Martin Griffiths

Observer's Guide to Variable Stars

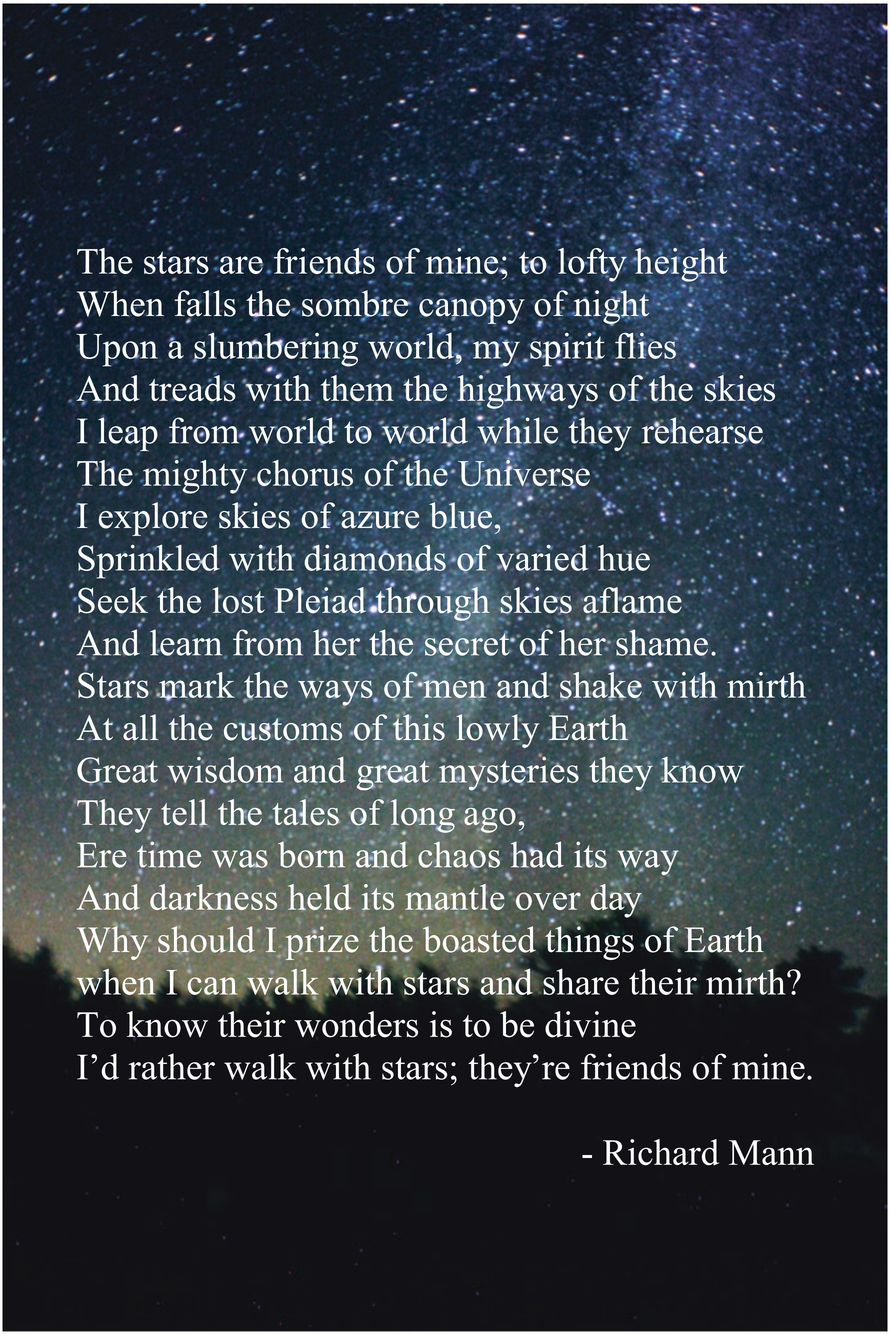
The Patrick Moore
Practical Astronomy
Series

The Patrick Moore Practical Astronomy Series

Series Editor

Gerald R. Hubbell
Mark Slade Remote Observatory, Locust Grove, VA, USA

More information about this series at http://www.springer.com/series/3192



The stars are friends of mine; to lofty height
When falls the sombre canopy of night
Upon a slumbering world, my spirit flies
And treads with them the highways of the skies
I leap from world to world while they rehearse
The mighty chorus of the Universe
I explore skies of azure blue,
Sprinkled with diamonds of varied hue
Seek the lost Pleiad through skies aflame
And learn from her the secret of her shame.
Stars mark the ways of men and shake with mirth
At all the customs of this lowly Earth
Great wisdom and great mysteries they know
They tell the tales of long ago,
Ere time was born and chaos had its way
And darkness held its mantle over day
Why should I prize the boasted things of Earth
when I can walk with stars and share their mirth?
To know their wonders is to be divine
I'd rather walk with stars; they're friends of mine.

