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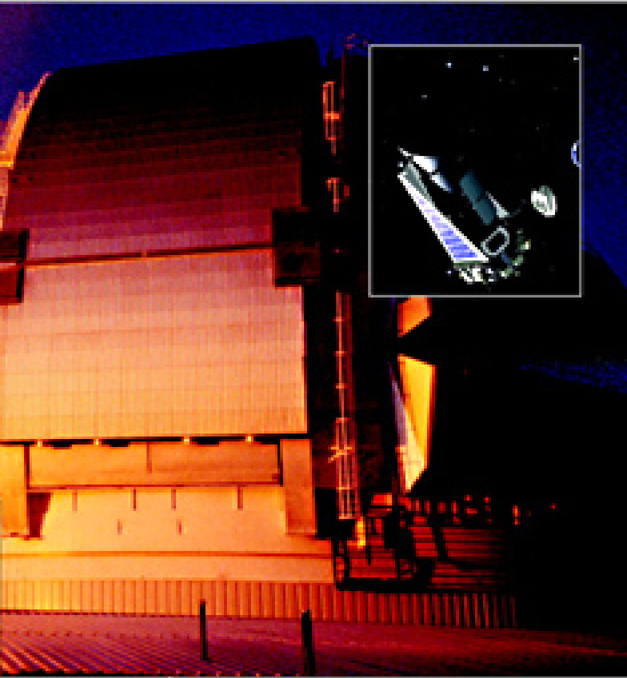
Introduction to Astronomical Photometry

Second Edition

Edwin Budding and Osman Demircan



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Introduction to Astronomical Photometry, Second Edition

Completely updated, this Second Edition gives a broad review of astronomical photometry to provide an understanding of astrophysics from a data-based perspective. It explains the underlying principles of the instruments used, and the applications and inferences derived from measurements. Each chapter has been fully revised to account for the latest developments, including the use of CCDs.

Highly illustrated, this book provides an overview and historical background of the subject before reviewing the main themes within astronomical photometry. The central chapters focus on the practical design of the instruments and methodology used. The book concludes by discussing specialized topics in stellar astronomy, concentrating on the information that can be derived from the analysis of the light curves of variable stars and close binary systems. This new edition includes numerous bibliographic notes and a glossary of terms. It is ideal for graduate students, academic researchers and advanced amateurs interested in practical and observational astronomy.

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Introduction to Astronomical Photometry

Second Edition

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CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK
Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521847117

First published in print format

ISBN-13 978-0-511-33181-7 eBook (Adobe Reader)
ISBN-10 0-511-33181-9 eBook (Adobe Reader)

ISBN-13 978-0-521-84711-7 hardback
ISBN-10 0-521-84711-7 hardback

Contents

Preface to first edition

The book which follows has grown out of my experiences in carrying out and teaching optical astronomy. Much of the practical side of this started for me when I was working with Professor M. Kitamura at what is now the National Astronomical Observatory of Japan, Mitaka, Tokyo, in the mid seventies. Having already learned something of the theoretical side of photometric data analysis and interpretation from Professor Z. Kopal in the Astronomy Department of the University of Manchester, when I later returned to that department and was asked to help with its teaching programme I started the notes which have ultimately formed at least part of the present text. I then had the pleasure of continuing with observing at the Kottamia Observatory, beneath the beautiful desert skies of Egypt, in the days of Professor A. Asaad, together with a number of good students, many of whom have since gone on to help found or join university departments of their own in different lands of the world.

In recent years – particularly since moving to Carter Observatory – another dimension has been added to my experience through my encounters with that special feature of the astronomical world: the active amateur! In previous centuries many creative scientists were, in some sense, amateurs, but in the twentieth century the tide, for fundamental research at least, has been very much in the direction of government, or other large organization, supported professionals, no doubt with very persuasive reasons.

Nevertheless, some features of contemporary life suggest that this tide is not necessarily conclusive in its effects. If there is one feature in particular, I would cite the personal computer. The range of possibilities for participation and active investigation which are now available to individuals on their home desk tops is already staggeringly large, and continues to increase, while the real costs of sophisticated electronics fall and demand grows as more people discover these potentialities for themselves.

A particular concept, which may become increasingly significant in the future development of astronomy, is that of the ‘PC-observatory’. Much of the more routine side of observational data collection can be put under the control of a personal computer. Automatic photometric telescopes (APTs), of up to half-metre aperture class, have been developed and operated by amateurs in their backyards. Data can be gathered by the tended robot, while the human designer has the freedom to ponder and relax in the way that humans are wont. I have seen this in action right here in Wellington, but do not doubt that at least similar capabilities exist in very many other places.

In the early eighties I started a correspondence with Professor M. Zeilik of the University of New Mexico, who shared my interest in the photometry and analysis of eclipsing binary systems. This later developed into exchange visits, and in the environment of Dr Zeilik’s active research and education programme, at Albuquerque and Capilla Peak, I began to appreciate more fully the momentum of the electronics revolution and its impact on optical astronomy and the propagation of information.

Enthusiasm and capabilities are thus already nascent in good measure, and against this background the appearance of a book with entry-point information, guidelines on equipment and methodology, astronomical purposes – general and specific, leading, it is hoped, towards definite new contributions in the field – seems opportune.

Introduction to Astronomical Photometry is then a textbook on astronomical photometry (essentially in the optical domain) intended for university students, research starters, advanced amateurs or others with this special interest. It avoids jumping directly into technical or formally presented information without some preparation. Each chapter is rounded off with a section of bibliographical notes. The book starts with an overview, and moves on through a historical background and glossary of terms. Then comes a chapter on the underlying physical principles of radiative flux measurement. Colour determinations and temperature and luminosity relationships are also examined here. From this base more wide-ranging questions in current astronomical photometry are approached. The central two chapters deal with principles of photometer design, including recent advances, and some common data-handling techniques for system calibration from standard star observation and the generation of light curves. The remainder of the book presents applications of photometry to selected topics of stellar astrophysics. Curve fitting techniques for various kinds of light curve from variable stars, including close binary stars, spotted and pulsating stars, are followed through. Inferences drawn from such investigations are then advanced.

There is a large number of people to whom I feel thankful for helping this book to be realized. Some of them I have mentioned already, but even if I didn't, I am sure the formative influence of Zdeněk Kopal would soon become clear to readers of the subsequent pages. Indeed, many of them were written whilst I shared his welcoming office during my sabbatical leave of 1990. Professor F. D. Kahn was principal host during my stay in Manchester, and his hospitality and that of his department helped make that year very special for me.

That period of leave, which gave me the time to collect things together, was essentially enabled through the generous support of the Carter Observatory Board, and approved by its Director, Dr R. J. Dodd, who also helped with remarks on the text. Useful comments were also provided by Dr J. Dyson (Manchester), Dr J. Hearnshaw (Christchurch) and Mr J. Priestley (Carter Observatory). Interest and encouragement were expressed by Dr M. Zeilik, and his colleagues and students at UNM, Albuquerque, with whom my leave started in 1990, by Drs B. Szeidl and K. Oláh during my August sojourn at the Konkoly Observatory (Budapest), and as well by Drs M. de Groot and C. J. Butler of the Armagh Observatory, where I similarly visited later that year.

Among the many others who I would like to acknowledge, though space unfortunately restricts, Mr T. Hewitt of the Computer Centre at Manchester University, who introduced me to the wonderful world of PCTEX, surely deserves mention. He helped this text materialize in a very real sense. I also thank John Rowcroft and Carolyn Hume for help with the diagrams.

Last, but not least, to my family and wife Patricia – thanks.

Preface to second edition

Some years ago professional colleagues suggested that a new edition of *An Introduction to Astronomical Photometry* could be useful and timely. The decision to act upon this did not come, however, until the warm and conducive summer of 2003, in the stimulative environment of north-west Anatolia, once home to great forefathers of astronomy, such as Anaxagoras and Hipparchos. The former set up his school at the surely appropriately named Lampsakos, just a few miles from where the present authors are working: the latter hailed originally from what is now the Iznik district of neighbouring Bythinia. Eudoxus too, after learning his observational astronomy in Heliopolis, moved back to Mysia to found the institute at Cyzicus (today's Kapu Dagh), while Aristotle's thoughts on the heavens must have also been developing around the time of his sojourn in the Troad, after the death of Plato. In such surroundings it is difficult to resist thinking about the brightness of the stars.

But that was just the beginning. It quickly became clear that the proposed task could not be lightly undertaken. There were at least three main questions to clarify: (1) what branches of modern astronomy can be suitably associated with photometry; (2) what level of explanation can be set against the intention of an introduction; and (3) who could become involved with what aspect of the subject? An approximate size and scope were originally based on the model of the first edition. Improvable aspects of that were known from the start; however, what was not then realized very clearly was just how much development had taken place in astronomical photometry over the last decade or so. This concerns not just the specific headings of the original text, but the growth of a large number of related new topics.

