typical visual 30-cm aperture	14	-	Galaxy PGC 21789 nr. Pollux
	15	20,000,000	IC 4617 Galaxy nr. M13
10-cm refractor, CCD 10x 30 seconds suburban sky	16	-	faint star in image with simple stacking, about 20,000 times more sensitive than by eye alone
10-cm refractor, CCD 10x 300 seconds suburban sky	18	-	faint star in image with simple stacking, about 1,000,000 times more sensitive than by eye alone
suburban sky	20	-	typical background magnitude in suburb
Hubble Space Telescope	31	-	galaxies 13.3 billion light-years distant

fig.1 This table highlights the limits of perception for the aided and unaided eye over a range of conditions and indicates the number of objects within that range. The advantage of CCD imaging over an exposure of 5–50 minutes is overwhelming. For Earth-based imaging, the general sky background and noise, indicated by the shading, will eventually obscure faint signals, from about magnitude 18 in suburban areas. The Hubble Space Telescope operates outside our atmosphere and air pollution, and at its limit can detect magnitude 31 objects. Its sensitivity is approximately 150,000 times better than an amateur setup.
It is important to note that magnitude, when applied to a large object, such as a nebula or galaxy, applies to the total amount of light being emitted. Two galaxies of the same magnitude but different sizes will have different intensities and will require a different exposure to have equal pixel values.

Absolute Magnitude

This is a measure of an object's intrinsic electromagnetic brightness and when evaluated in the visual wavelength range is termed absolute visual magnitude. Photographers are aware that the intensity of a light source reduces with distance, for instance the light intensity from a flashgun obeys the inverse-square law (for each doubling of distance, the light reduces by 4x). This same is true of cosmic light sources. Absolute magnitude is similar to apparent magnitude when measured from a fixed distance of 10 parsecs. (Since meteors and asteroids are very dim, compared to the nuclear furnace in a star, they use a magnitude definition set at 100 km and 1 AU distance respectively.) Absolute magnitude is of most interest to scientists, especially in the computation of an object's distance. For astrophotographers, the apparent magnitude from Earth is more useful, and for amateur supernova hunting, significant changes in a star's magnitude, compared to the star's standard photometry, indicate a possible discovery.

Optics

Advertising and consumer pressure tempt us to over-indulge in telescopes purchases for astrophotography. There are many optical and physical properties that distinguish a "good" telescope from a "bad" one, and just like with any other pursuit, knowing what is important is the key to making the correct purchasing decision. In the case of resolution, the certainty of an optical performance, backed up by physical equations, is a beguiling one for an engineer and I have to frequently remind myself that these are only reached under perfect atmospheric conditions (which I have yet to encounter). The needs of the visual observer and astrophotographer are different too since the human eye has a higher resolution than a conventional sensor (though with less sensitivity). Expensive apochromatic refractors focus all wavelengths of light at the same point, a quality valued by visual users or those imaging with a color camera. It has less significance if separately focused exposures are taken through narrowband or individual red, green or blue filters and combined during image processing.

Astrophotography has similarities to any other kind of photography; the final image quality has many factors and the overall performance is a combination of all the degradations in the imaging chain. It is easy to misinterpret the image and blame the optics for any defects. Long before digital cameras were popular, the premium optics, from companies such as Leica and Carl Zeiss, had more resolution than could be recorded on fine grain film. If a lens and a film independently have a resolution of 200 line pairs per millimeter (lp/mm), the system resolution is closer to 140 lp/mm. At the advent of digital photography, it was not uncommon to find self-proclaimed experts conducting a lens test using a digital body with a sensor resolution of just 50 lp/mm, half that of a typical monochrome film! It was amusing and annoying at the same time. The sensor plays a pivotal role in the final resolution achievable in astrophotography (just how much we discuss later on).

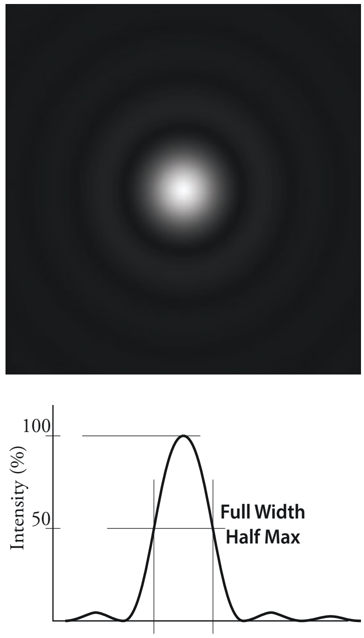

fig.2 This shows a simulated diffraction-limited star image and a profile of its intensity. The measure FWHM, which can be an angular measure, or a dimension on an image or sensor is read at a point where the image intensity is 50% of the peak.

Resolution?

In photography, many amateurs and not a few professionals confuse resolution and sharpness. They are not completely unrelated, but in an image they convey very different visual attributes. In simple terms, resolution is the ability to discern two close objects as separate entities. Photographic resolution tests often use alternate black and white lines in various sizes and orientations and astronomers use, not surprisingly, points of light. The common lp/mm resolution measure used in photography does not relate well to celestial object separations defined by angles. For that reason astronomers quote angular resolution, quoted in arc seconds or radians.

Post-exposure image manipulation cannot restore lost image resolution, but image sharpness can be increased later on using photo software. (Mild sharpening of an image may improve the actual perceived resolution of some coarser image details but often at the same time bludgeons delicate detail.) Image sharpness has no agreed measure but is our perception of contrast between adjacent light and dark areas, especially in the transition area.

The following example illustrates the difference between resolution and sharpness: On my journey into work, there is a string of electric pylons and power lines across the horizon. In the distance, I can clearly see the lines slung between the pylons arms and each line appears “sharp” in the clear morning air. As I draw closer, my eyes resolve these lines as pairs of electrical conductors, several inches apart; that is resolution.