- Richard Mann

Observer's Guide to Variable Stars

Martin Griffiths

Springer

Martin Griffiths
Dark Sky Wales, Blackmill, Bridgend
Wales, UK

ISSN 1431-9756 ISSN 2197-6562 (electronic)
The Patrick Moore Practical Astronomy Series
ISBN 978-3-030-00903-8 ISBN 978-3-030-00904-5 (eBook)
https://doi.org/10.1007/978-3-030-00904-5

Library of Congress Control Number: 2018957655

Image Credit: NASA

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

This book is dedicated to my wonderful wife Dena with thanks for all your support and love and to our mad dogs Gloria, Ianto and Jango that drive us crazy.

Preface

Variable stars are one of the most diverse and rewarding fields of study in astronomy. Such stars not only vary in brightness, but understanding the nature of this variability leads us to know the most amazing and wonderful sets of objects and a deeper knowledge of stellar systems and evolution. In short, variable stars are fascinating, beautiful and enchanting.

I have been an astronomer from a young age and have been captivated by many objects that have become personal favourites; as with most other astronomers, one returns time and again to old familiar ones no matter how often they have been examined in the past. Variable stars provide an observer with such a range of objects and a diversity of forms that the observer will always find something new to occupy them.

I have set this book out in a format that will hopefully enable the novice to pick up the information and go with it into the observing field. I do not expect everyone to engage completely with the astrophysical concepts, although learning about such adds stimulus to variable star research, as I believe that a good understanding of the processes involved can add to the observing experience. This field of research is also one in which individual discoveries can still be made, and the contribution of amateur astronomers is often all that we have as a scientific community on the nature and processes behind such stars. It is a field where the mundane is anything but that.

I hope that this volume will provide the tools necessary to start searching for these wonderful entities. It does not matter what the aperture of your telescope is or how frequently you observe. The stars included in this book I hope will please and delight most observers. I have attempted to strike a balance between easily visible objects that can be seen in any telescope or binoculars and variable stars that are a direct challenge to those with large aperture equipment or access to photometric tools and methods.

I have also attempted to cover a brief historical and physical analysis of variable stars in order that readers have a ready volume covering both observational and astrophysical aspects of the subject, which will give added understanding and impetus to their search. I find that when teaching students, the ability to see anything through a telescope is augmented by the fuller physical understanding of its intrinsic nature, leading to a greater appreciation for the object. Observing any object with relatively small telescopes is not going to reveal a professional, observatory quality image. But this lack can be turned to our advantage by imparting some foreground knowledge on the inherent nature of the item viewed, enabling an appreciation of cosmic distance, scale and stellar power from our fleeting earthly platform.

In the final analysis, I want observers to enjoy their experiences in hunting down these wonderful stars and discovering them for themselves. I hope this small book will help one to grow in knowledge and appreciation of one striking facet of the universe around us.

Dark Sky Wales, Blackmill, Bridgend, Wales, UK Martin Griffiths
2018

Acknowledgements

I have been looking at the stars since I was a young boy and have spent many nights marvelling at the wonders of the night sky. As I moved from amateur to professional astronomy, my love of the sky and my amazement at all it contains have never dimmed. Along the way, I have encountered many people who have encouraged me and have helped make my dreams come true, not least of which are those who encouraged me to write. This is the sixth book that I have written and one which I have enjoyed researching and writing. As an astronomer, I am keenly aware of the importance of variable stars and their application to so many fields of astronomical science.

I would like to thank the staff at Springer for their help and encouragement and also the helpful staff at the BAA Variable Star Section, especially Roger Pickard, to whom I am indebted for the images of star fields and comparisons for the final chapter of the book. In addition, the AAVSO staff and observers have proved to be very helpful in offering advice and allowing me to draw upon their expertise and online materials to provide examples and to illustrate how much help is available to variable star observers should they take up this field of research.

Unless otherwise indicated in the text, all photographs are copyrighted.

Contents

Chapter 1

An Introduction to Variable Stars

Monitoring and recording variable stars is one of the oldest and noblest activities in amateur astronomy. In very few other fields is it possible for the modestly equipped observer to make discoveries of extreme significance and enable professional astronomers to follow up on the astrophysical aspects of such phenomena.

We have learned an enormous amount from watching the differences in light output from such stars. Although the heavens were seen to be immutable and unchanging for millennia, the discovery of variable stars showed that the ancient ideas were incorrect. Variable stars ushered in a new era in science as their true nature demanded the application of various disciplines from physics and mathematics, from chemistry to spectroscopy and to photography, photometry and cartography.

With this in mind, it would seem that modern variable star observation by amateurs is redundant. However, nothing could be further from the truth. There are a huge range of large instrumental surveys of variable stars, but it must be remembered that they do not provide the same coverage that visual observers historically have. In addition, very few surveys fully cover the same brightness range available to visual observers, and many surveys are from a single location and are dependent on weather conditions and other factors. Having a host of observers worldwide covering many objects and overlapping some provides adequate coverage, a sense of purpose and the bonds of sharing something special together.

M. Griffiths, *Observer's Guide to Variable Stars*, The Patrick Moore Practical Astronomy Series, https://doi.org/10.1007/978-3-030-00904-5_1

What are variable stars? How were they discovered and what distinct types of variable stars are there? As one reads through this book it may seem to be a mindstorm of letters, abbreviations and catalogues, but remember that we are standing at the end of over 400 years of astronomical discovery. Let us examine the history of discovery and then turn to a brief overview of their types.

