1
Historical Overview

1.1
Discovery of the First Pulsating Variable Stars

Although cataclysmic variable stars of the nova or supernova type had been seen since antiquity (Stephenson & Green, 2002), by the sixteenth century stars were generally regarded as fixed and unchanging in both position and brightness (Hoskins, 1982). The outburst of a bright supernova in Cassiopeia in 1572 (Tycho's supernova) startled the astronomical community and reawakened interest in apparently new stars. Almost 14 years later, in 1596, David Fabricius (1564–1617) observed what he thought was yet another new star, this time in the constellation Cetus.

Fabricius's new star was only of the third magnitude, far less brilliant than Tycho's supernova, but nonetheless easily visible to the unaided eye. First seen in August, by October the star had faded below naked-eye visibility. However, Fabricius's star had not forever vanished. A few years later, it was recorded by Johann Bayer, who named the star omicron (*o*) Ceti and placed it on his 1603 star charts, although Bayer appears to have been unaware that he had rediscovered Fabricius's nova. In 1609, it was Fabricius himself who was surprised to see the new star make a reappearance. While *o* Ceti certainly seemed unlike Tycho's new star of 1572, Fabricius did not suspect that he had discovered a star that was not a nova but one that instead showed periodic changes in brightness (Hoskins, 1982).

In 1638, Johannes Holwarda (1618–1651) made yet another independent discovery of *o* Ceti. Like Fabricius, Holwarda watched the star fade from view, only to see it subsequently reappear. Now other astronomers began to pay increased attention to the variable, but nonetheless the periodic nature of its variability still eluded recognition.

Johannes Hevelius (1611–1687) carried out a detailed study of *o* Ceti, and, in 1662, he published *Historiola Mirae*, naming the star Mira (meaning *the wonderful* in Latin), a name which has ever since been applied to it. Ismael Bullialdus (1605–1694) made the next advance. He noticed that the peak brightness of Mira occurred about a month earlier each year, finally discovering the cyclic nature of its brightness changes. In his 1667 *Ad astronomos monita duo* he determined the period to be 333 days, about 1 day longer than the current determination

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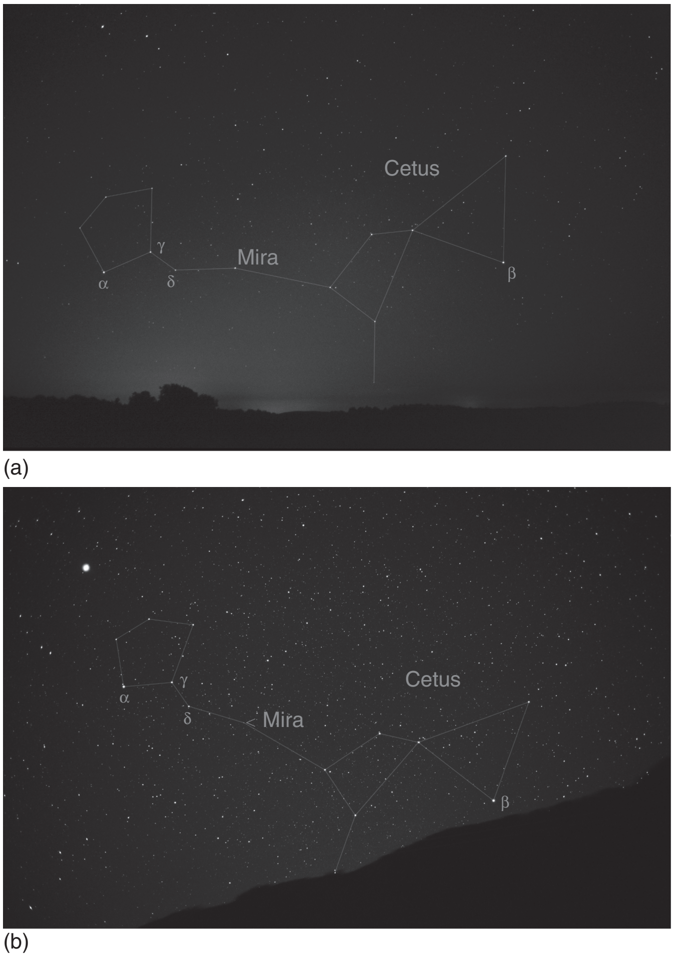