This is also a useful analogy for astrophotography; in many images the stars appear randomly sprinkled throughout an image with plenty of space between them and like the power lines on the horizon, we do not necessarily require a high resolution to see them, only contrast. Continuing with the analogy, we do not require a high resolution to appreciate the clouds behind the pylons and in the same sense images of nebulae and galaxies have indistinct object boundaries, in addition to which, many popular nebulae span a wide angle and do not require a high optical magnification or resolution. In these cases, not only is the seeing and optical resolution often better than the resolution of the sensor, but also the long exposure times required for dim deep sky objects often over-expose foreground stars, which bloat from light scatter along the optical path, destroying optical resolution. On the other hand, a high angular resolution is required to distinguish individual stars in globular clusters and double stars.

> Many optical equations use radians for angular measure. They have the property that for very small angles, the sin or tan of that angle is the same as the angle expressed in radians. This provides a handy method to simplify formulae for practical use. There are 2π radians in 360 degrees and as most of us are more familiar using degrees, nanometers and millimeters, rather than radians and meters, you will encounter, in more convenient equations, the numbers 206 in varying powers of 10 to convert angular resolution into arc seconds.

Resolution, Diffraction Limits and FWHM

Although a star is a finite object, it is so distant that it should focus to an infinitely small spot in an image. Due to diffraction and even with perfect optics, it appears as a diffuse blob with pale circular bands. The brightest part of the blob is at its center and a measure of its blobbiness is its diameter at which its intensity is half its peak value (fig.2). This defines the Full Width Half Maximum, or FWHM for short, and is often an information call-out within most image capture and focusing programs. (Most focus algorithms assume the optimum focus occurs when a star's FWHM (or a related measure, Half Flux Diameter) is at a minimum.) The minimum FWHM (in radians) of a point image is dependent upon the wavelength λ and aperture D by the equation:

$$FWHM = 1.03 \cdot \frac{\lambda}{D}$$

The same physics of light diffraction limits our ability to distinguish neighboring stars and is similarly dependent upon the aperture and wavelength. The theoretical resolution determined by Lord Rayleigh, referred to as the Rayleigh Criterion, is shown below, for resolving two close objects, in radians, through a circular aperture D and wavelength λ:

$$resolution(radians) = 1.22 \cdot \frac{\lambda}{D}$$

Conveniently, both the FWHM and Rayleigh Criterion have very similar values and can be treated as one and the same in practical calculations.

Either equation can be made more convenient by expressing the angular resolution in arc seconds:

$$resolution = 0.251 \cdot \frac{\lambda(nm)}{D(mm)}$$

The interesting feature of these equations is the resolution improves with aperture, and significantly, is irrespective of the focal length or magnification. The simulated image sequence in fig.3 shows two equal intensity stars at different degrees of separation. The point at which the two blobs are distinguished occurs when the peaks are at the Rayleigh Criterion distance or approximately one FWHM distance apart. These equations work for a simple refractor; those telescopes with central obstructions have more diffraction for the same aperture.

Astronomical Seeing

Astronomical seeing is an empirical measure of the optical stability of our atmosphere. Turbulence causes rapid (~10–30 ms), localized changes in air density and parallel beams are deviated through refraction.

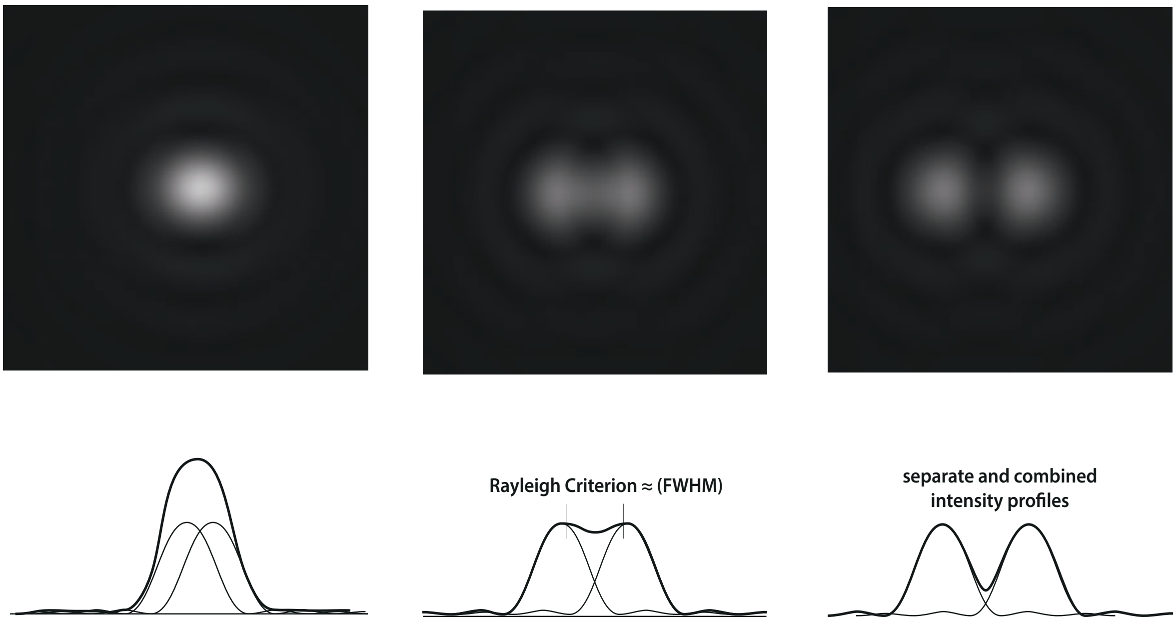

fig.3 These three simulated illustrations show diffraction-limited images from two identical stars at different angular separations. The profiles underneath show the separate and combined image intensities. The image on the left has the two stars separated by half the FWHM distance and although it is oblong, the two stars are not distinguishable. The middle image, at the Rayleigh Criterion separation, shows a clear distinction and exhibits a small dip in central intensity. This separation is just a little larger than the FWHM width of a single star. The right-hand image shows clear separation at a distance of 1.5 FWHMs apart.