History of Variable Stars

According to S. Porceddu et al writing in the *Cambridge Journal of Archaeology* in 2008 andagain in 2013, there exists an ancient Egyptian calendar comprised of lucky and unlucky days. Exactly what this means is not relevant here, but this calendar, composed some 3,200 years ago, contains some interesting astronomical information, and these scholars suggest that it may be the oldest preserved historical document of the discovery of a variable star. The star is the eclipsing binary Algol in the constellation of Perseus. We know that the Egyptians, among many other ancient civilizations, were avid watchers of the sky, so such an observation may well be possible. Indeed, the Persian astronomer Al Sufi in his *Book of the Fixed Stars* mentions the possibility of Algol's variability in the year A. D. 964.

The first definitive variable star was recorded in 1638 when Johan Holwarda noticed that o Ceti (later named Mira) pulsated in a cycle taking about 11 months. However, the star had previously been discovered by David Fabricius in 1596, but he thought that it was a nova. Holwarda's discovery, combined with the earlier supernova of Tycho Brahe in 1572 and that of Johannes Kepler in 1604, were ground breaking in that they proved that the stars were not invariable as Aristotle and other ancient philosophers had taught. In this way, the discovery of variable stars contributed to the astronomical revolution of the sixteenth and early seventeenth centuries.

The second variable star to be described was the eclipsing variable Algol, by Geminiaro Montanari in 1669, but it was left to John Goodricke to present the correct explanation of its variability in 1784. The long period variable χ Cygni was identified in 1686 by the astronomer Gottfried Kirch, then the star R Hydrae in 1704 by Dominico Maraldi.

To understand the variability of such stars, astronomers had to observe their variability over specified time periods and draw a graph showing the differences in brightness over time. Such graphs are known as light curves. In the study of objects that change their brightness over time, such as novae, supernovae, and variable stars, the light curve is a simple but valuable tool

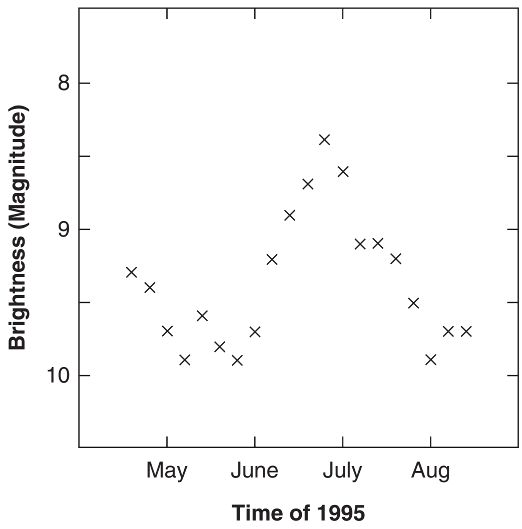


Fig. 1.1 Simple light curve (Image from https://imagine.gsfc.nasa.gov/science/toolbox/timing1.html)

to an astronomer and a tool that reveals much about the system under scrutiny. An example can be seen in Fig. 1.1.

The record of changes in brightness that a light curve provides can help astronomers understand processes at work within the object they are studying and identify specific categories (or classes) of variable events. Thanks to successive generations of astronomers studying variables and drawing light curves based upon observation, astronomers know generally what light curves look like for a class of variable star. In this fashion, when a new light curve of a variable star is plotted, we can compare it to standard light curves in order to identify the type of star under observation.

The gifted British astronomer John Goodricke discovered the variability of both δ Cephei and β Lyrae, while his astronomical companion Edward Piggott discovered η Aquilae in 1783. Working in concert with each other and communicating via letters (Goodricke was deaf and mute) Goodricke and Piggott distinguished two classes of variable star. The first type consisted of objects such as Algol, which exhibited a single sharp change in brightness on a regular basis. In the case of Algol, Piggott and Goodricke correctly surmised that the changes in brightness could be explained by transits of some dimmer object across the star, and they even postulated that it might be caused by a transiting planet. This remarkable achievement was tempered once it was known that Algol has a transiting fainter companion star rather than a planet.

The second type the pair distinguished included variable stars such as δ Cephei, whose brightness changed continuously and whose peak brightnesses were not necessarily identical from period to period. They inferred correctly that these irregularities meant that something had to be happening internally to the star, as a transit would produce a regular light curve with no differences between successive periods. Thus they heralded a new field of astrophysical phenomenon that took almost two centuries to understand. Goodricke's notes can be seen here in Fig. 1.2.