Figure 1.1 Mira near maximum (a) and minimum (b) light. The image (a) was taken from Römerstein, Germany, on July 17, 2004, whereas the image (b) was obtained on October 30, 2005, from Austria. Several of the nearby stars in Cetus are identified by their Bayer designations, and the Cetus constellation itself is also drawn. The bright object on the upper left corner in (b) is the planet Mars. The July 2004 image presents a view similar to that seen by David Fabricius at his discovery of that long-period variable star in August, 1596. (Images courtesy Till Credner, AlltheSky.com.)

of the mean period. Mira thus became the first variable star whose period was determined, and the archetype of the class of long-period variable stars now known as Mira variables. It would nonetheless be a long while before it was established that Mira's brightness changes had anything to do with pulsation (Hoskins, 1982).

Mira itself can become as bright as second or third magnitude at maximum light, making it easily visible to the naked eye (Figure 1.1). Other long-period variables, although not as bright as Mira, also have peak magnitudes that place them within the bounds of naked-eye visibility. That begs the question of whether Mira or other long-period variables might have been discovered before the time of Fabricius. Hoffleit (1997) summarized the evidence for pre-1596 observations of Mira. A number of possible pre-1596 observations have been suggested, going back to ancient times. Unfortunately, for none of the proposed pre-discovery observations is the historical evidence ironclad. The case is perhaps strongest for a 1592 "guest star" recorded in Asian records. However, Stephenson & Green (2002) concluded that even that object was unlikely to have actually been Mira.

The number of confirmed periodic variable stars increased only slowly following the recognition of the periodicity of Mira. For instance, in 1686 Gottfried Kirch discovered the variability of χ Cygni, a Mira variable with a period of 408 days (Sterken, Broens, & Koen, 1999). R Hydrae, a 384-day-period Mira variable, was found by Maraldi in 1704. A third Mira variable, 312-day-period R Leonis, was found by Koch in 1782. The long-period variability of these stars, and of Mira itself, would eventually be attributed to pulsation. However, little was known of shorter-period variable stars when the British team of Edward Pigott and John Goodricke took up the study of variable stars in earnest late in the eighteenth century.

Pigott and Goodricke soon confirmed the variability of Algol[1)] (β Persei), which had been originally established by Geminiano Montanari, and determined its period. Goodricke, in a 1783 report to the Royal Society, suggested that an eclipse might be responsible for the periodic dimming of Algol's light. Pigott discovered the variability of η Aquilae in 1784, and soon thereafter Goodricke identified the variables β Lyrae and δ Cephei. While β Lyrae proved to be an eclipsing variable star, η Aquilae and δ Cephei were the first representatives of the important Cepheid class of pulsating stars. The circumstance that Goodricke was deaf (and possibly mute) did not slow the progress of the pair, but Goodricke's untimely death at the age of 21 ended the collaboration in 1786 (Hoskins, 1982; French, 2012).

A list of the earliest discovered variable stars and their discovery dates is shown in Table 1.1, from which cataclysmic variables such as novae or supernovae have been excluded. The first column of this table identifies the variable star by name, while the second indicates into which category the variable star was eventually

1) The name comes from "al-Ghul," arabic for "the ghoul." It is often stated that this name was chosen to reflect the awe, and perhaps fear, that its variability would imply (to be contrasted with the name "Mira" that was given for *o* Ceti). However, and as discussed by Davis (1957), the name al-Ghul does not necessarily imply knowledge of the variability of Algol. Before the Arabs, β Persei was associated with the head of the Gorgon Medusa (as in Ptolemy). Davis says that the Ghul to the Arabs was a female demon and sorceress, and may have been adopted as a sort of monster similar to Medusa, rather than an indication of variability. On the other hand, Jetsu *et al.* (2013) have recently raised the intriguing possibility that the star's variability may have been known in ancient times to the Egyptians.