Among the striking new developments has been the increasing size and number of automated telescopes: up to the one metre class and beyond, and also the widening use of computer controlled CCD detectors, together with continued development and application of purpose-oriented filter systems.

Data accumulation has increased tremendously, while millimagnitude precision is regularly achieved in many observatories. The fantastic rise in capacity of modern data processors has allowed huge new surveys to be undertaken, with a consequent pressure for swift and effective analysis procedures based on realistic models.

As always, compromises are entailed; but, in response to such challenges, one entirely new chapter was produced, dealing with the timing of variable star phenomena and the astrophysical implications of such information. As well, four new sections and 14 subsections were added to other chapters of the original. Other parts, although listed under their original headings, have all been amended to some extent: in a few cases by almost complete rewriting.

A deliberate choice was made from the outset to give the content a more decidedly academic orientation than the first edition, although the aim of outreach is still present. It is hoped that many of the active amateurs making a real and recognized contribution to modern astronomical photometry will still find the balance helpful, even if only for consultation. In professional contexts, it is well to note that the book is still described as an *Introduction*. Chapter 4 tries to sketch some of the broad and exciting scope of current astronomical photometry, but of necessity, discussion of many worthy topics is very curtailed. The final five chapters select particular questions of stellar astrophysics for introductory analysis.

It is a pleasure to feel gratitude to the people who have helped the preparation of the second edition, though it is hard to list all their names. The rector, staff and students of the University of Çanakkale, Turkey, deserve grateful acknowledgement. In particular, members of the Physics Department have provided warm and collegiate help. Especially we thank Volkan and Hicran Bakış for very much appreciated practical assistance.

In New Zealand, Dr Denis Sullivan gave welcome support, especially through his facilitation of library and computer facilities at the Victoria University of Wellington. That university's library staff were invariably helpful in searching out information and resources. Drs Murray Forbes and Tim Banks, former Physics Department students, have also been helpful with information. The Carter Observatory's Honorary Research Fellowship to EB is recognized with thanks.

Last, but not least, to our families and close friends – many thanks.

1
Overview

1.1 Scope of the subject

This book is aimed at laying groundwork for the purposes and methods of astronomical photometry. This is a large subject with a large range of connections. In the historical aspect, for example, we retain contact with the earliest known systematic cataloguer of the sky, at least in Western sources, i.e. Hipparchos of Nicea ($\sim$160–127 BCE): the 'father of astronomy', for his magnitude arrangements are still in use, though admittedly in a much refined form. A special interest attaches to this very long time baseline, and a worthy challenge exists in getting a clearer view of early records and procedures.

Photometry has points of contact with, or merges into, other fields of observational astronomy, though different words are used to demarcate particular specialities. Radio-, infrared-, X-ray-astronomy, and so on, often concern measurement and comparison procedures that parallel the historically well-known optical domain. Spectrophotometry, as another instance, extends and particularizes information about the detailed distribution of radiated energy with wavelength, involving studies and techniques for a higher spectral resolution than would apply to photometry in general. Astrometry and stellar photometry form limiting cases of the photometry of extended objects. Since stars are, for the most part, below instrumental resolution, a sharp separation is made between positional and radiative flux data. But this distinction seems artificial on close examination. Thus, accurate positional surveys on stars take the small spread of light that a telescope forms as a stellar image, microscopically sample it and analyse the flux distribution, allowing statistical procedures to fix the position of the light centroid.

If photometry merges into more specialized fields at one side, it remains connected to simple origins at another. This has been a feature of the continuous overall growth of the subject over the last few centuries. Thus, when Fabricius noticed the variability of Mira in 1596 it was the beginning of the study of long period variable stars. Several thousand Miras are now known, each with their own peculiar vagaries of period and amplitude. The Miras are just one group among a score of different kinds of variable star. If we look into the vast and developing body of data on variable stars we will notice the special role in astronomical science for the amateur, particularly when his or her efforts are organized and collated. The human eye still plays a key part, especially in those dramatic initial moments of discovery, whether it be of a new supernova, an ‘outburst’ of a cataclysmic variable, or a sudden drop of a star of the R Coronæ Borealis type. An effort is made in this book to retain contact with this basic type of support: photometric quantities are related back to their origins in eye-based measurement, for example. We encounter also useful data sets that are within the reach of small observatories, amateur groups, or well-endowed individuals to provide.

On the other hand, a scientific discipline gives active motivation to serious effort, so long as frontier areas can be identified within its ambit. The later chapters address themselves to areas of variable star research where techniques are still being developed, and answers still unresolved. Although, in principle, all stars will change their output luminosity if one takes the time interval long enough, we think of variable stars as a subclass that shows intriguing effects over timescales usually much less than a human lifetime, and typically over the range from seconds (‘fast’) to years (‘slow’). Restrictions to the areas of research follow naturally by the implied concentration. These chapters expose this process, starting from fairly mainstream topics in astronomical photometry. They should pave the way towards more technical or specialized research.

1.2 Requirements

The remarkable spread of personal computers (PCs) and the electronic networks linking them over the last few decades open up all sorts of interesting activities, of which the control of astronomical equipment, the accessing of relevant information, the logging and processing of observational data, and the fitting of adequate physical model predictions are just a few – but a special few from our present point of view. High-quality optical telescopes that can be used for astronomical photometry are also increasingly available at competitive prices. Modern technology has thus placed within reach of a large number of potential enthusiasts the means of dealing with observation and analysis that would have been frontline a generation ago. For the reasons indicated in the preceding section these are additive to the overall course of astronomical science.

This point can be made more quantitatively. Detailed considerations will be presented in later chapters, but one of the most important specifiers is the ratio of signal to noise (S/N): the measure of information of interest compared with irrelevant disturbances of the measurement. 'Good' measurements are associated with S/N values of 100 or over. This quality of measurement can be attained in stellar photometry for a large number of stars with relatively modest sized telescopes. Consider, for example, the few hundred thousand stars included in famous great catalogues, such as the *Henry Draper Catalogue* or the *Bonner Durchmusterung*. Optical monitoring of such stars is possible at $S/N \gtrsim 100$, in good weather conditions at a dark sky observatory with a 'small' 25-cm aperture telescope. Such facilities could be considered at the minimal end of a range whose upper limit advances with the latest technological strides of the Space Age.

Generally speaking, differential photometry of variable stars, in order to stimulate attempts at detailed modelling, looks persuasive at $S/N \sim 100$, though this is a rather crude overall guide. Variable stars are known whose entire variation is only of order a hundredth of a magnitude. A particularly notable example came to light in 1999 with the photometric identification of the planetary companion to HD 209458 (Figure 1.1). More such cases have followed and many more can be confidently expected in future years. Clearly, such low amplitude 'light curves' require the utmost in achievable accuracy, as will be explained presently. On the other hand, traditional eye-based estimation of stellar brightness is usually thought to be doing very well at 10% accuracy. There are many variables of large amplitude where data of this accuracy are still useful, particularly when coverage is extensive, so that observations can be averaged.

It can be shown that accuracy to one part in a thousand is achievable even with a 0.6 m telescope and 2 min integrations from a ground-based site, provided that site is suitably located, for example at a few thousand metres altitude like the summit of Mauna Kea. On this basis, hour-long integrations with a >1 m telescope from similar locations should allow μmag accuracy to be approachable for brighter stars such as HD 209458. This star, also known as V376 Pegasi, turns out to be among the nearest of stars showing eclipses. This point alone suggests a likely high relative frequency of low light loss (planetary?), yet-to-be-discovered eclipses cosmically.

The availability of internet access to large-scale monitorings of cosmic light sources offers a range of new possibilities, for example, with the

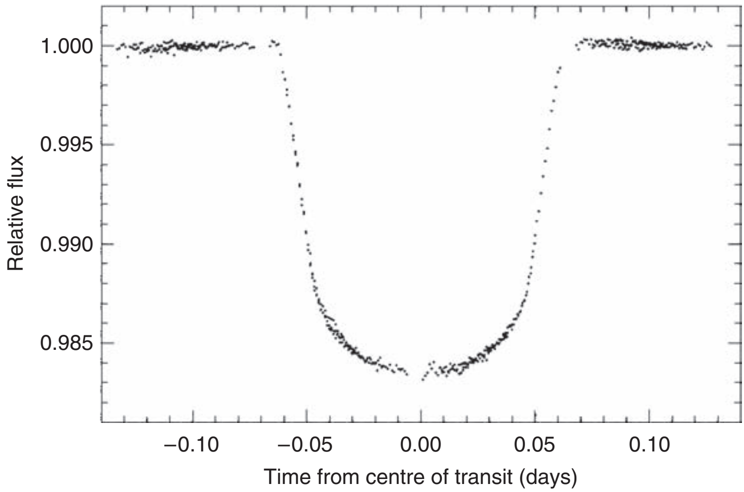

Figure 1.1 Eclipse of HD 209458 by its low-mass, presumed planetary, companion. The light curve has been combined from four separate recordings in April and May 2000 using the Imaging Spectrograph of the Hubble Space Telescope integrating over a yellow–orange region of the spectrum. Individual points are accurate to an estimated 1 part in 10 000. (From T. M. Brown *et al.*, 2001.)