By 1786 at least ten variable stars were known. The astronomer William Herschel also drew attention to variable stars and studied the light curves of δ Cephei, β Lyrae and η Aquilae in 1784. In 1787 he discovered that the

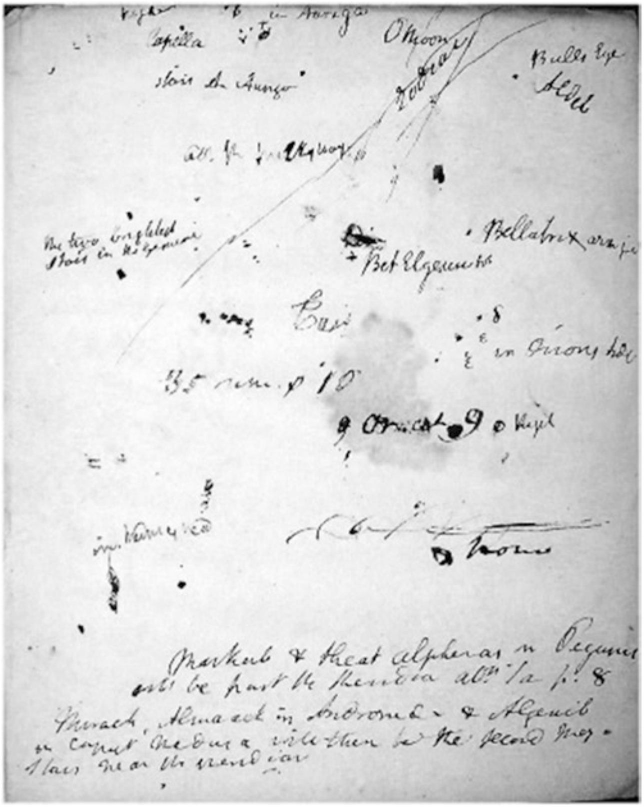


Fig. 1.2 Goodricke's notes of δ Cephei (Image from https://www.researchgate.net/figure/John-Goodricke-1764-1786-Pastel-portrait-by-James-Scouler-now-the-property-of-the_fig1_224861563.)

fainter component of the binary star ι Bootis was variable, and in 1795 he also discovered the irregular variations of the star α Herculis. His son, John Herschel, added to the catalogues of known variable stars with his observations of the southern hemisphere sky from Feldhausen in South Africa in the 1830's.

The following table lists the known variable stars up to the beginning of the 19th century.

Star	Year Discovered	Discoverer
o Ceti (mira)	1596	Fabricius
β Persei	1669	Montanari
χ Cygni	1687	Kirch
R Hydrae	1704	Maraldi
R Delphini	1751	Hencke
R Leonis	1782	Koch
μ Cephei	1782	Herschel
β Lyrae	1784	Goodricke
δ Cephei	1784	Goodricke
η Aquilae	1784	Pigott
R Coronae Borealis	1795	Pigott
R Scuti	1795	Pigott
α Herculis	1795	Herschel

The increase in discoveries in the latter half of the 18th century typifies the way in which scientific observations of the sky were being made in systematic sweeps by people such as William Herschel and Edward Pigott.

It was important that these new types of stars be given some significance so that observers could follow them as often as possible. Therefore, a system was developed by the German astronomer Friedrich Argelander, who gave the first previously unnamed variable in a constellation the letter R, which was the first letter not used by Johannes Bayer in his 1603 *Uranometria.* Today, in any given constellation, the first set of variable stars discovered is designated with letters R through Z. The letters RR through RZ and SS through SZ, and up to ZZ are used for the next variable stars in the constellation. Later discoveries used letters AA through AZ, BB through BZ, and up to QQ through QZ (the letter J is omitted, however). Once those 334 combinations are exhausted, variables are then numbered in order of discovery, starting with the prefixed V335 onwards.

Argelander's seminal star catalogue *Uranometria Nova*, published in 1843, encouraged worldwide interest in the study of variable stars. In fact, Benjamin A. Gould was a pupil of Argelander and became the first American astronomer to receive training in Germany. When he returned to America he encouraged variable star observation and produced his own catalogue of southern variables, called *Uranometria Argentina,* in 1879.

The 19th century saw the application of astronomers such as J. R. Hind in London and the American observers Seth C. Chandler, Edwin F. Sawyer and Paul S. Yendell to variable star work, who all observed from New England.

Chandler produced three catalogues of variable stars, and in 1878 he even produced papers on how to observe variable stars that were circulated among astronomers. In the following years, Chandler continued his variable star work at Harvard College Observatory, although he never became a member of the faculty. Edwin Sawyer was discovered to be a remarkable observer by Chandler, who promoted his interests to produce a catalogue of over 3,400 southern variable stars. The third member of this remarkable trio, Paul Yendell, contributed 140 papers in just 10 years to the journal *Popular Astronomy.* The incredible thing about all three observers was that they were amateurs with no formal training. Chandler was an insurance clerk, Sawyer a bank clerk and Yendell was a shopkeeper! However, being in close association with the director of the observatory at Harvard College, Edward C. Pickering could see the need for a formal society to collate information and disseminate ideas.

Pickering personally made over 6,000 variable star observations and produced catalogues for astronomical use, but by 1910 it was obvious that the sheer number of observations – and observers – required a fresh and organized approach. Eventually it was, once again, an amateur astronomer who took up the responsibility and began to correspond with variable star observers all over the United States. William Tyler Olcott offered his services to Pickering, and an American variable star observer's society began with an article in the November issue of *Popular Astronomy.* The dedication and patience of generations of observers laid the foundations for a society that has become instrumental in amateur and professional variable star work – the American Association of Variable Star Observers, or the AAVSO.