Table 1.1 Some of the first variable stars discovered.[a),b),c)]

Star	Type	Year	Discoverer	P(d)	V_{max}	A_V	SpT
o Ceti	Mira	1596	Fabricius	331.96	2.0	8.1	M5e-M9e
P Cygni	S Dor	1600	Blaeu	—	3.0	3.0	B1Iapeq
β Persei	Algol	1667	Montanari	2.8673043	2.12	1.27	B8V
η Carinae[d)]	S Dor	1677	Halley	—	−0.8	8.7	pec(e)
χ Cygni	Mira	1686	Kirch	408.05	3.3	10.9	S6,2e-S10,4e(MSe)
R Hydrae	Mira	1704	Maraldi	388.87	3.5	7.4	M6e-M9eS(Tc)
R Leonis	Mira	1782	Koch	309.95	4.4	6.9	M6e-M8IIIe-M9.5e
μ Cephei	SRc	1782	W. Herschel	730	3.43	1.67	M2eIa
β Lyrae	β Lyr	1784	Goodricke	12.913834	3.25	1.11	B8II-IIIep
δ Cephei	Cepheid	1784	Goodricke	5.366341	3.48	0.89	F5Ib-G1Ib
η Aquilae[e)]	Cepheid	1784	Pigott	7.176641	3.48	0.91	F6Ib-G4Ib
ι Bootis	W UMa	1785	W. Herschel	0.2678159	5.8	0.6	G2V+G2V
R Coronae Borealis	R CrB	1795	Pigott	—	5.71	9.09	C0,0(F8pep)
R Scuti	RV Tau	1795	Pigott	146.5	4.2	4.4	G0Iae-K2p(M3)Ibe
α Herculis	SRc	1795	W. Herschel	—	2.74	1.26	M5Ib-II
R Virginis	Mira	1809	Harding	145.63	6.1	6.0	M3.5IIIe-M8.5e
R Aquarii	Mira, Z And	1810	Harding	390	5.2	7.2	M5e-M8.5e+pec
ϵ Aurigae	Algol	1821	Fritsch	9892	2.92	0.91	A8Ia-F2epIa+BV
R Serpentis	Mira	1826	Harding	356.41	5.16	9.24	M5IIIe-M9e
S Serpentis	Mira	1828	Harding	371.84	7.0	7.1	M5e-M6e
R Cancri	Mira	1829	Schwerd	361.60	6.07	5.73	M6e-M9e
α Orionis	SRc	1836	J. Herschel	2335	0.0	1.3	M1-M2Ia-Ibe

a) The properties of these stars, as given in the last four columns, are taken from the online edition of the *General Catalogue of Variable Stars* (Kholopov *et al.*, 1998).
b) Excluding novae and supernovae; see, e.g., Zsoldos (1994) for a historical explanation.
c) R Delphini is incorrectly shown in Table 3 of Petit (1987) with a discovery date of 1751. The star's variability was actually discovered in 1851 by M. Hencke.
d) Enlightening reviews of historical observations of this star are provided by de Vaucouleurs (1952) and Smith & Frew (2011).
e) η Aquilae will also be found in early writings as η Antinoi, after the (now defunct) constellation of Antinous. Antinous was the name of Roman emperor Hadrian's favorite and posthumously deified lover, turned into a constellation by Imperial decree.

classified. The discovery date of the variable star is given in the third column, followed by the name of the discoverer. In some cases, there are questions as to what should be called the actual discovery date: the date at which variability was first suspected or the date at which the variability was clearly established. The period of the variable, if it is periodic, is listed in the fifth column, while the brightest visual magnitude and amplitude of the variable are given in columns six and seven. Finally, column eight lists the spectral type of the variable. Note that all of the variable stars in this table reached naked-eye visibility, with the possible exception of S Serpentis, which at its peak brightness is just fainter than the usual magnitude limit for the naked eye.

1.1.1 Nomenclature

The perceptive reader will have noticed, from Table 1.1, that the first variable stars to be discovered have names that begin either with a Greek letter or with an R. The Greek letters follow the original nomenclature proposed by the German lawyer and amateur astronomer Johann Bayer (1603) in his groundbreaking atlas entitled *Uranometria*.[2] In Bayer's atlas the stars were assigned letters of the Greek alphabet, then, when those were exhausted, letters of the Roman alphabet, first in lower case, then starting anew in upper case, until the letter Q was reached – the last one to be used in Bayer's atlas. In all cases, the letter is followed by the Latin genitive form of the constellation's name. Hence β Persei, for instance, corresponds to Algol, the second brightest star in the constellation Perseus. It is a common misperception that the Bayer letters are always ordered by apparent magnitude, with the brightest star in a constellation assigned the Greek letter α, the second brightest β, and so on, but this is an oversimplification. In Bayer's days precise stellar photometry was not available. Bayer usually ordered his letters according to the traditional magnitude groups (magnitude 1 including the brightest stars and magnitude 6 those just visible to the naked eye). However, he did not order the stars by apparent brightness within each magnitude. Thus, although α is usually the brightest star within a constellation, that is not invariably so (Swerdlow, 1986).