Hipparcos Epoch Photometry Annex (HEPA) or the Sloan Digital Sky Survey. The latter is a 'big-science' project involving an international consortium of research institutes and universities aimed at determining accurate positions and absolute brightness values for more than 100 million celestial objects. Data from the HEPA has been easily obtainable for some years from www.rssd.esa.int/Hipparcos/EpochPhot.html. It can be displayed diagrammatically, in a manner that allows on-line education and experimentation. Hipparcos acquired estimates of the magnitudes of about 100 000 stars about 100 to 150 times throughout the four-year mission of the satellite.

Regarded as a future successor to Hipparcos is the GAIA mission, whose objective is to provide an unprecedented scale of precise astrometric, photometric and radial velocity measurements for about one billion stars in our Galaxy and throughout the Local Group. It is confidently estimated that tens of thousands of new extra-solar planetary systems will be analysable from this data source, as well as comprehensive information on minor bodies in our Solar System, through galaxies in the nearby Universe, and on to some 500 000 distant quasars. Numerous specialists have been in consultation on desirable filter and detector characteristics for this mission that has been planned for launch in 2011.

1.3 Participants

The foregoing indicates several levels of potential support to astronomical photometry. Eye-based data from skilled observers continues to have a significant place, especially with certain kinds of irregular or peculiar variable star, and appears likely to do so for the foreseeable future. Many of these observers are working with telescopes of the 10-inch class.

When a person or group has the skills and resources to combine PC capabilities with a telescope of this size, a photometer utilizing photoelectric detection principles, particularly an areal CCD-type camera, and sufficient awareness of procedures, an order of magnitude or more of detail is added to the information content of data obtained in a given spell of observing. There are also good organizations to support the growth in value of such work: like, for example, the International Amateur–Professional Photoelectric Photometry association, the long-established Vereinigung der Sternfreunde, or the Center for Backyard Astrophysics. Relatively small and low cost, highly automated photometric telescopes (APTs) have also appeared in this context, offering very interesting avenues for future developments in photometry.

The main components – telescope, photometry-system and PC – can, of course, be separated. Apart from instrument control and data management, a computer is also directed to archiving and analysis. It is in this latter area where one main thrust of this book lies. The analysis of data provides the essential link between observational production and theoretical interpretation, which can seem like two halves of a driving cycle. Naturally, each side is in a continual process of growth and development, but it is hoped that this book will be helpful to students and enthusiasts, interested in catching hold of relevant procedures and helping develop them.

Astronomical photometry will then be seen to have an important bearing on our knowledge of the natural Universe. Recognition of the deep significance of such knowledge to general human understanding and culture gives rise to a professional position about the subject. People taking up such a profession will be generally seeking to make new and original contributions, of a standard that can be critically read and accepted by colleagues similarly motivated, in a global context. Considerable efforts, with due periods of specialist training in suitably equipped environments that incur consequent significant expenses, are usually required to achieve this. The acceptance of such implications, together with high standards of checking and review, fosters a common professionalism among persons thus involved. On this basis, professional astronomy should serve the wider community well; especially regarding the reliable presentation of fundamental physical knowledge. Acknowledging such a standpoint, we may start to appreciate more about the worth of data such as that shown in Figure 1.1.

1.4 Targets

Astronomical photometry leads into a much wider range of topics than we have space for. After the essential groundwork of Chapters 2 and 3, Chapter 4 sketches selected areas of the field that show exciting levels of current interest and endeavour: from new discoveries in the Solar System to the behaviour of active galactic nuclei. Further essentials, from the practical point of view, are covered in Chapters 5 and 6. Certain specific issues then arise that form the more concentrated subject matter of later chapters.

Concerning broadband light curves of close binary systems, introduced in Chapter 7, by the end of Chapter 9 we progress to a sixteen-parameter program which can describe the major features of a standard close binary model (including orbital eccentricity), where the components may be well distorted by their mutual proximity. But many light curves are more complicated than this: for instance, those of the close binary CQ Cep (Figure 1.2), whose hot, massive Wolf–Rayet component gives firm spectral evidence of a strong flux of matter from the surface in a very enhanced ‘stellar wind’. This must entail high-energy interactions with its companion. The light curves show peculiar asymmetries that may be anticipated from separate evidence, but for which the standard model is inadequate. One line of such separate evidence comes from subtle changes of orbital period: relatively easy to measure, though often challenging to find a fully satisfactory explanation for. This subject forms the theme of Chapter 8. The problems raised by such interacting binaries surely call for more development of appropriate physical models.

Very close and strongly interacting binaries raise the model *adequacy* issue, which arises from time to time as the text proceeds. Unfortunately, as the physical situation becomes more complex, light curves alone do not necessarily match this. Their form may in fact become more simple – less determinate. CQ Cep shows broadband light curves that are without the informative sharp corners of classical eclipsing binary light curves, resembling only slightly distorted sine curves. From an empirical viewpoint, such light curves are given, in principle, by only a small number of well-defined parameters. They are not very informative; alternatively, when considered in isolation, they may fit into a wide range of possible explanatory scenarios. One way to proceed

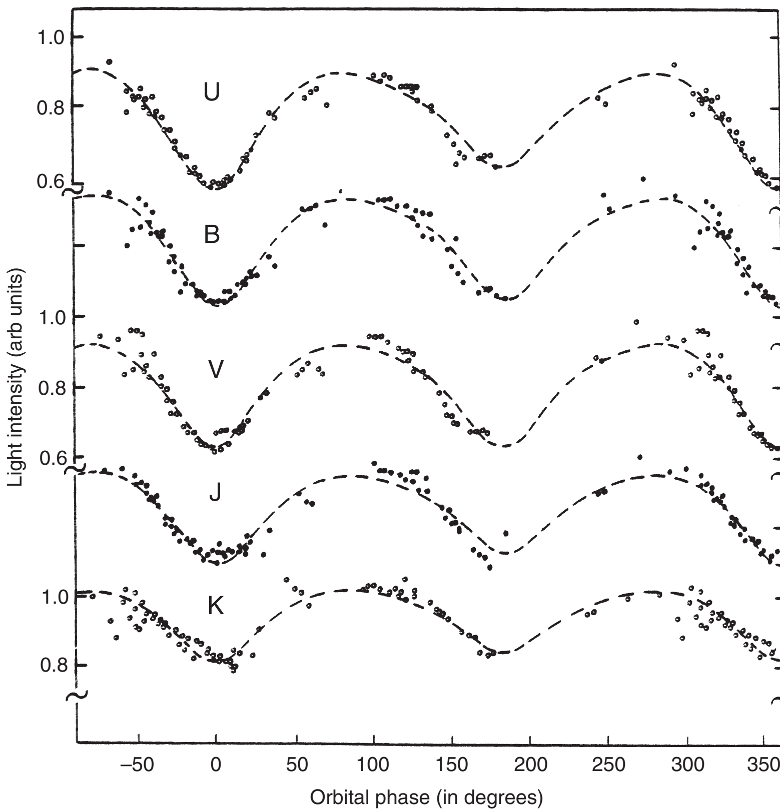

Figure 1.2 Light curves of the binary system CQ Cep in different broadband wavelength ranges

is to combine many different spectral or time-distributed data, and then seek one coherent underlying model.

Narrowband photometry of the relatively mildly interacting binaries U Cep and U Sge, presented in Chapter 9, illustrates such a process, albeit in rather a straightforward progression. From broadband light curves we infer that these stars are 'semidetached', i.e. the less massive components are filling their surrounding 'Roche' lobes of limiting dynamical stability, indeed overflowing them, according to standard ideas on interactive binary evolution. Basic geometric parameters are derived from curve fits to such photometry. We can then approach corresponding narrowband light curves with some of the key quantities already known. In a more general approach, one seeks a simultaneous or concomitant explanation of concurrent data sets, with information feeding across from one curve-fitting to another.

Something like this happens in the successive approximations analysis we carry out for the spotted RS CVn type stars. In Chapter 10, great increases in observational surveillance of these 'extensions to the solar laboratory' are anticipated, with the exploitation of automated photometric telescopes and other techniques. But the fitting of the wave distortions in these systems is notoriously imprecise. Basically, we face a stringent information limit if we rely only on broadband photometry. Either we admit to a frustrating smallness of derivable parameter sets, or give in to the temptation to advance plausible models that can match the data well, but actually specify more information than it really contains. Again the answer will be to combine as many data sets as possible, spectroscopic as well as photometric, to uncover a unified picture. Increased combinatorial use of new techniques, such as Zeeman Doppler Imaging, or multi-band stellar radio astronomy, should allow valuable progress to be made in this context.