In Great Britain a similar society was inaugurated under the British Astronomical Association (BAA), and it predates the AAVSO. The BAA was founded in 1890, and in the same year a section of variable star observers was set up to encourage observations and produce papers and materials for distribution to other amateurs. The Variable Star Section (VSS) still maintains the aim of collecting and analyzing observations of variable stars. Reports to its members are given via the VSS circulars published four times a year, and there are many articles in the bi-monthly BAA journal.

With the invention of the spectroscope and astronomical photography, the number of known variable stars increased rapidly to the point that now, in the 21st century, the *General Catalogue of Variable Stars* lists more than 46,000 variable stars in the Milky Way alone, as well as 10,000 in other galaxies and over 10,000 'suspected' variables.

Broad Groups of Variable Stars

Variable stars are so different in type and variety that trying to pull them all together into simple headings is a difficult task. However, astronomers noticed that there is a broad distinction that can be used. Whatever happens to cause the variability of any star is due to just two factors: something is happening to the star internally, or something is affecting the star externally. These two reference points then can produce a broad category for variable star discovery once we have a good light curve.

Intrinsic variable stars are stars where the variability in light output is being caused by changes to the physical body of the stars themselves. The following light curve in Fig. 1.3 illustrates the activity of such stars.

As can be seen, the period of variability is over 5.4 days. There a sharp rise to maximum light (maxima), which reveals that the underlying mechanism inflates the star quite quickly to maximum size and luminosity. As the stellar surface cools and relaxes, the star returns to normality in a smooth decline that is not as sharp as the original rise. This shows that radiation is escaping the star in a gradual process almost like a release valve, allowing the surface to return to normal in a controlled fashion before the

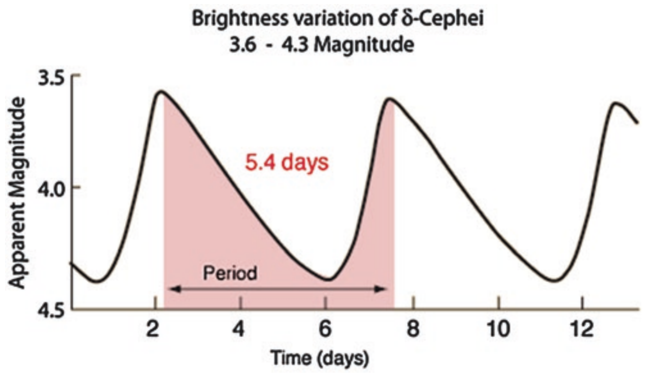


Fig. 1.3 Intrinsic variable light curve (δ Cephei). (Image from http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/cepheid.html.)

whole process starts again. We will deal with the mechanism of expansion and contraction in the chapter on the astrophysics of such objects.

Overall, intrinsic variables follow a general pattern of the above light curve, with subtle or extreme changes dependent on the type. Intrinsic variable stars can be divided into three main subgroups:

Pulsating variables:

Wherein the star's radius alternately expands and contracts as part of its natural evolutionary processes. The stars literally swell in size before declining back to their (almost) original size (see Fig. 1.3).

Eruptive variables:

These are stars that experience physical eruptions on or from their surfaces such as flares or mass ejections.

Cataclysmic or explosive variables:

These are stars that undergo a cataclysmic change in their properties, like novae or supernovae. Although some of these types interact with a companion star they fall within the intrinsic variable bracket, as the mechanism of variability happens to the main star.

The second major group of variable stars is what are called extrinsic variable stars. These are stars where the variability is caused by external properties such as rotation or eclipses with a binary companion. The illustration here in Fig. 1.4 shows the mechanism behind an eclipsing variable star.

This is the light curve of Algol, a typical eclipsing binary and one of the most studied objects in the heavens. As Piggott and Goodricke discovered, the light curve and period of variability are very constant.

When the line is flat, both stars are visible from Earth; then a primary eclipse begins as the fainter companion stars moves in front of the primary and causes the light output to decline rapidly. In some eclipsing variables there will be a flat bottom to the prime eclipse. This shows that the eclipsing star takes some time to move across the line of sight of the primary. Details such as this give us such information as relative size of each star, the orbital period and a host of other factors.

Once the companion moves away from the primary, a sharp increase to normal light is achieved before the secondary star goes into eclipse behind the primary, and a smaller, shallower eclipse of the fainter star is seen before the orbit brings both into view and the light output returns to normal once more.

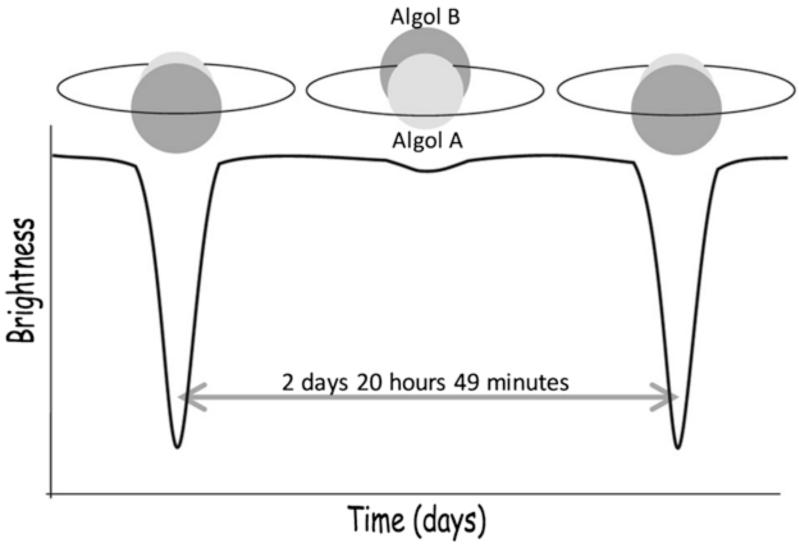


Fig. 1.4 Eclipsing variable (Algol) (Image from http://www.adirondackdailyenterprise.com/opinion/columns/2016/12/look-into-medusas-eye-for-the-demon-star/.)