Astronomers look through about 20 miles of atmosphere (looking straight up) and double that, closer to the horizon. Turbulence makes stars shimmer or blur when viewed through a telescope. At any one time the light beams pass through adjacent small air pockets (a few centimeters across) with different refractive indices. This occurs mostly in the denser air near the ground or from tiny convection currents within the telescope tube. At high magnifications, typical with planetary imaging, the individual video frames jump about the screen, some are badly blurred and others remarkably sharp. When the light path has a consistent refractive index, a frame is sharp and when it is variable, blurred. During longer exposures, the photons from these sharp, blurred and displaced images accumulate onto the sensor, creating a smeared star image. Seeing affects angular resolution and it is measured in the same units (arc seconds). Astronomical forecasts of seeing conditions around the Earth are available from websites, some examples of which are shown in figs. 4 and 5 opposite. Others include "metcheck" and various applications for mobile devices such as Scope Nights. Humidity and pressure readouts from portable devices also help to predict atmospheric transparency and mist.

For a prime site, a seeing condition of 0.5 arc seconds is possible but values in the range of 1.5–3.5 are more typical for most of us. More often than not, the prevailing seeing conditions will limit the resolution for any given telescope. The table in fig.6 shows the theoretical limits of visible light resolution for several common amateur telescope sizes in relation to typical seeing conditions. It is quite sobering to realize the limitation imposed by typical seeing conditions through the atmosphere is equivalent to a telescope with an aperture in the region of 3 inches (75 mm).

Seeing conditions are particularly sensitive to perturbations in the dense atmosphere closest to Earth, and generally improve with altitude and proximity to large expanses of water (due to the moderating effect on thermal generation). The mountain observatories in Hawaii and the Canary Islands are good examples of prime locations. Seeing conditions also change with the season and the amount of daytime heating. The local site has an immediate bearing too; it is better to image in a cool open field than over an expanse of concrete that has received a day's sunshine. Astronomers choose remote sites not to be anti-social; they just need to find high altitude, clear skies, low light pollution and low air turbulence. Knowing and predicting the prevailing conditions is a key part of our day-to-day activity. In some countries especially, each opportunity is a precious one.

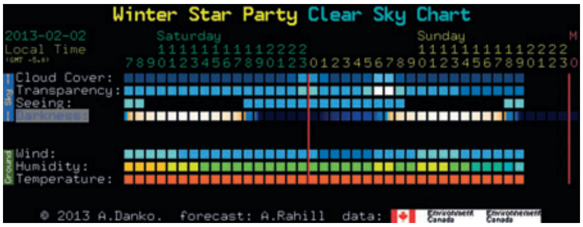

fig.4 This screen capture is of a typical clear sky chart for a site in North America. It is available from www.cleardarksky.com

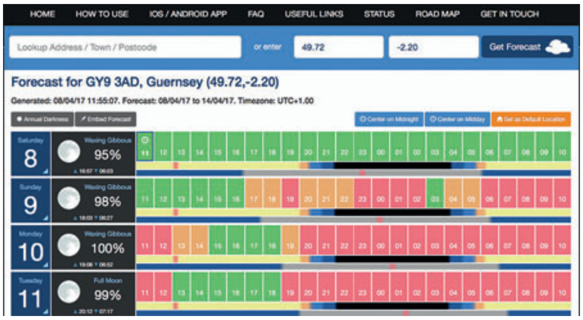

fig.5 Another forecast site, this time from First Light Optics

Other Atmospheric Effects

We become increasingly aware of light pollution as soon as we take up astronomy. As we have seen earlier, light pollution masks the faint stars and nebula. This light is scattered back from atmospheric aerosols, dust and water vapor and places a (typically) orange-yellow fog over proceedings. A full moon too has a surprisingly strong effect on light pollution and puts a damper on things. After it has been raining, the air is often much cleaner and the effects of light pollution are slightly reduced due to better atmospheric transparency. Atmospheric transparency can be forecast and is included in the readouts in figs. 4 and 5 along with dew point, moon-phase, humidity and wind.

Why then do so many sources recommend buying the largest affordable aperture and that "aperture is king"? Larger apertures technically have the potential for better resolution, but above all, capture more light. For visual use, the extra aperture is the difference between seeing a dim galaxy or not. For imagers, the extra light intensity delivers an opportunity for shorter exposure times or more light captured over a fixed period, which reaps benefits in sleep deprivation and lower image noise.

Not all telescope designs are equal; there are some subtle differences between the optical performance of the various telescope architectures; the more complex have additional losses in transmission, reflection and diffraction at each optical boundary. Of the telescope designs, for any given aperture, refractors are the simplest optically and have the highest image contrast, followed

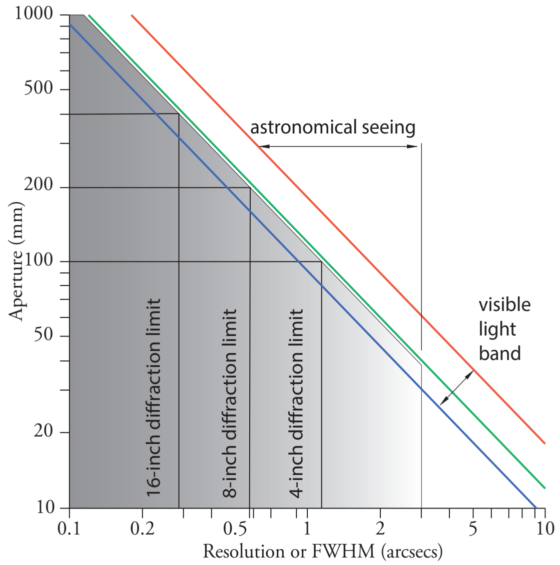

fig.6 The chart above indicates the diffraction-limited resolution for visible light, in arc seconds, for any given aperture in relation to the limits imposed by typical seeing conditions.

by Newtonian reflectors and then folded designs which, for the moment, we will collectively call Schmidt-Cassegrain's or SCTs. On top of the limitations of the optical path, vibration, flexure, focus shifts, tracking accuracy and atmospheric effects contribute to the blurring of the eventual star image. If it was going to be easy, it would not be nearly as rewarding or half as much fun!