As several of these stars were eventually shown to be variable, their original Bayer name was retained. However, the discovery of fainter variable stars that were not included in Bayer's original catalog required a new convention, or at least an extension to the Bayer scheme. This was provided by the Director of the Bonn Observatory, Friedrich Wilhelm August Argelander, when he produced the *Uranometria Nova* (Argelander, 1843), followed by the monumental Bonn Observatory Survey (the famous *Bonner Durchmusterung*, or BD).

Argelander reasoned that it would be only natural to continue the lettering sequence from Bayer, and thus named the first variable star detected in a constellation that did not have a Bayer symbol with the letter R, again followed by the Latin genitive of the constellation's name. As a matter of fact, an explanation that R stood for a continuation of the Bayer symbols, rather than, for instance, the first letter of "Rot" ("Red" in German, or "Rouge" in French, or "Rojo" in Spanish), as had often been speculated – not an unreasonable hypothesis, since so many of the stars in Table 1.1 are very red – appears to have been given by Argelander only a few years later, in his article on R Virginis published in the *Astronomische Nachrichten* (Argelander, 1855). Thus, for instance, R Leonis was the first variable star without a Bayer letter to be cataloged in the constellation Leo. One natural drawback of Argelander's proposed scheme was that, from R to Z – the available letters of the alphabet for variable star classification – there were only nine available "slots," and thus no more than nine new variable stars could be classified in this way. Argelander, however, never thought this could

2) http://www.lindahall.org/services/digital/ebooks/bayer/index.shtml

pose a serious problem (Townley, 1915), since in those days stellar variability was still considered a rare phenomenon – and indeed, a mere 18 variable stars in total were included in the table of variable stars compiled by Argelander.[3)]

Naturally, the number of reported variable stars quickly increased over the 18 originally reported in the BD, and by 1912 the number of known variables was already around 4000 (Cannon, 1912). Ironically, it was partly Argelander's invention of the "step method" of visual estimation of the magnitudes of variable stars (see Hearnshaw, 1996) that was responsible for the increased number of variability reports around the world, as quantitative estimates of stellar magnitudes became more widespread among amateur astronomers in particular. Naturally, the other key development that helped make the number of reported variable stars skyrocket was the development of the photographic plate. One way or another, the fatal limit of nine variable stars per constellation was quickly surpassed, and therefore an extension to Argelander's scheme became necessary.

To achieve this goal, Hartwig suggested, at a meeting of the *Astronomische Gesellschaft* in 1881, that double letters – still in the range between R and Z – be used (Townley, 1915). Thus, after the variable star Z in a given constellation, to the next variable star the letters RR would be assigned, followed by RS, RT, and so on, until RZ – followed by SS, ST, … , SZ, then TT, TU, … , TZ, and so on, and ending with ZZ. This gives an additional 45 slots, thus bringing the grand total to 54. Thus, RR Lyrae is the tenth variable star (without a Bayer letter) in the constellation Lyra, whereas ZZ Ceti is the fifty-fourth such star in Cetus. This scheme seems to have first been adopted by Chandler (1888) in his variable star catalog, where RR Virginis can be found.

Soon enough – more specifically, with the discovery of ZZ Cygni in 1907 – even 54 slots became insufficient, and so astronomers eventually resorted to the remaining letters of the alphabet, following a suggestion by the astronomer Ristenpart to the *Astronomische Gesellschaft*. In order to avoid confusion with the Bayer letters, however, two such letters were always used. From A to Q, the only letter that was not utilized was J, in order to avoid confusion with I.[4)] At the time – and again reflecting an amazing shortsightedness of the astronomical community in the late 1800s and early 1900s – it was widely believed that even the letters QZ would likely never be reached in any constellation (Schweitzer & Vialle, 2000).