With extrinsic variable stars there appear to be two main subgroups:

Eclipsing binaries:

These are double stars where, as seen from our vantage point here on Earth, the stars occasionally eclipse one another as they orbit their common centers.

Rotating variables:

These are stars whose variability is caused by phenomena related to their rotation. Rotating variables may be subject to such phenomena as extreme ‘sunspots,’ which then affect the apparent brightness of the star or in some cases they are stars that have fast rotation speeds, which cause them to become ellipsoidal, or egg shaped!

In both intrinsic and eclipsing variable stars, the subgroups themselves are further divided into specific types of stars that are usually named after their prototypes.

Catalogue Classifications

The common types as seen above are of course subdivided due to type and into subgroups that illustrate the peculiarities of some of the variable star systems. There are additional identification markers that illustrate the wide variety of variable stars and also show that just one sort of variability is not inimical to some systems. Several sub-types show behavior that is typical of several different types, and as a result, these features need to be illustrated for correct classification.

The most important reference source for variable stars is the *General Catalogue of Variable Stars* (GCVS), which contains data for 52,011 individual variable objects discovered and named as variable stars by the year 2015 and located mainly in the Milky Way. From this source is taken the *International Variable Star Index* (VSX) used by the AAVSO, and one can register and scan the VSX at this website: https://www.aavso.org/vsx/. It is instructive to note that variable classes and types are all in uppercase bold letters, so a star such as R Coronae Borealis will be known as RCB, while γ Cassiopeia systems will be GCAS. Some measure of knowledge of constellations is required to tease the names out, but this should be *de rigeur* for amateurs who are going to undertake such work with variables. To learn more about the *General Catalogue of Variable Stars* and to peruse it, then check out this website: http://www.sai.msu.su/gcvs/gcvs/vartype.htm**.**

Some of the types of variable stars that one will encounter in this book are placed here as a rough and quick guide with some examples of the nomenclature given for certain stars. We shall examine these types in more detail in each chapter on them.

Eruptive variables:

BE, FU, GCAS, I, IA, IB, IN, INA, INB, INT, IT, IN(YY), IS, ISA, ISB, RCB, RS, SDOR, UV (UV Ceti), UVN, WR (Wolf-Rayet types).

It should be noted that the I types here are generally poorly studied and amateurs with the correct photometric equipment may make some valid scientific contributions to their field of study. Many of them (IN to INYY) are commonly known as Orion-type variables, so we are generally looking at young objects.

Pulsating variables:

ACYG, BCEP (β Cephei), BCEPS, BLBOO, CEP, CEP(B), CW, CWA, CWB, DCEP, DCEPS, DSCT, DSCTC, GDOR, L, LB, LC, LPB, M (Mira types), PVTEL, RPHS, RR, RR(B), RRAB, RRC, RV, RVA, RVB, SR, SRA, SRB, SRC, SRD, SRS, SXPHE, ZZ, ZZA, ZZB, ZZO.

The pulsating variables are a fascinating group, as they generally pulsate in regular fashion in a radial expansion. However, some types, such as L to LPB, reveal irregular behavior that is probably due to non-radial pulsation. Sections of the star are moving inward and outward in different modes, and so the star is no longer a spherical object. Some Mira-type variables exhibit such behavior.

Rotating variables:

ACV (A Canes Venaticorum), ACVO, BY, ELL, FKCOM, PSR, R, SXARI.

Rotating variables, as the name suggests, are stars without a uniform surface brightness, although the mechanism for some of their variability remains unclear. Most often the periods are due to the stars being ellipsoid in shape due to fast rotation. Occasionally, the stars vary as large spots or groups of spots are brought into view by the rotation of the star, or there may be some form of thermal or chemical differences in the photosphere or chromosphere, possibly created by a magnetic field. It is thought common to these stars that these intense magnetic fields may not have polar axes in the same plane as the rotational axis.

Cataclysmic variables:

N, NA, NB, NC, NL, NR (recurrent nova), SN, SNI, SNII, UG (U Geminorum types), UGSS, UGSU (SU Ursae Majoris types), UGZ, ZAND (Z Andromedae).

Irregular outbursts characterize these stars, and the group contains not just the supernovae types but the more common U Geminorum types, known as dwarf novae. The UGSS types are SS Cygni stars while the UGZ are very interesting Z Camelopardalis-type stars. After outburst they do not always return to their original luminosity but remain a magnitude or so above their mean.