Imaging Resolution

The term sensor describes the light sensitive device that resides in a camera. Digital sensors are quite complex and they have their own chapter. For now, a single light-sensitive element on the sensor, or photosite, corresponds to a pixel in the image. It converts photons into an electrical signal. This signal is amplified, sampled and stored as a digital value. An imaging sensor has a grid of photosites of fixed pitch, typically in the range of 4–7 microns. The photosites simply accumulate electrons, triggered by incident photons and largely irrespective of wavelength. To make a color "pixel" requires a combination of exposures taken through red, green and blue filters. This can either be achieved from separate exposures taken through a large filter placed in front of the entire sensor or a single exposure through a color filter mosaic fixed over the sensor (Bayer array). Astrophotographers use both approaches, each with benefits and drawbacks and these are discussed later on.

The pitch of the photosite grid has a bearing upon image resolution. Up to now, the discussion has revolved around angular resolution. To consider the physical relationship between angular and linear resolution on an imaging sensor we need to take account of the focal length f_L of the optics.

The angle subtended by 1 pixel (arc seconds per pixel) is given by the following simplified equation from basic trigonometry (f_L in mm):

$$arcsecs/pixel = 206 \cdot \frac{pixelspacing(microns)}{f_L}$$

Classical (Nyquist) sampling theorems might suggest two pixels are required to resolve a pair of stars but experts settle on a number closer to 3.3 adjacent pixels to guarantee the resolution of two points. (Stars do not always align themselves conveniently with the sensor grid and must consider all angles. The pixel spacing on the diagonal is 40% larger than the grid axis.) The angular resolution of a CCD is 3.3x its arc second/pixel value and changes with the focal length of the optics.

It is interesting to compare this to the diffraction limit and calculate the equivalent pixel pitch for the same resolution:

$$3.3 \cdot 206 \cdot \frac{pixelspacing}{f_L} = 0.251 \cdot \frac{\lambda}{D}$$

This simplifies, assuming green light to:

$$pixelspacing(microns) = 0.18 \cdot \frac{f_L}{D}$$

In the case of my refractor, it has a measured focal length of 924 mm and an aperture of 132 mm and I use it with a sensor with a pixel pitch of 5.4 microns. The telescope has a diffraction-limited resolution (x) of approximately 1.0 arc second, but the sensor's resolution (y) is 4.0 arc seconds. For the CCD to match the diffraction-limited performance of the optics, it would require a smaller pitch of 1.4 microns. That might look quite damning but there is another consideration, the effect of astronomical seeing: The CCD resolution of 4.0 arc seconds is only marginally worse than typical seeing conditions (z) of say 3.0 arc seconds in a suburban setting. The system resolution is a combination of all the above and defined by its quadratic sum:

$$\sqrt{\left(x^2+y^2+z^2\right)} = 5.1 \text{ arcsecs}$$

The system resolution is a combination of the individual values and is always less than the weakest link in the imaging chain. This resolution is further degraded by star tracking issues too, which can be significant during unguided exposures. (Guided exposures in a well adjusted system typically have less than one arc second of error.)

To sum up, in this typical setup, the telescope's optical diffraction has little influence on the final resolution and more surprisingly, the CCD is the weakest link. The seeing and CCD resolution are similar though, and while sensors with a finer pitch can be used (albeit with other issues), in astrophotography the most difficult thing to change is one's environment. All these factors are weighed up in the balance between resolution, image requirements, field of view, signal strength, cost and portability. The conventional wisdom is to have a CCD whose arc seconds/pixel value is about 1/3rd of the limiting conditions; either the seeing condition or the diffraction limit (normally on smaller scopes).

Dynamic Range

In the early days of digital imaging, many wedding photographers preferred the results from color negative film as it captured a larger brightness range than a digital camera. In effect, what they were saying was that film could distinguish a higher ratio of light levels between highlights and shadows. Comparing analog and digital systems, however, is not easy; there is more at play here than just the difference in light levels; there is tonal resolution too, and this is where film and digital sensors are very different.

Astrophotography is particularly demanding on the dynamic range of a sensor. In any one image, there may be bright stars, very dim clouds of ionized gas and somewhere in the middle, brighter regions in the core of a galaxy or nebula. The Orion Nebula is one such subject that exceeds the abilities of most sensors. Extensive manipulation is required to boost the dim clouds, maintain good contrast in the mid range and at the same time emphasize the star color without brightening them into white blobs. For this to be a success, the original image data needs to not only record the bright stars without clipping but also to capture the dim elements with sufficient tonal resolution so that they both can withstand subsequent image manipulation without degradation.

In one respect, the dynamic range of a sensor is a simple measure of ratio of the largest signal to the lowest, expressed either as a ratio or in decibels (dB) calculated by:

$$dB = 20 \cdot \log(\text{light ratio})$$

In photography, dynamic range is related to bit depth, which is measured by the number of binary digits output from the sensor's analog to digital converter (ADC). A 16-bit ADC has 2^{16} voltage levels, over 65,000:1. In practice, this is not the whole story: Firstly, many sensors require less than one electron to change the output value and then there is image noise. The other fly in the ointment is that sensors are linear devices and we are accustomed to working in logarithmic units; in a digital image, there are fewer signal levels per magnitude at the dark end than at the bright end of the exposure scale.

Full Well Capacity, Bit Depth and Noise

Just as with system resolution, there is more to dynamic range than one single measure. First there is bit depth: Consumer cameras record JPEG files and these are made with three 8-bit values each for red, green and blue. That is just 256 levels per color channel, even though the sensor may have more detailed information, typically 16–32x better. Color fidelity in astrophotography is not a primary concern, but low color noise and fine tonal resolution in the shadow areas are essential qualities in the original downloaded file. Image capture programs obtain the maximum bit depth possible from the sensor, similar to the RAW file formats found on advanced digital cameras. For example, the Kodak KAF8300M monochrome sensor has a 16-bit readout and one might assume that it has 65,000 output levels. There is a snag; this sensor only requires 25,000 electrons to saturate (max-out) a photosite. In reality, it has 25,000 states, equivalent to just over 14-bit. This number of electrons is known as the Full Well Capacity and varies between sensor models. This is not the end of the story; random electrons introduced during the sensor readout process further reduce the effective dynamic range. This concept is a little difficult to appreciate but noise affects a sensor's dynamic range and set a minimum exposure requirement.