The Baade–Wesselink technique, outlined in Chapter 11, is another area where the temptation to derive and utilize numerical parameters may exceed proper caution. Even so, the suggested dangers are perhaps not that serious. Those inferences in the method which are prone to unreliability are well known, and continue to be investigated to find firmer versions. Fortunately, there are also quite independent means of testing the overall reliability of Baade–Wesselink results.

Whether or not present techniques will remain useful, we can find in them viable approaches to a fuller appreciation of the meaning of photometric data.

1.5 Bibliographical notes

The 1998 edition of A. A. Henden and R. H. Kaitchuk's *Astronomical Photometry* (Willmann-Bell) recognizes much of the same scope of the subject as our overview, and addresses comparable requirements and participants. Its special usefulness regarding practical details will become apparent in the bibliographic notes of later chapters. Willmann-Bell (www.willbell.com/) have produced a selection of other textbooks in the field, including a re-edition (1998) of D. S. Hall and R. M. Genet's useful *Photoelectric Photometry of Variable Stars* that features the work of the remarkable amateur astronomer Louis Boyd. Other earlier publications of the Fairborn Press throw light on the development of the productive interaction of small telescope and personal computer, while the groundwork of C. Sterken and J. Manfroid's *Astronomical*

Photometry: A Guide (Kluwer, 1992) and V. Straizys's *Multicolor Stellar Photometry* (Pachart, 1995) should not be missed.

More recently, C. Sterken and C. Jaschek have compiled an overview of variable star photometry in their *Light Curves of Variable Stars: A Pictorial Atlas* (Cambridge University Press, 1996). The earlier C. and M. Jascheks' *Classification of the Stars* (Cambridge University Press, 1989) was also a useful broad-based text reviewing the role played by photometry in developing understanding for stars of all types. That book, in turn, cited M. Golay's *Introduction to Astronomical Photometry* (Reidel, 1974) as an important seminal work on astronomical photometric science. Although the present text aims at a reasonably complete introduction, references are made, from time to time, to such comprehensive backgrounders.

Concerning the aim of broad outreach indicated in Section 1.1, the continuous network of communications organized by observers' societies and groups in many countries should be consulted. These include the British Astronomical Association (Variable Star Section: www.britastro.org/vss/), the American Association of Variable Star Observers (www.aavso.org/), the Association Française des Observateurs d'Etoiles Variables (cdsweb.u-strasbg.fr/afoev/), the Variable Star Observers League in Japan (vsolj.cetus-net.org/), the German Vereinigung der Sternfreunde (www.vds-astro.de/), relevant sections of the Royal Astronomical Society of New Zealand (www.rasnz.org.nz/) and their various equivalents in other countries. Most of the above websites give links to similar organizations; or, in any case, relevant information could be accessed through the International Astronomical Union (IAU – www.iau.org/Organization/), probably via its Divisions V and XII. A good backgrounder for such activities was provided in G. A. Good's *Observing Variable Stars*, in Patrick Moore's practical astronomy series (Springer-Verlag, 2003). A nice review of the role of visual monitoring in variable star studies was given by Albert Jones in *Austral. J. Astron.* (**6**, 81, 1995).

Specific short contributions on astronomical photometry appear in the Information Bulletin on Variable Stars, whose production has arisen from a background of efforts through Commissions 27 and 42 of the IAU, and is published by the Konkoly Observatory (www.konkoly.hu/IBVS), Budapest, Hungary. The International Amateur–Professional Photoelectric Photometry organization (www.iappp.vanderbilt.edu/) also addresses itself across national boundaries (T. D. Oswalt, D. S. Hall & R. C. Reisenweber, *I.A.P.P.P. Commun.* **42**, 1, 1990), while *Peremeniye Zvezdiy* records comparable activities in the Russian language. A useful set of papers relevant to this context also appeared in *The Study of Variable Stars Using Small Telescopes*, ed. J. R. Percy

(Cambridge University Press, 1986). The Center for Backyard Astrophysics can be accessed via cba.phys.columbia.edu/.

Quantitative data on S/N values for real photometers appear in the Optec (tradename) Manual, as well towards the end of A. A. Henden and R. H. Kaitchuck's *Astronomical Photometry*, where a full explanation of the underlying principles is given. Figure 1.1 comes from the paper of T. M. Brown *et al.* (*Astrophys. J.*, **552**, 699, 2001). This remarkable light curve of a roughly Jupiter-like planet transiting a stellar disk was brought about after photometric attention was directed to HD 209458 following the precise measurement of small variations of radial velocity (cf. Mazeh *et al.*, 2000). Figure 1.2 appeared in D. Stickland *et al.* (*Astron. Astrophys.,* **134**, 45, 1984). Information on Hipparcos photometry is available from astro.estec.esa.nl/Hipparcos/, similarly on the SDSS at www.sdss.org/ and the GAIA mission at astro.estec.esa.nl/GAIA/.

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2
Introduction

2.1 Optical photometry

Astronomical photometry is about the measurement of the brightness of radiating objects in the sky. We will deal mainly with optical photometry, which centres around a region of the electromagnetic spectrum to which the human eye (Figure 2.1) is sensitive. Indeed, photometric science, as it concerns stars, has developed out of a history of effort, the greatest proportion of which, over time at least, has amounted to direct visual scanning and comparison of the brightness of stellar images. In this context, brightness derives from an integrated product of the eye's response and the energy distribution as it arrives from the celestial source to reach the observer. Still today there is a large amount of monitoring of the many known variable stars carried out (largely by amateurs) in this way.

With the passage of time, however, there has been a general trend towards more objective methods of measurement. The use of photometers with a non-human detector element has become increasingly widespread, though the term optical remains to denote the relevant spectral range (Figure 2.2), which significantly coincides with an important atmospheric 'window' through which external radiation can easily pass. This is presumably connected with biological evolution: in fact, the maximum sensitivity of the human eye is at a wavelength close to the maximum in the energy versus wavelength distribution of the Sun's output (∼5000 Å).[1] Instrumental applications have extended the usage of 'optical' down to ∼3000 Å at the ultraviolet end of the spectrum, and ∼10 000 Å at the infrared end.

[1] The angstrom unit (10^{-10} m) is frequently used in contexts where broad historical continuity is convenient.

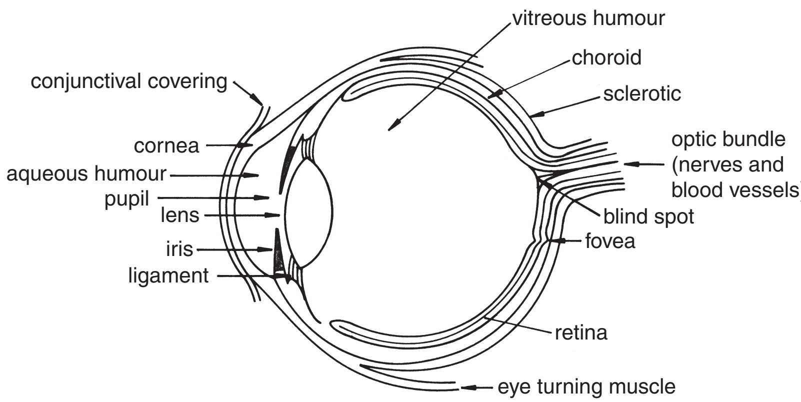

Figure 2.1 The human eye (schematic): a remarkable instrument for general photometry with a very wide dynamic range

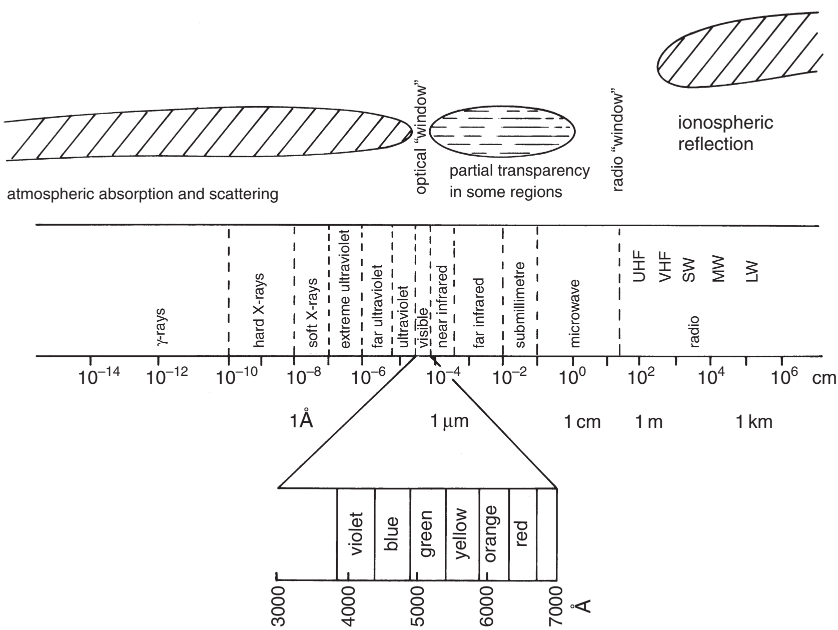

Figure 2.2 The electromagnetic spectrum

Closely connected to brightness is colour. More formal statements about these terms will be made later, but colour broadly measures the difference in brightness of an object observed at two specified wavelength regions of observation. This can be scaled in the adopted units, and descriptions such as reddish, blue and so on, assigned numerical values within the scheme. The term colour index is sometimes used for celestial sources, and the determination of such indices forms a basic objective of the subject.