Including these letters, all combinations starting with AA, AB, … , AZ, BB, BC, … , BZ, until ZZ become available (again except for those involving the letter J).

3) Of course, when the first variable stars were discovered, Argelander's naming scheme had not yet been created. Therefore, other names were initially given to those stars, based on the naming conventions of other catalogs (unless the star was already present in Bayer's catalog, in which case – as we have seen – its Bayer letter was usually retained). Other such catalogs included, in particular, John Flamsteed's, which was edited and published (unauthorized) by Edmund Halley in 1712. Interestingly, when Flamsteed eventually published his catalog himself, he did not include the famous " Flamsteed numbers" for designating stars (Bakich, 1995). Hence, for instance, R Leo was initially called 420 Mayer Leonis or 68 (Bode) Leonis (Zsoldos, 1994, and references therein).

4) Recall that in many languages "I" and "J" have the same pronunciation – it is no coincidence that the acronym "INRI" in the Christian cross stands for "Jesus of Nazareth, King [Rex, in Latin] of the Jews."

Since there are 25 combinations involving the letter A, 24 involving letter B, 23 involving letter C, and so on and so forth, down to a single one for letter Z (i.e., ZZ), we find, based on the expression

$$\sum_{i=1}^{n} i = \frac{n(n+1)}{2} \tag{1.1}$$

with $n = 25$, that a total of 325 additional "slots" can be obtained in this way – which, on top of the original nine single-letter ones, gives a grand total of 334. This is the maximum afforded by the expanded Argelander scheme.

Even before 334 variables were first found in a constellation – which finally happened in 1929, with the discovery of QZ Sagittarii – some authors realized that this too would be insufficient, and therefore alternative, more intuitive naming schemes were suggested. In particular, Nijland (1914) and Townley (1915) suggested, following Chambers (1865), that it would be much more reasonable to simply adopt a "V" followed by the order of discovery of the variable – and this is the approach that has been followed until the present, starting with variable 335 in any given constellation.[5] The first star to be classified in this way was then V335 Sagittarii. The next several constellations to "overflow" the original 334 variable star name slots were, in succession, Ophiuchus (1929), Cygnus (1933), Centaurus and Scorpius (1936), and Aquila (1937). According to the latest available edition of the *General Catalogue of Variable Stars* (GCVS; Kholopov *et al*., 1998), as presented by Kazarovets *et al*. (2009), the constellation with the highest number of cataloged variables is Sagittarius, with 5579 stars, followed by Ophiuchus, with 2671. On the other hand, many constellations are still far from exceeding 334 classified variables; for instance, in the constellation Caelum (the Chisel), the list extends only as far as SX Cae (i.e., no more than 24 stars), whereas in Equuleus (the Little Horse) the list reaches TX Equ (31 stars). This reflects the fact that constellations located close to the Galactic plane tend to contain many more variable stars than those at higher Galactic latitudes.

To avoid confusion, variable stars are usually given a provisional name upon classification, before entering the GCVS – at which point its naming is considered definitive. For a description of how provisional names are usually chosen, the reader is referred to Schweitzer & Vialle (2000).

With the advent of extensive variability surveys, such as EROS, MACHO, and OGLE[6] – to name only the first gravitational microlensing ones – the naming of variable stars has started to become once again quite chaotic, and the previously described naming scheme is often not followed by the teams in charge of these projects. This is the reason why recently discovered variable stars are nowadays

5) As a matter of fact, both Nijland (1914) and Townley (1915) envisioned that this system should be used to rename the 334 stars from AA to ZZ in every constellation, as well as those with Bayer letters – thus, for instance, Algol/β Persei would be renamed V1 Persei, SS Cygni = V20 Cygni, SY Andromedae = V25 Andromedae, and so on. This went a bit beyond what traditionalist astronomers would have preferred, and so these stars have kept their original designations.