The previous formula sets the effective dynamic range. In the case of the KAF8300M sensor, the read noise is typically 7 electrons, yielding a dynamic range of 3,570:1 or about 12-bit. The 16-bit ADC in the sensor has sufficient resolution above the signal resolution to ensure that it does not introduce sampling noise, which is of more concern in high-quality audio reproduction.

We also need to go back and consider the linear nature of imaging sensors: Starting at a data level of 1, successive doubling of light intensity (think aperture stops on a camera lens) produce pixel values in the sequence 1, 2, 4, 8, 16, 32, 128, 256, 512 and so on. At the dark end, there are no intermediate values and the tonal resolution is 1 stop. At the other extreme, there are 256 values between 256 and 512 giving a tonal resolution of 1/256 stop. Fortunately in conventional photography the human eye can discriminate smaller density changes in print highlights than it can in shadow areas, by a factor of about 5x and thankfully the highlights are the key to any photograph.

The challenge of astrophotography is that much of the interesting information is not only invisible to the visual observer but has to be boosted out of the shadows through intense image manipulation. The astrophotographer needs all the tonal resolution they can muster in the shadow regions. The numbers tell a worrying story too: How can smooth images be stretched out of a signal with only 3,570 data levels? The answer is that it is highly unlikely from a single image exposure. We are jumping ahead of ourselves a little but it is good to know that the astrophotographer has two ways to significantly improve the dynamic range of an image. We will discuss again in more detail later on but for now, here is a preview.

fig.7 This enlarged section of a single CCD sensor bias frame shows the read noise from the sensor. It has a standard deviation of 22, that is 68% of all values are in the range of ±22. Each electron is 2.6 units, so the read noise is 8.5 electrons.

fig.8 This enlarged section of the average of 50 CCD sensor bias frames shows the read noise from the sensor. It has much less randomness and has a standard deviation of 4, a little higher than the predicted value of 3.1 due to other artefacts.

Improving Dynamic Range

The wonderful thing about noise is that it is mostly random. If you flip a coin enough times, the number of heads or tails will be about the same. The same is true with astrophotography. If an image pixel wants to be 1,001.67 units, successive exposures from the sensor will be either 1,001 or 1,002 in the main or occasionally numbers further out, due to noise. Assuming an even noise distribution, the values of 1,002 or higher will occur twice as often as the value 1,001 or lower in subsequent exposures. If many (aligned) images have their pixel values averaged, the math can achieve an intermediate level, close to the true noiseless value.

With an increasing number of averaged exposures of the same subject, the random noise in the image is reduced and the Signal to Noise Ratio (SNR) is improved by:

$$factor = \sqrt{no\ of\ samples}$$

For example, if 10 samples are taken with the KAF8300M sensor, the read noise is reduced to about 2.2 electrons and the dynamic range is closer to 25,000 / 2.2 = 11363:1 (equivalent to a bit depth between 13 and 14-bit).

It is standard practice to combine (integrate / stack) multiple images to improve the image SNR, to boost shadow resolution (and noise) to enhance faint nebulosity and extend galaxy perimeters as well as remove one-off events such as cosmic rays and plane trails.

The second trick is to cheat! For those of you who are familiar with advanced digital photography, you will likely know that a subject with a high dynamic range can be captured by combining long and short exposures of the same scene that have been individually optimized for their shadow and highlight regions. Photographers can use a fancy Photoshop plug-in to combine them but I'm not a fan of its unnatural smudgy ethereal look. In astrophotography, however, it is considerably easier to disguise the boundaries since there are fewer bright mid-tones in an image.

In practice, a simple combination of optimized exposure sequences for bright stars, bright nebulosity and dim nebulosity will improve the dynamic range of an image. The grouped images are aligned and averaged and then the (three) stacked images are aligned and selectively combined, for instance using Photoshop. Here, each image is assigned to a layer and each is blended using a mask generated from inverted image data. The result is a photo-fit of bright stars, bright nebulosity and dim nebulosity with a dynamic range many times greater than the imaging sensor. The masks are tuned to ensure smooth transitions between the image data in the three layers. This trick is not always required but there are a few objects, the Orion Nebula being one, where it is a helpful technique to capture the entirety of its huge brightness range with finesse. Using a combination of exposure lengths, the dynamic range is extended by the ratio of the longest and shortest time, as much as 100x or about 5 magnitudes. The same is true for imaging the enormous Andromeda Galaxy (M31), although less obvious. The core of the galaxy saturates a CCD sensor in under 2 minutes but the faint outer margins require 10 minutes or longer to bring out the details. (The processing details for M31 appear in one of the first light assignment chapters.)

Choosing Equipment

NGC 7635 (C11) or Bubble Nebula using narrowband filters (Hubble palette)

The Ingredients of Success

Some practical considerations to steer one through the maze of options. After all, success breeds success.

When I was planning the chapters on equipment selection, I wondered how to go about it in a logical way. In my case, I started off by buying an entire used outfit and basically played with it. Over time I worked out what to keep, upgrade, change or modify. Looking back, I might have rationalized the essential requirements for astrophotography and then made more sense of the overwhelming equipment choice. It is very easy to deviate into exciting details and lose sight of the bigger picture. What follows is a mixture of practical considerations and more technical qualities that you look for when you choose and setup equipment. The themes noted here resonate through later chapters and become a guiding influence on system setup. Some of these terms may be unfamiliar at present but will be explained later. These requirements broadly group into three areas: planning, equipment and imaging essentials.