More detailed than colour determination is the specifying of relative intensity level at each wavelength over a range of the spectrum, or spectrophotometry. This would often be distinguished from conventional photometry, largely because of its different background of development in instrumentation. A key point is that photometry is generally done with the simple interposition of coloured glass, or glass covered, filters in the optical path to the light detector. With a filter of varying transmission that can be changed in a controlled way during operation, it is possible to approach spectrophotometry with a similar set up to conventional photometry, though uniform fixed-bandwidth filters are much more normal. More elaborate dispersing instruments achieving higher spectral resolution would usually be employed for regular spectrophotometry.

In carrying out photometric measurement, the framework of mean relative intensities of known light sources – stellar, i.e. point-like; and extended, as clusterings or nebulae – is evaluated and checked. Certain well-known sources, with near-constant or predictable fluxes, are designated standards. Feedback from the data on such standards then allows calibration of any particular observer's measurement system and the data it produces on a source of interest. Alternatively, the reference framework may be extended to include further objects whose brightness values are added to allow further calibration, particularly at fainter flux levels or in particular locations, such as stellar clusters.

In comparison to most other fields of scientific measurement, stellar photometry is relatively imprecise. The best that the ancients could do by naked-eye methods, for instance, was to judge brightness to within about a third of the time-honoured magnitude classes: on a linear scale this means guessing the rate of energy output of a star to within anything from about 75% to 135% of its real value. This compares with an accuracy of one part in a thousand, or better, to which they could fix position in the sky in angular coordinates. Modern photoelectric methods give individual measurements of brightness to better than 1%, but the absolute accuracy to which the entire system can be standardized is usually (depending on *which* system) not much better than 1%. Positional determinations, meanwhile, are now routinely attained with an accuracy of 1 in 100 000 000 or better. There are, and always have been, therefore, several powers of ten in the ratio of accuracies of specification of stellar position compared with brightness. Nevertheless, the importance of knowing the rate at which energy is radiated from the outer layers of a star, for understanding stellar constitution, became clear as soon as people began to develop physical ideas on this.

The side of photometry dealing with calibration issues is sometimes seen as playing a supporting role to a more attention-catching activity connected with variable stars. Alternative purposes again appear in this connection. Some information retrieval and processing is to check, or further refine our knowledge of, the underlying physics, such as with 'classical' variables, e.g. cepheids, or normal eclipsing binary systems. On the other hand, certain observations are made with some expectation of discovery; either by finding variability in a hitherto unsuspected object, or by monitoring seemingly unpredictable types of irregularity, for instance with flare stars, cataclysmic variables, BL Lacerate type objects and such-like.

Astronomical photometry was originally largely concerned with the relative brightness values of stars, and the magnitude system in which these are expressed. Stellar surfaces are below the eye's limit of resolution, even through the world's largest telescopes, and are thus point-like. Some of the most familiar astronomical objects – the Sun, the Moon, the Milky Way or the sky itself – are extended, however. Their local brightness can be expressed, in traditional units, as 'n stars of magnitude m per unit square angular measure', with the meaning that the light received from e.g. an area of surface subtending 1 arcmin by 1 arcmin (about the limit of resolution of a typical human eye) would be the same as if coming from n of mth magnitude stars ($m = 10$ might be used for this), or, alternatively, simply as magnitude x per square arcsec, say. There are many extended sources, but usually with relatively faint surface brightness values. With improved linear areal detectors and more large telescopes there continue to be impressive developments in the detailed surface photometry of faint nebulae and galaxies.

Photometry has thus a range of important roles to play in astrophysics. By providing basic reference data on stellar brightness and colour, such as via the well-known colour–magnitude diagrams, fundamental tests to ideas of stellar structure and evolution have been provided. The continual discovery of new kinds of photometric phenomena in objects as varied as members of the solar system to active galactic nuclei, regions of nebulosity, supernovae, spotted stars, cataclysmic variables or high-energy bursters . . . all helps build up and develop physical theory.

2.2 Historical notes

The historical basis for stellar brightness determinations centres on the magnitude system in which they are evaluated. This system goes back at least as far as that ancient compilation of data on stars, the catalogue of Hipparchos,[2] completed by about 130 BCE. Just how the system originated appears 'lost in the mists of time'. It is known that Hipparchos, along with earlier Greek astronomers, referred to still earlier Babylonian star and constellation identifications, but the details in such information transfer are no longer clear. In any case, the magnitudes of Hipparchos, as conveyed to posterity through Claudius Ptolemy's great *Megali Syntaxis tis Astronomias*, are essentially similar to present-day values for the 1000 or so brightest stars.

During the cultural flowering of the Abbasid caliphate the astronomical works of the Greeks became known and studied in a new setting. Translated into the *Kitab al Majisti* (the Almagest), Ptolemy's treatise stimulated not only the attention of Islamic scholars but also their active experimental investigation. The enlightened Abdullah al Mamun, in the early part of the ninth century of our era, founded the renowned observatory at Baghdad, where astronomy was supported by new and improved instrumentation, as well as advances in theory and methods of calculation. It was from this background, for example, that Al Battani (Albategnius), on the basis of new observations (mainly at Ar Raqqah), substantially improved on Ptolemy's value for the precession constant.

Also benefitting from the Almagest, Abd al Rahman Sufi, at Isfahan in the tenth century, decided that not only the positional determinations of the stars as given in the Almagest, but also their magnitudes, could be checked, or reassessed. Sufi published a new list of magnitudes of all the thousand or so stars of the Almagest he could actually observe, adding also a hundred or more new ones of his own. There is no doubt that Sufi's magnitudes represent an improvement in precision over the run of values attributed to Ptolemy. Magnitude values given in Ptolemy's catalogue have an average accuracy of not less than half a magnitude division, which becomes about a third of a division in Sufi's work (magnitude units were divided into three subdivisions in these ancient catalogues). The scholar of ancient astronomy, E. Knobel, pointed out that Sufi also appears to have been the first astronomer to take account of a galaxy external to our own, i.e. his was the first map to indicate the Andromeda Nebula.

The differences that existed between Sufi's and Ptolemy's magnitude values were not overemphasized. Presumably, Sufi and his followers supposed that the earlier observers had just not been assiduous enough, after all shortcomings in some of Ptolemy's positional work had already come to light. The possibility of inherent variation of starlight, while it may well have occurred

[2] sometimes spelled Hipparchus.

to Sufi, would probably have been regarded with some demur, for the trend of opinion among the ancients, epitomized by no less an authority than Aristotle, was that the sphere of the fixed stars was something eternal and invariable (‘*incorruptible*’). Apparent short-term variation of starlight (i.e. twinkling) could be put down to shortcomings of human eyesight. Sufi’s improved magnitudes were therefore accepted as definitive in Ulugh Beg’s recompilation of the classical stellar catalogue for the epoch 1437 AD: nearly five centuries after Sufi’s time.

The idea of a permanent, invariably rotating outer sphere of the stars was in harmony with prevalent philosophical concepts of the Middle Ages in Europe; but a certain shakiness to this model was introduced by the sudden appearance in 1572 of a bright ‘new star’ (*nova*), which captured the attention of Tycho Brahe, then a 26-year-old Danish nobleman, with scientific interests, looking for his calling in life. As with Hipparchos himself, who, according to Pliny, had been stimulated to compile his catalogue by just such an event some 1700 years previously, Tycho was to go on to produce his own new catalogue of the stars; though, apparently, he did not live to see the work brought to a final published form.

Another important, but rather fortuitous, event in the life of Tycho was the appearance of a bright comet in 1577, not long after the astronomer had established himself in his new observatory at Uraniborg, on a small island between Zealand and Sweden. From his series of observations of the comet Tycho was able, at last, to bring firm evidence to deny the Aristotelian contention that no substantial changes have effect beyond the sphere of the Moon. We know also that, in his meticulous way, Tycho was marking in his catalogue manuscripts the magnitude values of some stars by dots, where he believed there was some discrepancy between previously recorded values. Tycho would not have been dismayed, therefore, by the announcement in 1596 by David Fabricius of the new appearance of what was later called Mira: the first known variable star in the more normally used sense.[3] Fabricius was in correspondence with Johannes Kepler, then about the same age as Tycho had been at the time of the new star of 1572. The following year (1597) both he and the now middle-aged Tycho, who had left his native land, were working together in Prague.

