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 (~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

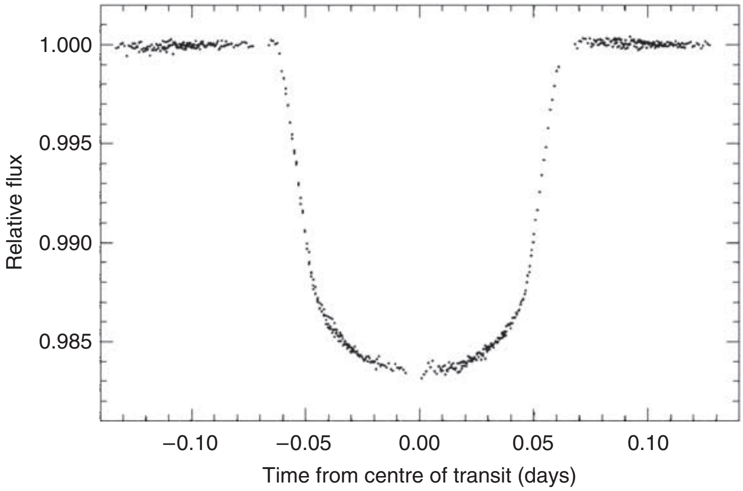

Figure 1.1 Eclipse of HD 209458 by its low-mass, presumed planetary, companion. The light curve has been combined from four separate recordings in April and May 2000 using the Imaging Spectrograph of the Hubble Space Telescope integrating over a yellow–orange region of the spectrum. Individual points 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

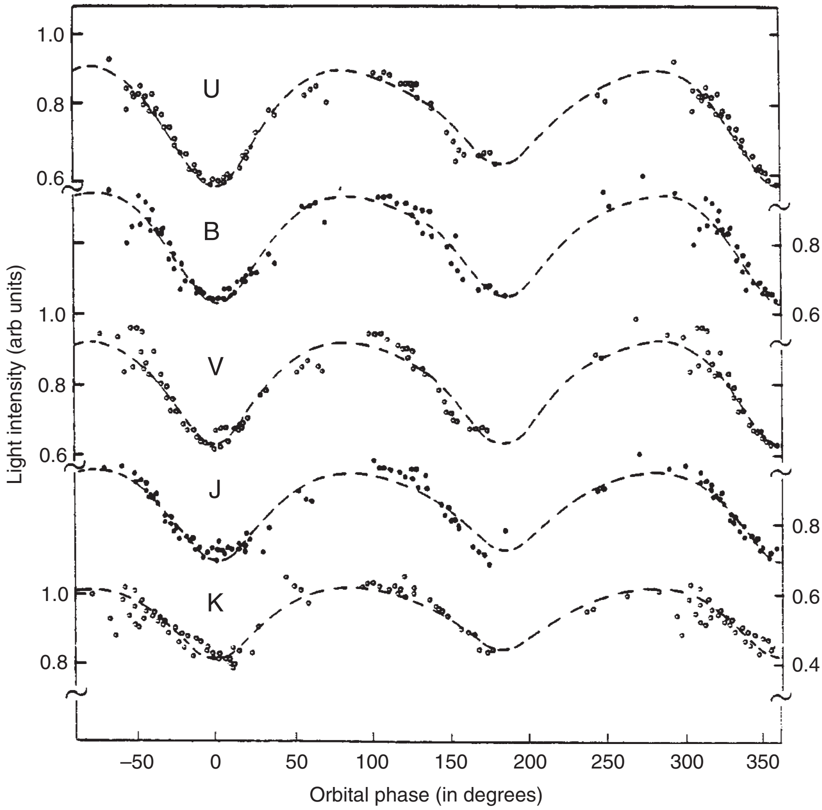

Figure 1.2 Light curves of the binary system CQ Cep in different broadband wavelength ranges

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/.

References

Brown, T. M., Charbonneau, D., Gilliland, R. L., Noyes, R. W. & Burrows, A., 2001, *Astrophys. J.*, **552**, 699.
Golay, M., 1974, *Introduction to Astronomical Photometry*, Reidel.
Good, G. A., 2003, *Observing Variable Stars*, Springer-Verlag, 2003.
Hall, D. S. & Genet, R. M., 1998, *Photoelectric Photometry of Variable Stars*, Willmann-Bell.
Henden, A. A. & Kaitchuk, R. H., 1998, *Astronomical Photometry*, Willmann-Bell.
Jaschek, C. & Jaschek, M., 1989, *Classification of the Stars*, Cambridge University Press.
Jones, A., 1995, *Austral. J. Astron.*, **6**, 81.
Mazeh, T., Naef, D., Torres, G. *et al.*, 2000, *Astrophys. J.*, **532**, 55.
Oswalt, T. D., Hall, D. S. & Reisenweber, R. C., 1990, *I.A.P.P.P. Commun.*, **42**, 1.
Percy, J. R., 1986, *The Study of Variable Stars Using Small Telescopes*, Cambridge University Press.
Sterken, C. & Manfroid, J., 1992, *Astronomical Photometry: A Guide*, Kluwer.
Sterken, C. & Jaschek, C., 1996, *Light Curves of Variable Stars: A Pictorial Atlas*, Cambridge University Press.
Stickland, D., Bromage, G. E., Burton, W. M., Budding, E., Howarth, I. D., Willis, A. J., Jameson, R. & Sherrington, M. R., 1984, *Astron. Astrophys.*, **134**, 35.
Straizys, V., 1995, *Multicolor Stellar Photometry*, Pachart.