Planning

- Location
- Safety
- Power
- Comfort
- Weather and Planning
- Timing

Equipment

- Familiarity
- Mechanical Integrity and Stability
- Tracking and Alignment
- Autoguiding
- Dew control
- Focus and Focusers
- Essential Software

Imaging Essentials

- Cleanliness
- Sensor Size
- Pixel Size
- Sensitivity
- Image Noise Reduction
- Calibration
- Optical Correction
- Setting Up and Note Taking

Planning

Location

An early decision is whether or not to have a permanent installation; assemble a portable setup in the back yard each time or to travel to a dark site for your photography. Light pollution and the typical atmospheric conditions for a general location set the upper performance limit for astrophotography. Dark sites offer the best conditions but one must be willing, ready and able to set up at a remote dark site each time the weather looks good. On the other hand, the convenience of a back yard beckons, but with the possibility of greater light pollution, an interrupted horizon and the neighbor's insecurity lights. Early enthusiasm can wane and although we might start off with good intentions, the practicalities and effort of remote site operation may be worthwhile for just a few guaranteed prolonged imaging runs in fantastic conditions or in a social context. In my case, I have a worthy dark site about 20 miles away on the coast, with low light pollution and a convenient grassy car park, set in the marshlands of east Essex, but I have not tried it.

Most of us would love the turn-key convenience of a permanent observatory but cannot justify the cost or eyesore, especially if the weather limits its use. With a little practice it is possible to deploy a portable setup and be imaging within an hour. If a shower takes you by surprise, a large waterproof cover can be thrown over in seconds and at the same time permit a setup to remain for a few days. The installation decision influences the equipment choice, since telescopes, mounts, counterweights and tripods are neither light or small. After all, a portable setup needs to be just that, portable, and it is surprising just how quickly the repeated assembly of a large articulated mass in cold dark damp conditions can reduce the appeal of this hobby! For example, my first acquisition was a used 8-inch Meade LX200 SCT, weighing in total at around 43 kg. The previous owner had bought it for his retirement but quickly changed to a lighter telescope. It is not just a case of lifting a large weight; equipment requires transport, carrying and assembly, often in the dark, without tripping, damage or injury. The box for the LX200 head filled the back of my car on its own. The same story plays out in the many adverts for large,

fig.1 This 8-inch Meade LX200 telescope with an equatorial wedge is a handful for a portable setup; the equivalent 10- and 12-inch versions weigh considerably more and are better suited for a permanent installation.

used telescopes. In a permanent setting however, larger and heavier mounts, scopes and installations are a one-time problem. These systems remain fully assembled and the cables routed permanently so that remote operation is safe and feasible. In a portable setup, the needs are different: There will be trade-offs in weight and rigidity and all the mechanical and electronic components must endure repeated assembly without failure or damage. In these situations, refractor telescopes are certainly more compact and robust during transport and do not require alignment before use.

Safety

It goes without saying to “be safe” but I’m compelled to highlight a few things on personal safety. The conditions and the remote locations that astrophotography encourage can create some unique situations. Clearly lighting is essential; a powerful torch and a wind-up spare, in case the batteries fail. You may also have to consider personal security in a remote location; although mobile phones are commonplace, there may be no signal at the site and someone should know where you are. Increasingly, there is also the subject of physical safety and the best practice of lifting and moving large heavy pieces of equipment (in the dark). Those vehicles with a flat load-space (like a van or wagon) are particularly back-friendly since they allow heavy objects to be slid in and out without lifting with a bent back. Capped boots are a sensible precaution too; a dewy counterweight once slipped through my fingers and missed my sandaled feet by a few inches.

Power

Power has its own safety considerations. Most astronomy equipment requires 12–14 volts DC, but some devices, like USB hubs, only require 5, for which I use an encapsulated 12 to 5 volt DC converter. (A few mounts also use 24 or 48 volts.) Lead-acid cells are the most common source for mobile DC power. They conveniently store a high capacity (measured in amp-hours) but this lowers after each discharge/charge cycle, an effect which accelerates with the level of discharge. There are several lead-acid battery designs; those ones for hobby-use are best; they are designed to be more tolerant of deep discharge, whereas car battery versions are optimized to deliver bursts of high current but quickly lose charge capacity after repeated cycling. Gel-filled batteries or AGM designs are maintenance free and do not need to be kept upright. Large capacity lithium-ion batteries, up to about 24 Ah are also available, but at premium prices. These are considerably lighter and smaller than the lead acid versions.

Power supply quality is important too and the DC supply to a CCD camera should have as little electrical noise as possible. A simple solution is to use two batteries; one for the imaging and guiding cameras and the other for the “noisy” motor and switching functions such as dew heaters, focus control and the telescope mount. Battery charging is a potentially hazardous activity. Dead or damaged batteries should not be used but properly recycled. Modern batteries require a little care to prolong life and capacity. Some do not like over-charging or being charged too quickly. If in doubt, check the recommendations for charging and use the recommended charger.

For a domestic site, mains power is also an option but only with care: Any mains extension cable run out through the back yard or buried in the back yard should not only be armored to protect from accidental rupture but employ an earth leakage current breaker (ELCB) at the power source. Just as significantly, many regulated DC power supplies, including some that are supplied by mount OEMs, are designed for indoor use only. Dew and general dampness go hand-in-hand with astronomy and there is an obvious risk of electrocution or failure with

fig.2 *The combination of frugal power management settings in the MacBook Pro with an external lithium-ion battery is sufficient for a full night's imaging. The orange plastic armor and keyboard cover add some protection against knocks and dew.*

some models. One alternative is to place the power supply in the house or in a suitable enclosure and use a length of heavy-duty speaker cable to carry DC, with minimal loss, to the telescope. The same safety considerations apply to domestic plug-in-the-wall power adaptors and desktop computers sited in outdoor situations. They need protection from moisture and should be appropriately earthed. Spare mains sockets should be kept away from moisture and fitted with a plastic child safety cover for good measure. If there is any doubt, ask a qualified electrician to check over your installation. The only stars you should be seeing are those through the telescope!