Tycho died in 1601, a year after W. Janszoon Blaeu found another famous variable of the northern skies – P Cygni – and three years before Kepler saw

[3] Of course, we now know that the novae are also variables, i.e. stars, normally too faint to be seen, that suddenly become very much brighter, so sometimes allowing temporary naked eye visibility.

his own bright new star in the form of the supernova of 1604. So it was that by the seventeenth century the concept of new or variable stars became accepted: catalogued magnitudes were checked again, more variables were discovered and Aristotle's immutable outer sphere began to fade into oblivion. Tycho's catalogue was eventually published in comprehensive form by Kepler in the *Rudolphine Tables*, but already by 1603 his work was attracting attention through its artistic rendering in the form of the star charts of Johann Bayer's *Unranometria*. These famous maps included the 48 classical constellations of the ancients drawn by the Renaissance artist Albrecht Dürer. Janszoon Blaeu and Bayer also recognized 12 new constellations not among those listed in the Almagest. These were in the far southern parts of the sky, invisible to ancient astronomers of the Near East. Data on these stars had come from early explorers, but particularly through the tabulations of the Dutch sailors P. D. Keyzer and F. de Houtman.

This period of growth in astronomy occurred side by side with the development of the telescope as a scientific instrument; championed in those early days, of course, by Galileo. Galileo gave attention to stars fainter than sixth magnitude – the faintest class of Hipparchos' subdivisions – and decided on a simple extension to seventh, eighth and so on, so as to follow in a consistent progression. The system was kept by Flamsteed and others, indeed right up to our own day when, since, in principle, the zero point of the magnitude scale coincides with a certain average originally based on the Ptolemaic values, we still maintain an observational link with that first compilation of Hipparchos (which itself may have been influenced by earlier sources) more than 2000 years ago.

Some of the stars catalogued by Ptolemy were very far to the south of his Alexandrian sky, and, with the additional apparent displacement resulting from the precession and nutation of the equinoxes, apart from the generally higher latitudes of observers, dropped from the attention of the mediæval European astronomers. Some of these stars (e.g. α and β Sagittarii) attracted the notice of young Edmond Halley, who, from his observations on the island of St Helena, published in 1679, provided another of the early catalogues of stars of the southern sky. Halley, still trustful of the Almagest writings, and pondering over the two magnitudes or so discrepancies, speculated on the possibility of inherent variations of this scale in the fifteen hundred years since Ptolemy had recorded their magnitudes.

Early in the eighteenth century a further important development to astronomical photometry came with the introduction of specific instrumentation by Pierre Bouguer, who might be regarded as a *patron* of much of the subject matter of this book. Bouguer was, for instance, the first to make a systematic study of the extinction of light from celestial bodies by the intervening atmosphere, and showed that the increase in magnitude (diminution in brightness) thus caused was directly proportional to the mass of intervening air. He is credited with the more basic establishing of the inverse square law diminution of light flux (*in vacuo*) (proposed by Kepler). He also quantified that effect, which may well have been noticed in earlier times, known as the limb darkening of the Sun, i.e. the tendency of the surface brightness to fade towards the edge of the solar disk. The effect has been a source of extensive astrophysical interest, aspects of which will be met later in this text.

Bouguer's methodology appears to have been neglected through the century that followed, though this is mollified by its ultimate dependence on that rather non-impersonal element the human eye, whatever the intervening instrumentation; up until the advent of photographic methods, at least. So even by the mid nineteenth century when Argelander and his associates were engaged with the very large undertaking of the *Durchmusterungen*, ultimately recording around half a million magnitude estimates, a very simple eye-based procedure was considered expedient; though it is also true to say that a careful, instrument-based approach, such as that followed in the more intensive work of John Herschel, had its reward in terms of a much better scale of internal self-consistency.

It had been during the earlier years of the astronomical career of John Herschel's father, William, that an important class of variable star, the eclipsing binary system, was discovered with the memorable work of young John Goodricke. Binary systems, or double stars as they are also known, were a strong interest of W. Herschel at the time, but though he gave Algol, the binary whose eclipsing pattern was first recognized by Goodricke, close attention with the large telescopes at his disposal, he could not discern two components by eye. The period of the binary's orbital revolution is relatively short – less than three days – so that with a few inferences about the consequent likely angular size of the orbit at an expectable distance, Herschel's failure to resolve the components becomes not surprising. Herschel's introduction of more powerful light collectors, and his interest in the ability to resolve detail, particularly in faint and diffuse patches of light, paved the way for the photometry of extended sources; though more quantitative work on this had to await the appearance of purpose-built photometric equipment.

Living in the same county as Goodricke, not more than 40 km away, was another astronomer of the eighteenth century, the significance of whose work seems to have been largely overlooked for a century or more after his death in 1793. This was John Michell, who was the first to recognize the probable gravitational binding of many double stars on the basis of reasoned statistical argument. He also conjectured on the existence of 'black holes' (as they are now called): highly condensed stars with gravity so strong as to confine photons to a surrounding bound region. Michell seems to have encountered Herschel in Yorkshire already in the 1760s, and it is likely that later he at least came to know of Goodricke. Among his achievements was another remarkable result published in 1767: a determination of the 'photometric parallax' of Vega at 0.45 arcsec. The corresponding distance, of the right order of magnitude but only around a quarter of modern values, results from the assumption of an equal inherent luminosity for Vega and the Sun, with some additional estimates about the apparent brightness of Saturn as an intermediate step in his calculation. Interactions with the work of Herschel, as it happened, around the same time as Goodricke's discovery, supported Michell's later realization that stars must come in inherently different luminosities and indeed he would have understood the full circumstances of Goodricke's eclipsing binary hypothesis as well as Herschel's failure to resolve it.

More advanced astronomical photometer designs, utilizing the null principle for brightness comparison, and incorporating controlled diminution of source brightness, e.g. by the use of polarizing agents, appeared by the middle of the nineteenth century, notably that of J. K. F. Zöllner, who based his photometer on a design of François Arago.

It became apparent by about the middle 1800s that the traditional magnitude scale should be not too far from logarithmic in the received fluxes of visible starlight; a point related to the physiology of sensation as investigated by G. T. Fechner and E. H. Weber. The formal rule for stellar magnitudes which became generally adopted is usually associated with the name of N. R. Pogson, who, in 1856, set out a relation of the form:

$$m_1 - m_2 = -2.5 \log(f_1/f_2), \tag{2.1}$$

so a difference of 5 magnitudes (m) corresponds to a flux (f) ratio of 100. The choice of coefficient here seems a good compromise between mathematical simplicity and tradition, although a closer study of the early catalogues indicates the ancient magnitude values not to have followed a strictly logarithmic system.

There are some significant consequences of this logarithmic system which have favoured its retention. The first relates to the attenuation of incident radiation by the Earth's atmosphere, i.e. Bouguer's law, which can be directly validated with the logarithmic scale. Then the magnitude system adapts itself well to a differential scheme; useful, for example, if one was primarily interested in tracking the relative brightness of some particular variable star. The overall changes of brightness, associated with variations in the atmosphere's transparency from night to night or secular drifts in the response of the receiver easily drop out as zero constants on a logarithmic scale. Only when one wishes to tie in measurements with an absolute system of units (not necessarily an immediate objective) does it become required to evaluate just what (in watts per square metre, say) would correspond to the radiation from a zero magnitude star. These matters will be considered in more detail in the next chapter. Colour too, defined as a difference of magnitudes at different wavelengths, lends itself well to some quasi-empirical relationships of a simple form relating to the temperature of the radiation emitting surface.

In the nineteenth century efforts started to be made for a more systematic basis to magnitude determination through the medium of photography. For various reasons this proved not to be so straightforward, however, and until relatively recently photographic magnitude determinations were not greatly superior in accuracy to eye-based measures of a trained observer using specially prepared equipment. This was the case with the meridian visual photometer, developed towards the end of the nineteenth century at Harvard College Observatory by E. C. Pickering and his associates. Thus, if the ancient catalogue of Sufi listed stellar magnitudes to an internal accuracy of about a third of a magnitude, the skilled observers using the Harvard meridian photometer could improve on this so that their amplitude of uncertainty was no worse than half that of Sufi, while a tenth of a magnitude accuracy characterized photographic determinations of better quality in the first half of the twentieth century.

Despite its objective nature, there are a number of complicating and often non-linear effects which take place between the original incidence of starlight and the final forms of darkened grain stellar images in the emulsion over the exposed plate (or film). These complications make reliable extraction of a corresponding set of magnitude values a difficult exercise. A number of the early investigators, e.g. Bond, Kapteyn, Pickering, Scheiner, Bemporad (and others), looked for some empirical formula to relate magnitude with something easily measured, such as image diameter, but there was no uniformity of opinion as to what the formula should be, each worker generally preferring his own.