Eclipsing binary systems:

E, EA, EB, EP, EW, GS, PN, RS (RS Canes Venaticorum), WD (stars with white dwarf components), WR (eclipsing Wolf-Rayet stars), AR, D, DM, DS, DW, K, KE, KW, SD.

Many eclipsing variables are stars that evolve within binary systems and thus fill an area known as the Roche lobe. If they do this as they expand, then materials can tip over the inner Lagrange point and mass transfer begins. The characteristics of such light curves are complicated by rotation around their gravitational centers, the spread of material masking the light output of the stars and the contribution to the light curve from hotspots in accretion discs. Obviously, they are not as simple as the typical Algol system!

Additional methods of identification are used in both catalogues. For example, an upright character (I) between two different types gives the distinction "or" if the classification of the star is uncertain. A typical example of this is ELLIDSCT, where the star may be an ellipsoidal binary system or a δ Scuti-type pulsating variable.

The symbol + means that there are two different variability types in the same star system. An example of this would be ELL+DSCT, where one of the components of an ellipsoidal binary system is again a δ Scuti-type pulsating variable.

The slash (/) symbol indicates a subtype of star. In the case of binary systems, it is used to help describe either the physical properties of the system (E/PN or EA/RS) or the luminosity class of the components (EA/DM). These are some common components of the standard General Catalogue of Variable Stars classification system.

Most star designations are self-evident as typical of their sub-types or are named after the progenitor star of their type. So, as examples, we can discern non-eclipsing RS Canes Venaticorum-type stars as (RS), Wolf-Rayet stars as (WR) and so on. For some cataclysmic variable stars, the subtypes of NL or "nova-like" are designated NL/V, or NL/VY are designated as independent classes since these subtypes do not apply to a class other than NL.

We have to be as careful and as accurate as possible in defining variable subtypes, as many variables show more than one type of variation. In order to distinguish these types, it is easier to identify the primary cause of variability and use that as the basis of classification. For example, S. Doradus-type stars (SDOR) show both eruptions and pulsations, but they have been included in the eruptive group only. The type of definition gives an instant explanation of their chief behavior. Another example can be seen from the R. Coronae Borealis (RCB) stars, which also pulsate. However, their main variable feature is a deep plunge from their normal magnitude to something very dim; then they are included in the eruptive group only. Similarly, the mechanism of variability of the λ Eridani types (LERI) is not well known. It is thought that their variability may be due to either rotation or pulsation, but they are included in the class of rotating variables only.

Now that we have looked at a brief history of their discovery and a basic explanation of variable star types, perhaps it is instructive to ponder exactly what is going on with these stars. Why do they vary and what are the underlying mechanisms that drive such behavior? That will be the subject of our next chapter.

Chapter 2

The Astrophysics of Variable Stars

Stars experience stages of birth, growth, middle and old age and finally death. Astronomers talk of these stages as progressive stellar evolution, although it bears no resemblance to the biological theory of evolution proposed by Darwin. They begin with nebulae and generally end with a nebula, whether it be a planetary nebula or the expanding mass of a supernova explosion. Stars are the only entities in our universe that follow the strict rule of evolution, slow change with time, but they always remain stars, of course, for the majority of their lives.

The remarkable thing about stars is that, while they remain constant for long periods of time, during their birth phase and during their mature years they all undergo variability of some kind. The different forms of variability have given rise to many types of variable class, some of which are tied together due to age and general features of the spectral type, some of which are dependent on their mass and others which are dependent on age. Variable stars can also change their spectral class and color as they vary, while most stars undergo some transformation in color and luminosity as they either settle down to a long life or age and die. Knowing something about the life cycle of stars and their origins will therefore inform us as to the types of variable stars we are observing.

M. Griffiths, *Observer's Guide to Variable Stars*, The Patrick Moore Practical Astronomy Series, https://doi.org/10.1007/978-3-030-00904-5_2

Population Types

A classification that is important to the nature of the variable is the grouping of stars into what has become known as stellar populations. Thankfully, there are only two of these classes. This rule of thumb has arisen due to the discovery that not all stars are equal in their chemical composition. Many stars that have great ages were found to be deficient in many common metals such as sodium, magnesium, etc. This is entirely due to their periods of origin. Older stars are of relatively low mass and are found in the nucleus and halo of the Milky Way Galaxy in addition to being members of the globular clusters.

These stars are known to be at least 10 billion years old or more, and to have formed at a time when our galaxy, indeed most of the universe, was forming. As the greater majority of galaxy building material was hydrogen, then these stars are primarily hydrogen based, whereas stars of later generations, while also predominantly hydrogen, have a large admixture of metals. These second generation stars are to be found only in the discs of galaxies, where nebulae and clouds of dust abound to create more young stars.

Thus astronomers classify old halo and nuclei stars as Population II, and young stars of the galactic disc are called Population I. The classification is easy to remember if you consider their location in any galaxy:

Population I - Stars of the galactic disc and star clusters
Population II - Stars of the galactic halo, galactic nucleus and globular clusters

Variable stars of the Population I group include classical Cepheid variables, the majority of long period variables (LPV) and luminous blue variables (LBV). Variable stars of Population II are RR Lyra-type variables, W Virginis stars and some LPV's. We shall examine these stars in due course, but it may be instructive to understand how stars are classified and know the story of stellar evolution.