In a portable setup, the laptop is the computer of choice, preferably with a battery life in excess of 5 hours. Aggressive power saving settings are great but remember to turn off the sleep-mode or your imaging run could unexpectedly terminate! Some models have hot-swappable batteries but most are internal. An alternative is to use a reserve high capacity lithium-ion battery. These have a programmable output voltage and are supplied with multiple adaptors to suit the most popular laptops. A third option is to use an inverter. These convert 12 volt DC into AC mains, which then supplies the laptop's power adaptor. As before, check the models are safe for outdoor operation. Lastly, some power supplies are floating and to avoid potential static discharges, connect all the equipment together before powering up.

Comfort

Astrophotography is physically demanding, especially in cold conditions. The manual exertion during the setup may keep you warm but the body cools down with the extended inactivity during image-capture. It's the same with hill walking; you need to layer up when you stop exerting yourself. When I'm watching the exposures roll in I add a few layers and put on a ridiculous hat, gloves and warm boots. Over extended imaging times, food, drink and diversion are essential. I use an iPod rather than the vehicle radio or mobile phone to preserve the important batteries. A number of laptops and tablets have touch sensitive controls and will not work with conventional gloves. If you look around, gloves are now available with conductive fingertips. Extreme cold does have one advantage though; it keeps the insects at bay.

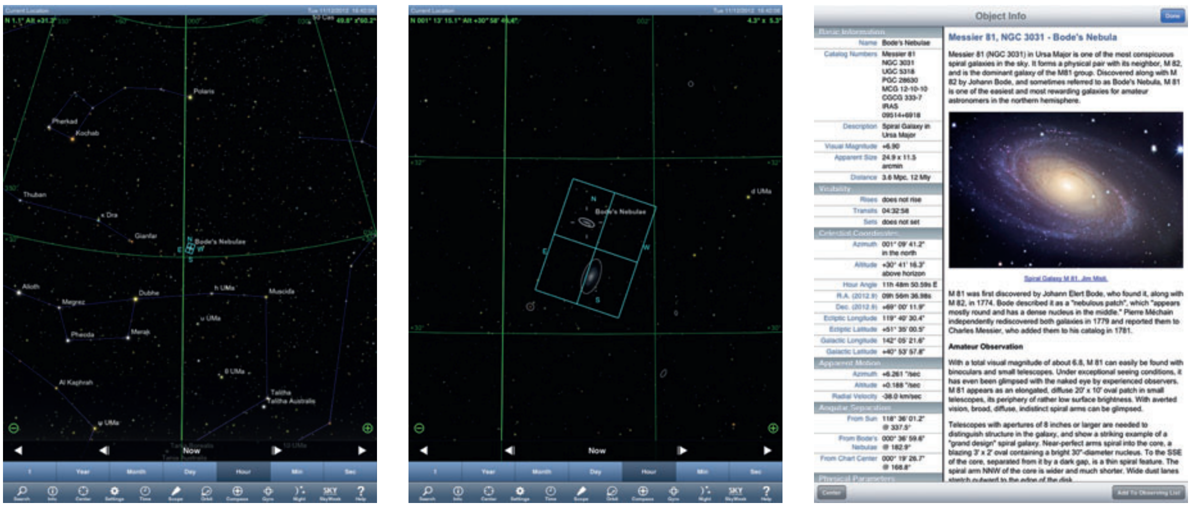

fig.3 *This SkySafari® application on an iPad® can plan a night's imaging, from left to right, determining when the object will cross the meridian, checking the field of view for the telescope and sensor combination and essential object information, including magnitude.*

Insects like astronomers, so mosquito repellent and bite cream are a few more essentials to keep in mind.

Weather and Planning

It happens to all of us: The cloud is unbroken and each weather front merges into an unending overcast month and you have almost come to the point of giving up astronomy. Then, one evening, surprise, it is clear. We suddenly have an opportunity for imaging ... of what exactly? Meteorology is not an exact science but weather systems are predictable to some extent (even in the UK). It is possible to recognize cloud sequences from cold and warm fronts and the characteristics associated with areas of high pressure. A little knowledge of clouds certainly comes in handy; for instance, small cumulus clouds in the evening generated by thermals are more likely to disperse than high cirrus clouds signalling a warm front. The on-line weather reports and those with dedicated sky forecasts are a useful resource to anticipate clear skies in the next 48-hour period although the timing may be slightly out. During the day, the local cloud conditions help to realign the forecast, especially if corroborated with information from other sources, say a weather station.

Next, we have to decide what to image. Many objects, especially those at lower declinations have a preferred season when they are visible for some of the night. Ideally, they will have an altitude of about 30° in the east (for those of us in the northern hemisphere) at the start of the night, which maximizes imaging time. Those objects nearer the pole never set and those over 70° from the celestial horizon (for UK sites) are safe bets too. At a latitude of +50°, objects with a DEC between -10° to -90° will never have an altitude greater than 30° and will be a challenge to image. Planetarium programs usually have a "tonight's best" option, usually for short term visual purposes. Luckily every object's visibility is predictable and it helps to identify those objects that will be optimally positioned each month beforehand. You can make a target list with a planetarium program or an application like AstroPlanner. These identify those objects that are in a good starting position for an imaging run, for each month of the year. For example, the high declination objects or those low declination objects whose altitude is about 30° in the east at dusk. (Charles Bracken's *The Astrophotography Sky Atlas* has a comprehensive set of maps for all seasons and latitudes.) Ideally, I set up at dusk when my object's position is low on the Eastern horizon. By the time I have calibrated the mount and set the focus, it will have risen sufficiently to clear my neighbor's roof line. I also check the azimuth of the target and note if, and when, it is going to cross between east and west over the meridian (if the image acquisition system requires manual intervention). Before using Sequence Generator Pro I had to stop the exposure, flip, realign the target and restart autoguiding and the imaging sequence with the mount on the opposite side.