In the early years of the twentieth century the theory of photographic image formation was explored more fully by K. Schwarzschild, and more elaborate procedures for calibration were devised, involving things like objective partial-covering screens, plate holders capable of easy movement for repeated exposures, image plane filters, tube sensitometers and the densitometry of extrafocal images. Methods generally required the setting up of

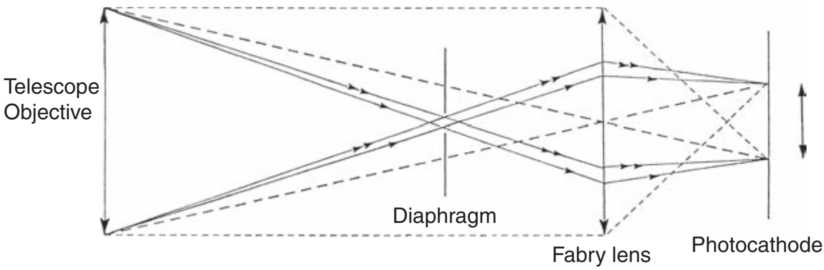

Figure 2.3 Principle of the Fabry lens. The image on the detector is that which the small lens forms of the objective (dotted lines) as illuminated by the object of interest. Light from a stellar image (full lines), which may drift around in the focal plane, always ends up in the same place

semi-empirical calibration curves, in which the measured photographic effect was plotted against a controlled variation of incident (log) flux. An interesting idea was advanced by C. Fabry for extrafocal image measurement. This made use of a small additional lens close to the main focal plane of the objective (Figure 2.3). Fabry demonstrated advantages in stability and methodology of the arrangement. The patch of light studied was always uniformly illuminated and of the same size, even from an extended object. This concept is still retained in many photometer designs.

In the early days of photography, emulsions were all essentially blue-sensitive compared to the eye: the ‘actinic’ radiation which causes darkening of the silver halide grains being relatively energetic. Later ‘orthochromatic’, or even ‘panchromatic’, emulsions appeared with enhanced sensitivity at longer wavelengths. The early photographic magnitude scale did reflect a physical difference from the visual one, though, due to the difference in effective wavelengths. Hotter objects of a given visual (m_{v}) magnitude, which are therefore relatively brighter towards the blue region, have correspondingly reduced photographic (p_{g}) magnitude values. The emulsions of increased sensitivity at longer wavelengths allowed the setting up of a ‘photovisual’ (p_{v}) magnitude scale, directly comparable with the eye-based system.

Ancient catalogues tended to have a greater self-consistency in magnitude estimates for stars closer to the celestial North Pole. This is presumably related to the greater relative constancy of the intervening air mass. Pickering, directing a Harvard programme on magnitude determinations in the early twentieth century, similarly favoured the use of standards from around the vicinity of the North Pole when it came to setting up a basic reference sequence for photographic magnitudes. It was eventually decided, by an international congress of astronomers, that Pickering’s North Polar Sequence (which originally consisted of some 47 stars) should define the basic photographic (p_g) magnitude scale. This was to be linked with the pre-existing visual scale by the requirement that the mean of all p_g magnitudes for stars of spectral type A0 in the magnitude range 5.5–6.5 be equal to the mean of the visual magnitudes for those same stars, as determined by Harvard meridian photometry. In 1912 Pickering published the photographic magnitudes of the chosen North Polar Sequence, which had by then grown in number to 96 stars.

Although difficulties with the use of the North Polar Sequence began to be found when it was used to calibrate magnitudes in other parts of the sky, after careful cross-checks, notably by F. Seares at Mt Wilson, the system was eventually shown to be relatively accurate internally (probable errors of standards generally less than five hundredths of a magnitude) and probably represented an adequate basic reference for a number of years in the photographic photometry era. A large number of secondary sequences were set up in time, with particular attention being paid to specially selected regions, such as those associated with the name of J. C. Kapteyn of the Groningen Observatory (Holland), or the 'Harvard Standard Regions'. These latter are arranged in declination bands from +75° to −75° labelled A to F. Calibrations then moved to the southern hemisphere, including a South Polar Sequence, and photographic photometry of the Magellanic Clouds.

Developments also occurred in the method of magnitude determination from photographic plates. Popular for a time was the Schilt type photometer, which allows a fine pencil of light from a standard lamp to be directed through the plate to be studied. The small spot of light passing through the plate could have its diameter varied, and would normally have been set as small as conveniently possible for the range of magnitudes to be measured. The beam was directed to the centre of a stellar image, where its attenuation would be maximized. The beam, thus reduced in intensity, would then be transmitted to a suitable detective device, such as a photocell and galvanometer combination.

Later a null-method arrangement was introduced by H. Siedentopf. Sometimes known as the iris-diaphragm type of photometer, the underlying principle is one of comparison of a beam which traverses an adjustable neutral density filter with one which passes through an iris surrounding a star of interest (Figure 2.4). The largest star image in the range to be covered would be selected first, and the iris closed down around it. Arrangements whereby the shadow of the iris and the star image field are conveniently projected onto a large screen, for easier viewing, were used (with increasing degrees of automated action) until the later decades of the twentieth century. An advantage of the method was the relatively large range of approximate linearity of the empirical calibration curves.

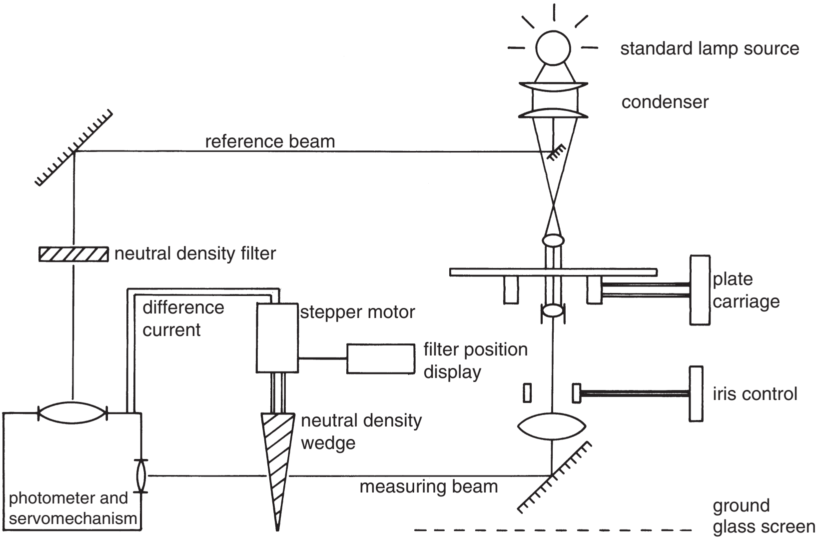

Figure 2.4 General arrangement (schematic) of an iris type photographic photometer

While work was underway to set up the North Polar Sequence reference system for photographic magnitudes, efforts were already being made in the development of a photoelectric approach. The selenium cell was introduced into astronomy by G. M. Minchin, who first performed photometry of Venus and Jupiter with it at the home observatory of W. H. S. Monck of Dublin in 1892. Among the first to obtain 'well-marked' effects with this device (from the Moon) was G. F. Fitzgerald, whose name is perpetuated by his original proposal for the spatial contraction of moving objects now associated with special relativity.

The Irish pioneers of photoelectric photometry had to contend with the vagaries of their climate, relatively small telescopes and, seemingly most troublesome, electrometry of the signal, which depended on an older generation of quadrant electrometers of notorious instability. By opting for the alternative of measuring the photoconductive decline of resistance of an illuminated (and refrigerated) selenium cell in a Wheatstone bridge arrangement Joel Stebbins began to achieve a more continuous success in the early years of the twentieth century at Urbana, Illinois. By 1910, Stebbins had secured the first photoelectric light curve of a variable star – that of the famous eclipsing binary system Algol (Figure 2.5) – with a probable error of no greater than 0.02 magnitudes, an exceedingly accurate set of data for its time. Indeed,

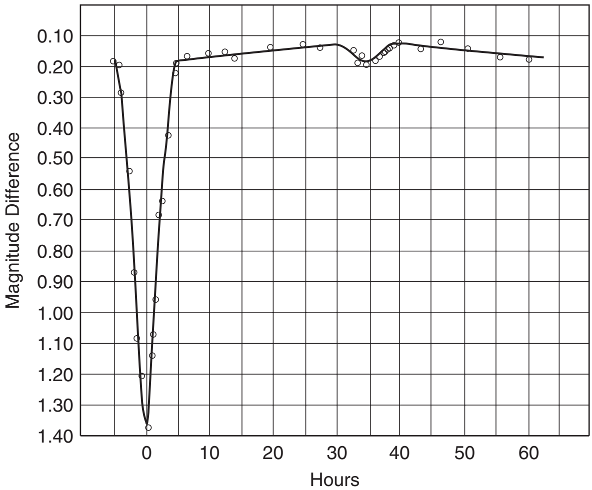

Figure 2.5 Stebbins' (1910) light curve of Algol

Stebbins was the first to establish, in this way, the existence of a secondary minimum to the light curve of Algol.