6) For a list of the abbreviations and acronyms commonly employed in this book and/or which are widely used in the relevant literature, the reader is referred to the Glossary at the end of this volume.

often classified into such complicated-looking, “telephone number-like” classes as “EC 14026” (after star EC 14026-2647, from the Edinburgh-Cape Survey), or “PG 1605+072” (after the star in the Palomar-Green Survey). As pointed out by Kurtz (2002b), the MACHO project alone has discovered tens of thousands of variable stars, “and they have chosen to use their own naming convention, and even changed conventions part way through the project giving two naming schemes.” The ongoing *Vista Variables in the Vía Láctea* (VVV) project (Minniti *et al.*, 2010; Catelan *et al.*, 2011, 2013) alone is expected to discover of order one million variable stars in the Galactic bulge direction. With Gaia and the LSST, variable stars will be discovered by the hundreds of millions, and perhaps billions. Therefore, Kurtz’s question – *How will we name them?* – is very pertinent. After all, as he points out, it may not be very practical “to work on a star called ES 220418.23+190754.62, and refer to it always like that;” his advice is accordingly that astronomers “continue with tradition,” and thus number the stars in each constellation in its order of discovery – even if these numbers will unavoidably become very large at some future point or another. Indeed, the present authors tend to agree with this view: while it may not be particularly pleasant to work with a star called (say) V12345678 Sgr, it may be even worse to have to deal with one called ES 220418.23+190754.62 on a daily basis. An important drawback, on the other hand, is to establish the actual order of discovery, with an unavoidable delay between discovery and the establishment of an official “V-number” designation.

1.2
The Recognition of Pulsation as a Cause of Variability

By the early twentieth century, numerous examples of stars that we should today class as RR Lyrae variables, Mira variables, and Cepheids had been discovered. These are all types of variable stars now long recognized as pulsating stars, but at that time, the cause of their variability was still unknown. As early as 1667, Bullialdus had suggested that the brightness changes of Mira might be caused by rotation, with one side of the star being more luminous than the other. In 1783 Goodricke added the idea that the periodic dimming of Algol might be caused by an eclipse. The realization that stars might vary because of pulsation was longer in coming. In fact, even the eclipse model for Algol remained in doubt until Vogel’s (1890) spectroscopic observations confirmed it (Clerke, 1903).

By the start of the twentieth century, variable stars of the δ Cephei type posed a particular problem for astronomers trying to understand the nature of their light changes. Spectroscopic binary stars had been discovered not long before: as we have already noted, Vogel (1890) used the Doppler shift in its spectroscopic lines to determine the radial velocity of the brightest star in Algol throughout the light cycle. The changes in radial velocity confirmed the eclipsing binary explanation of Algol’s brightness changes. A few years later, Bélopolski (1895) observed the spectrum of δ Cephei, finding that its radial velocity also changed during its light cycle. Because periodic radial velocity variations were, at that time, known only for binary stars, where the changes in velocity indicated orbital motion, it

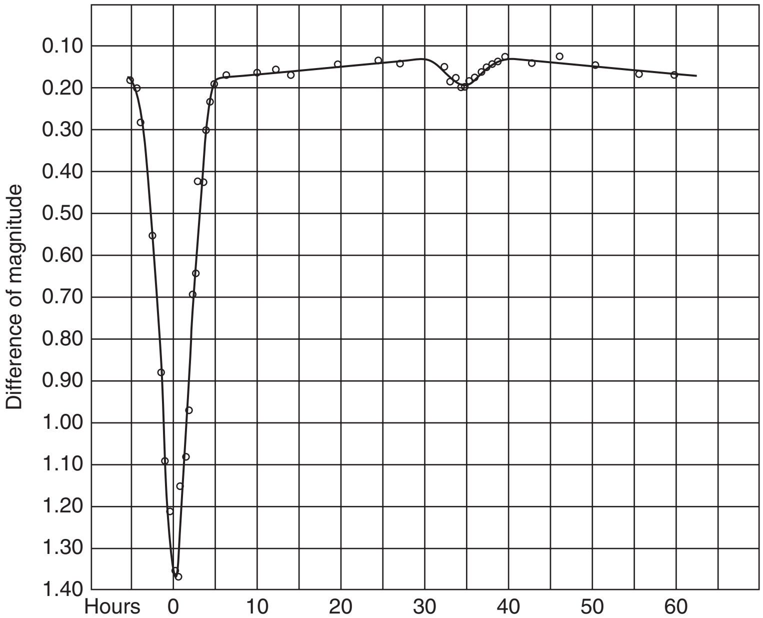

Figure 1.2 Joel Stebbins's 1910 photoelectric light curve of the eclipsing variable Algol, showing the near symmetry of the primary and secondary eclipses. (From Stebbins (1910).)

was believed that Cepheids, too, were binary stars. The light curves of Cepheids, however, did not at all resemble the light curves of eclipsing binaries such as Algol (Figure 1.2). They often had asymmetric light curves, with a steep rise to maximum light followed by a slower decline (Figure 1.3). A further clue came when Schwarzschild (1900) found that the Cepheid η Aquilae changed in color as well as brightness during its light cycle.