Timing

Imaging is not a quick fix (well, other than short planetary videos). It is really frustrating to start a promising imaging sequence only to be obliged to break off before you have enough imaging data to make a quality image. To prevent this, a quick evaluation of the likely overall exposure duration and available time helps. Image quality benefits hugely from multiple exposures (or "subs" as astrophotographers call them), the more the merrier. Dim galaxies and nebula benefit from at least 10 hours of data or more, especially

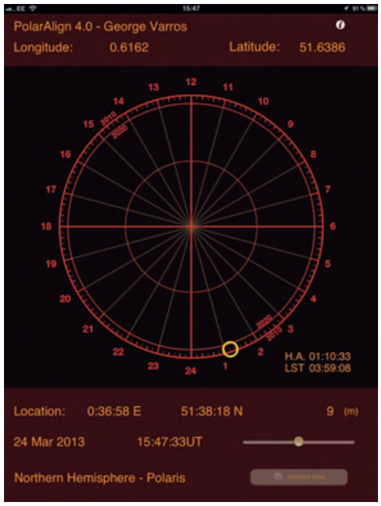

fig.4 This polar scope setting application on an iPad not only shows the position of Polaris as viewed through the eyepiece but a readout of the Hour Angle (HA) which can be quickly set directly on the mount's RA scale (after a one-time calibration).

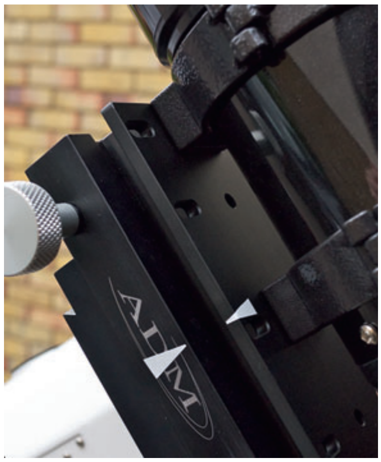

fig.5 Good planning helps with the setup too. Here, the balance point for the telescope (fully assembled and in focus) is marked on the dovetail plate with a piece of white tape and aligns with a corresponding marker for quick and easy balance setup.

when using narrowband filters. For high quality images it is normally necessary to image over several nights and combine images. Again, programs like Sequence Generator Pro are intelligent and remember what you were imaging and how far through the intended exposure plan you were when you shut down. They can start up and continue on another night with ease.

The Internet once more is a useful resource to plan exposures: An Internet search of the deep sky object often links to other's images that usefully indicate the equipment setup and exposure details, possibly with the same sensor. Some bright objects might be captured in a single night, others require perseverance over several.

Equipment

Familiarity

Equipment and software setups soon become quite complex and complete familiarity really helps with quick and reliable operation. This reduces "real-time" frustration, which often occur in portable setups or after a software update. My better half calls it "playing" but a few daylight dry-runs to practice assembly, balancing and alignment make night-time operation second nature. Some preparatory work can make this easier still; for instance, the balance points can be marked on the telescope dovetail plates for instant assembly and the polar scope reticle calibrated to the RA scale and centered during daylight. The mass of a dangling cables affect balance and tracking and loose cables may catch during slewing. I found Velcro cable-ties were an easy way to secure cables from snagging and relieve stress on the connectors. In addition, I made simple colored markers with electrical tape around each end of the many USB cables. This is a quick way of identifying which cable is which, handy for when a single device requires a power reset, without disturbing the scope-end of things.

Little things like systematic storage, say using clear and labelled plastic food storage boxes, protects small items from dew and dust and avoids rummaging in the dark. The smaller boxes can be organized into larger ones for imaging, observing and common accessories, which helps when loading up. I save the silica gel bags from various purchases and pop them in for good measure.

Understanding the software operation is essential and often underestimated: My early setup used 8 pieces of software, six of which interact (C2A, Maxim DL, FocusMax, MaxPoint, ASCOM and EQMOD) with many USB devices (camera 1, camera 2, focuser, filter wheel, GPS receiver, EQ6 Mount and a USB over Cat 6 extender). It saves a lot of time to pre-configure

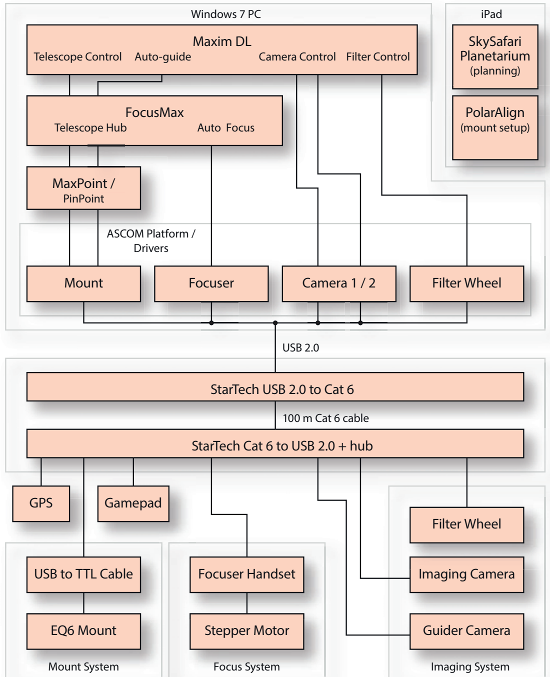

fig.6 This figure illustrates the information flow between the software applications and the hardware of my initial system. It looks more complicated than it is in practice but it does illustrate the need for preparation and familiarity with the software and hardware settings and connectivity. In this setup, the full planetarium program resides on an iPad and a simple one in Maxim DL.

each to work with the others and enter the site (time, horizon, location) and equipment data (camera type, mount type, focal length, pixel resolution, filter setup and so on) that most of these programs individually require. Even when you think everything is perfect, software can kick back; in some versions of Windows, if a USB camera plugs into a different port connector, the operating system demands the driver file is loaded again, causing unnecessary aggravation, especially at a remote site, without the CD or Internet.

I am not the first or last to waste imaging time due to poor preparation: Recently, after a SSD drive upgrade to my laptop, I failed to realize that the PC clock had changed to daylight saving, confusing my alignment and plate solving attempts for two precious clear nights. The software startup sequence can be established during a dry run and the hardware drivers checked beforehand for reliable operation on each of the different USB ports, especially after any software upgrade or update.

One simple way is to record the power-up sequence. This increases the chances that the equipment connects