Despite this accuracy, photoelectric methods were still rather a long time in development; generally because of technical complications and the required brightness of the object of interest to achieve a reasonable signal to noise ratio. By 1932, however, A. E. Whitford had developed an electronic amplifier to deal with the very weak current produced by a photoemissive cell. Further improvements in photometer design and procedure were presented in G. E. Kron's PhD thesis, published in 1939. The selenium cell had by this time been replaced as a detective device by alkaline metal photocathodes, and differential measurement accuracies better than 0.01 magnitude were regularly achievable, at least for stars brighter than about sixth magnitude. The magnitude limitation, essentially a consequence of amplification noise, was circumvented, in due course, by use of the avalanche effect of repeated secondary emissions from suitably positioned electrodes (dynodes) in the photomultiplier tube. A successful prototype photomultiplier was produced by the Radio Corporation of America by the late 1940s with the trade name 1P21. Kron's (1946) paper on the applications of the photomultiplier to astronomical photometry aroused widespread interest.[4]

4 One early consequence, in the southern hemisphere, was G. Eiby's use of such a device on the 9-inch Crossley refractor of the Carter Observatory in Wellington, New Zealand, in 1949.

This type of tube was used by H. L. Johnson and W. W. Morgan in the early 1950s when they set up the three-colour *UBV* photoelectric system, which, despite certain well-known limitations, has been in general use up to present times. In effect, the *UBV* magnitudes, because they have been applied to so many stars, at present probably represent the de facto most generally used basic reference for stellar magnitudes, though other physically advantageous schemes, notably the *uvby* system, are increasingly met with. In setting up the *UBV* system, Johnson and Morgan returned to photovisual magnitudes traceable to North Polar Sequence values, and the principle of letting the relatively common A0 type stars locate, by their average, the zero point of the $B - V$ and $U - B$ colour scales. Since the system was one of essentially improved accuracy, however, ultimately it defined the magnitude scale, though in essential agreement with earlier representations.

A key point here is the use of specifically designed filters in the definition of a magnitude system. In this connection, a significant problem with the earlier photographic procedures came to light after the introduction of mirror aluminization techniques in the 1930s. The more effective reflectivity of aluminized over silvered reflectors, particularly in the ultraviolet, showed up as significant differences in photographic magnitudes from plates taken with different types of mirror surface. By the time of World War II, it was clear that the key to more reliable magnitudes lay in a better definition of the optical transmission properties of the entire photometer, i.e. the combination of objective, intermediate reflecting and refractive media and the response function of the detector itself. Postwar professional stellar photometry has essentially taken careful definition of an adopted set of filters as axiomatic to procedure. The process of defining a magnitude scale then becomes one of continued persistent checks and rechecks of measurements of selected stars with such filters: slowly weeding out slightly variable or peculiar stars and building up increasingly reliable averages for the remaining standards. Certain meritorious photometrists, in both hemispheres, have devoted considerable efforts to this aim. The broadband photoelectric photometry based on that of Johnson and Morgan is perhaps most well known in this respect. But any particular photometric system of n filters can be regarded as well defined, insofar as an ample number of reference stars are secured, each within its sufficiently precise box of n-dimensional space – the Golay box.[5]

A kind of complementarity existed in the middle years of the twentieth century, in which the precision and speed advantages of a single-channel

[5] This oft-cited term comes from M. Golay's informative *Introduction to Astronomical Photometry*, Reidel, 1974.

photoelectric detector were balanced by the multi-channel and compact information storage advantages of photographic media. One 36 cm square plate from the UK Schmidt Telescope (UKST), for example, could register of the order of a million stars and galaxies over a 6.6 deg square region of sky. During the 1970s and 80s, the UKST was operated by the Royal Observatory, Edinburgh, and carried out deep sky surveys of the southern hemisphere. Elaborate machines were built to carry out automatized digital recording of the vast amount of information that could be recorded on such plates.

Various groups later attempted to combine these information capabilities in electronographic areal detectors of one form or another. Astronomy-specific image tubes tended to be expensive and cumbersome. Adaptations of the widely produced television type electron-gun scanning devices, on the other hand, lacked suitable image storage and control facilities or precision. But in 1970 the charge coupled device (CCD) was introduced at Bell Laboratories. By 1975, the CCD camera had been placed at the focal plane of some large telescopes and their diffusion through observational astronomy has continued ever since.

Although the information management requirements imposed by the necessities of digital sampling and recording of images at or near the resolution limit still entails relatively small areal coverage compared with, say, Schmidt camera plates, CCDs are effective in both precision and object multiplicity. Moreover, individual chips can be arranged in mosaic form to cover larger areas of sky, as in large-scale surveys. Lower work functions associated with the photoconductive property of semiconductors generally entails more reach into longer wavelength spectral regions (i.e. into the IR) than the earlier photoemissive detectors. In turn, this has required filter redesigns, so that broadband magnitude systems can be continuous through the change of detection media, but such issues were generally in hand by the early 1990s. Colour–magnitude diagrams for star clusters that reach to twentieth or more magnitude are now commonplace, even with telescopes of less than 1 metre aperture: there has thus been something of an information 'explosion' since the arrival of CCDs.

Fortunately, the concomitant growth of speed and data storage capabilities of small computers has permitted this explosion to remain manageable. In turn, this has allowed various large new ground-based surveys to be initiated towards the end of the twentieth century. These have often been primarily motivated by specific research aims, e.g. the MACHO project's searches for gravitational lens effects, but they have yielded very interesting by-products through the collection of regular photometric data on millions of stars. Large numbers of new variables were thus discovered, often in previously unstudied areas, such as among the fainter parts of globular clusters or external galaxies.

Keeping pace with and contributing to such large information growth has characterized ground-based optical photometry through the late years of the twentieth century, but a new era opened up with the launch of the Hipparcos satellite in 1989. This ESA supported mission regularly included estimates of Johnson V magnitudes of each of its $\sim$120 000 programme stars around 100–150 times throughout the four-year mission. Subsequent systematic analysis enabled existing light curves of known variable stars to be checked and also brought to light several thousand previously unknown variables. The satellite's on-board Tycho experiment aimed at providing more precise two-colour (B and V) data for at least 400 000 stars. Useful information on Hipparcos photometry has been publicly available from the 'Hipparcos Epoch Photometry Annex' of the programme's education webpage (astro.estec.esa.nl/Hipparcos/education.html). At the present time there are plans to follow Hipparcos with comparable, but more extensive and precise, new space-based surveys to collect more detailed photometric knowledge, from faint members of the Solar System to remote galaxies and quasars.

A useful marrying of space-based astronomy with the extensive amount of earlier photographic material came with the electronic digitization of such data, as carried out by the Catalogs and Surveys Branch of the Space Telescope Science Institute. The first such catalogue (GSC I) was published in 1989, mainly as a support for positional needs in satellite control systems, but its widespread availability proved a valuable scientific resource for astronomers generally. The later version (GSC II) is based on 1 arcsec resolution scans, and records of the order of a billion objects at two epochs and three wideband, photographic emulsion-based bandpasses.

2.3 Some basic terminology

A short glossary of frequently encountered terms is presented next, but many of these are subjects of more detailed discussion in later chapters.

absolute magnitude M

This takes out the distance dependence of brightness, and therefore reflects the intrinsic amount of light put out by the source. It is defined as the apparent magnitude (see below) that the source (in the absence of light loss in the intervening space) would have if situated at a distance of 10 parsecs.[6] M then satisfies:

$$m - M = 5 \log \rho - 5, \tag{2.2}$$

where ρ is the distance to the source in parsecs. If interstellar extinction (see below) reduces the brightness of the source, i.e. adds A magnitudes into the apparent magnitude value, then this quantity must similarly be added to the right hand side of (2.2).

apparent magnitude m

This is the brightness of a star in the traditional system as it has evolved to its modern form. The basic formula has been given already as (2.1).

Balmer decrement measures D, c_1

The discontinuity at the end of the Balmer series of hydrogen absorption lines is a conspicuous feature in the near ultraviolet of stellar spectra. It is sensitive to surface gravity as well as temperature, consequently various photometric systems include some monitoring on either side of the discontinuity, to determine the size of the jump in energy terms, or the decrement value D. In the intermediate bandwidth *uvby* system the colour index combination $(u - v) - (v - b)$ is found to correlate with the Balmer decrement D. This has been given the special symbol c_1.

bolometric magnitude m_{bol} and **correction** BC

Bolometric magnitudes go beyond the restriction of magnitude at some particular wavelength, or range of wavelengths, and refer to the total power of the source integrated over all wavelengths. The bolometric correction is then the quantity that must be added to the visual magnitude to obtain the bolometric one. In general, it is negative in value.

brightness

This directly perceived datum is closely associated with the apparent magnitude for point-like sources, i.e. stars. For extended objects further specification is required. More physical details, connecting also with the related term 'intensity', are given in Chapters 3 and 4.

colour excess

Due to the strong correlation between colour index and surface temperature, if the temperature of a certain star is known a priori it should be possible to predict its normal colour index. Sometimes, however, stars or other astronomical sources produce anomalous effects, such as

[6] 1 parsec (pc) is the distance at which the mean Earth–Sun distance would subtend an angle of 1 arcsecond.