Despite the very different light curves of Algol and Cepheid stars, the radial velocity argument in favor of binarity seemed persuasive to many (Brunt, 1913; Furness, 1915), as noted in Gautschy's (2003) historical review. It followed that the cyclic brightness changes of Cepheids must in some way be caused by the existence of a binary star system, even if the exact mechanism remained obscure. Perhaps the companion star somehow caused an eruption on the primary star that became stronger as the two stars approached. However, the absence of a satisfactory binary star mechanism to explain the variations of the Cepheids caused some to contemplate alternative explanations. Plummer (1913), noting the difficulty in explaining Cepheid variability under the binary hypothesis, raised the alternative of radial pulsation, but he did not explore the possibility in depth. It remained for Harlow Shapley (1914) to put forward a strong argument that pulsation underlay the variations of Cepheid-type stars.

Shapley (1914) marshaled several arguments against the binary hypothesis. His strongest argument employed the recent discovery of the existence of giant and dwarf stars. Shapley argued that the Cepheids were giant stars, in fact so large

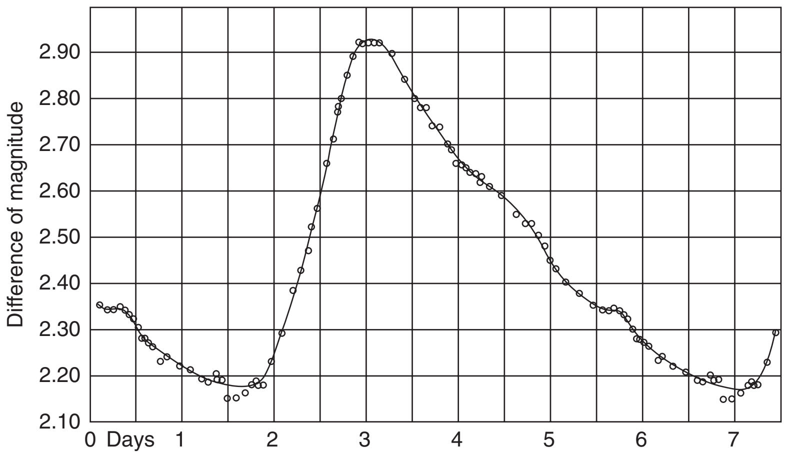

Figure 1.3 Stebbin's 1908 light curve of the variable δ Cephei (with brighter magnitudes toward the top). Unlike that of Algol, the light curve of δ Cephei shows a steeper rise to maximum light followed by a more gradual decline in brightness. (From Stebbins (1908).)

that their radii exceeded the calculated sizes of the orbits in the supposed binary systems: "Interpreted as spectroscopic binaries these giant stars move in orbits whose apparent radii average less than one tenth the radii of the stars themselves." Could such binary systems actually exist, if the Cepheids were so large as to engulf the supposed companion stars? It seemed unlikely. That was an argument from which the binary hypothesis never recovered – although attempts at resurrecting it did pop up occasionally (Jeans, 1925), and in fact, somewhat surprisingly, as late as 1943 a theory of Cepheid variability was advanced in which members of a binary system moved within a common atmosphere (Hoyle & Lyttleton, 1943).

Shapley advocated radial pulsation as an alternative to the binary hypothesis, although he offered no detailed model as to how stellar pulsation might be established and maintained in Cepheid variables. At the time of Shapley's publication, theorists such as Ritter (1879) and Emden (1907) had considered some aspects of the physics of pulsating stars, but the processes that might drive stellar pulsation were unknown. Within a few years, Eddington (1918a, 1919a) would significantly advance the discussion of the physical processes that would be needed to keep a star pulsating. Nonetheless, three more decades would elapse before Zhevakin (1953) and Cox & Whitney (1958) began to elucidate the specific driving mechanism behind the pulsations of Cepheid variable stars (see Chapter 5).