Stellar Classification

Most of the public is completely unaware that stars have different colors. Color perception is a personal thing, and just a little training by examining different stars will enable one to identify these colors quite easily. This color difference is extremely important as color is related to the stellar temperature.

The first time stars were grouped according to color was at Harvard University at the end of the 19th century. The eminent astronomer Edward Pickering brought together a fine group of young ladies to do the work of assisting him in his quest to catalogue stars by spectral appearance. This was an unusual step to take, when astronomy was generally considered a gentleman's pursuit. As a result, the group become affectionately known as "Pickering's Harem," but these young ladies proved to be a valuable resource; several of them, such as Henrietta Leavitt, Cecilia Payne-Gaposhkin and Annie Jump Cannon, made discoveries of literally cosmic importance as their work moved into the 20th century.

Recognizing the importance of color as a function of temperature, the Harvard ladies first thought to catalogue the stars by using the English alphabet A, B, C, D, etc. However, the constraints placed upon the colors and spectral characteristics of stars led to the representation that is used today, as many of the original classifications turned out to be false leads or were repetitions of other stars. This classification by color revealed that the hotter the star, the more blue it was; the cooler the star, the redder it was. This reflects the electromagnetic spectrum itself, where the component of visible light that we see between 390 and 700 nm (nanometer or nm = 1 billionth of a meter or 1×10^{-9} m) follows the grouping of colors familiar to us from the rainbow in Fig. 2.1. The shorter (violet) end of the spectrum is at 400 nm and the longer wavelengths (red) are close to 700 nm.

The grouping that the Harvard computers eventually settled on as representative of all stellar spectra, using the strength of the hydrogen Balmer lines and Wein's law as a guide is simply this: O B A F G K M, as seen in the illustration here. These are taken singly below:

Type 0 stars are blue-white and extremely hot, typically around 25,000 K and higher. These quite massive stars are very luminous and are the most

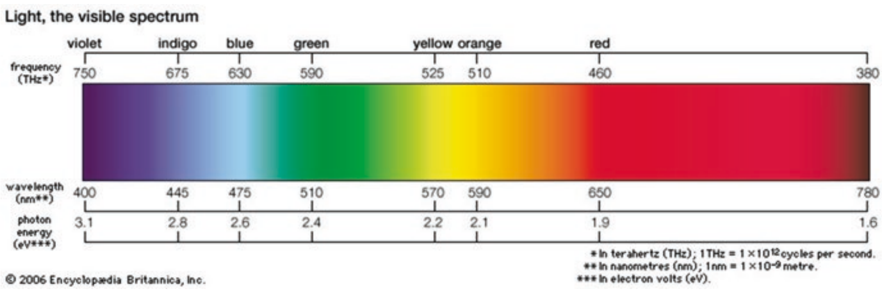


Fig. 2.1 The visible spectrum

short-lived of stars. Their spectra show lines from ionized helium, nitrogen and oxygen. A typical example of this class is Iota Orionis.

Type B stars are blue-white and very hot, with temperatures of around 20,000 K. Stars of this type are generally massive and quite luminous. Their spectra display strong helium lines. Rigel, Spica and Regulus are good examples of this class. Compare Rigel and Regulus as an exercise.

Type A stars are white, with temperatures of around 10,000 K. Their luminosities are usually about 50 to 100 times that of the Sun. At these temperatures no helium lines are present, but strong hydrogen lines appear in the spectra. Sirius, brightest star in the night sky, is of this class as are Vega and Altair, part of the summer triangle.

Type F stars are yellow or yellow-white, with temperatures of about 7,000 K. Their spectra show weaker hydrogen lines, but strong calcium lines. In some of the later classes the spectra of metals begin to appear. The winter star Procyon in Canis Minor is of this class.

Type G stars are yellow, with temperatures of about 6,000 K. Their spectra show weaker hydrogen lines, but stronger lines of many metals. The sun is a typical G-type star.

Type K stars are orange, with temperatures of about 4,000 to 4,700 K. They have faint hydrogen lines, strong metal lines and hydrocarbon bands in their spectra. Aldebaran in Taurus and Arcturus in Bootes are good examples.

Type M stars are red, with temperatures of about 2,500 to 3,000 K. They have many strong metallic lines and wide titanium oxide bands, with other exotic compounds in their spectra. Betelguese and Antares are spectacular and easily visible examples of this class.

There are three other classes, namely R, N and S, now referred to as C-type stars, but these refer to fairly rare types of stars. A useful way of remembering the classification is by using the phrase: **O**h **B**e **A** **F**ine **G**irl **K**iss **M**e **R**ight **N**ow **S**mack! The groups can be seen in the H-R diagram below. Each of the classes are further divided into the numbers between 0–9 so that a better approximation can be made of the spectral type. Under this taxonomy a star can be a B5 type with spectral features of the typical B class but with additional elements appearing within the spectra due to the star being slightly cooler than a B0.

Due to this color and temperature relationship, it is possible to take the peak visible output of a star in nm and work out the peak wavelength of light – or its dominant color by using a mathematical relationship first postulated by the German physicist Wilhelm Wein in 1893. This is known as Wein's law. Simply put, Wien's law is the relationship between the peak