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History and development

Sometime, far back in prehistory, people first began watching the sky. They must certainly have noted the daily and yearly motions of the sun, the waxing and waning of the moon, and perhaps even the wanderings of the planets. They might even have noted changes in the stars, not changes of *position* but changes of *brightness*. There are hundreds of these *variable stars* among the naked-eye stars, and the changes of some of them are so striking that they could not escape the notice of a careful eye.

Written records of skywatching begin in the Near East around 2000 BC, and in the Far East around 1000 BC. Unwritten records may also exist: paintings, rock and bone carvings, alignments of giant stones. The study of these has been called *archaeoastronomy*. The interpretation of *any* ancient records is a challenge to both the astronomer and the historian, and many interesting books and articles have been written on the topic.

The Babylonians laid the foundations of Western astronomy through their mathematics and through their systematic observations of the sun, moon, planets, and stars (albeit for astrological purposes). Babylonian astronomy was absorbed into Greek culture, where it eventually led to 'models' of the visible universe. In some schools of philosophy, these models were intended as mathematical conveniences, designed only to represent or predict solar, lunar, or planetary motions. In other schools, these models took on wider significance: they were intended to represent physical reality. Aristotle (384–322 BC), for instance, wrote that the world was made of four elements: earth, water, air, and fire. Bodies beyond the sphere of the moon were made of a fifth element or 'quintessence', which was ingenerable and incorruptible, and underwent only one kind of change: uniform motion in a circle. Variable stars could not exist in Aristotle's universe.

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Aristotle's works had tremendous impact on Western thought. They survived in translation even after the original versions (such as those in the famous library at Alexandria) were lost. Perhaps for this reason, there are few if any records of variable stars in Western literature. The 'chronicles' maintained by monasteries in mediaeval times record many astronomical and meteorological phenomena, but variable stars are not among them. There is only one European record of the 'new star' of 1006 AD, now classified as a supernova – the brightest one known – and that record is controversial.

In the Orient, observers were not inhibited by Aristotle. In fact, their cultures often placed great importance on omens, such as unexpected events in the sky. Chinese, Japanese, and Korean records are a fruitful source of information on supernovae, novae, comets, eclipses, and other such events, if one can interpret the records correctly. It appears that about 80 'new stars' were recorded up to about 1600, eight being supernovae and the rest being ordinary novae. Other cultures, such as aboriginal North Americans, may also have recorded these 'new stars', but they apparently did not do so in the precise, methodical fashion of the Orientals.

1.1 Tycho's and Kepler's stars

In the West, the sixteenth century brought a renaissance and revolution in scientific thought. Ironically, the seeds were contained in the writings of Aristotle: by laying the basis of the scientific method, he developed the weapons with which his philosophy was later attacked and overthrown. By happy coincidence, Nature provided two rare events – supernovae – which would help to usher in the modern age of astronomy. The first occurred in 1572. In November of that year, Tycho Brahe (1546–1601) recorded a 'new star' in Cassiopeia. He (and independently the English astronomer Thomas Digges) established its position and its fixed, stellar nature, and measured its changing brightness relative to planets and stars. At maximum brightness, it rivalled Venus! He published his results in a book entitled *On a New Star, Not Previously Seen Within the Memory of Any Age Since the Beginning of the World*. His observations were so careful and systematic that later astronomers (notably Walter Baade) could reconstruct the changing magnitude of Tycho's star to an accuracy of ± 0.2. Since the distance to the remnant of the supernova can now be determined, the absolute magnitude of the supernova at maximum brightness can be found. This provides a bench mark which can be used to determine the distance to other supernovae.

Just over three decades later, in October 1604, Johannes Kepler (1571–1630) recorded another 'new star.' He (and independently David Fabricius, pastor

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in Osteel in Ostfriesland) established its position and its fixed, stellar nature, and recorded its changing brightness. Kepler's star was somewhat fainter than Tycho's, but still at maximum brightness it rivalled Jupiter.

Only a few years later, the telescope was first applied to astronomy by Galileo Galilei (1564–1642), and since then astronomers' technical resources have increased by leaps and bounds. Unfortunately, no supernova in our galaxy has been seen since 1604.

1.2 The beginnings of modern astronomy

Variable stars (or variables for short) continued to be discovered and observed sporadically, occasionally through deliberate, systematic measures but more often by chance. In 1596, Fabricius noted that o Ceti (subsequently called *Mira*, the wonderful) was sometimes visible, sometimes not. Furthermore, the cycle of visibility repeated regularly every 11 months. The star was a periodic variable.

Towards the end of the eighteenth century, another burst of progress was made. Some of this must be attributed to William Herschel (1738–1822), the 'father' of modern stellar astronomy. His development of large reflecting telescopes, his efforts to gauge the distances of the stars from their apparent brightnesses, and his interest in the physical nature of stars and nebulae, all contributed to the development of the study of variable stars. He discovered the variability of two stars – 44i Bootis, and α Herculis. It is interesting to read what his son John Herschel (1792–1871) said about variable stars in the 1833 edition of his *Principles of Astronomy*:

> this is a branch of practical astronomy which has been too little followed up, and it is precisely that in which amateurs of the science, provided with only good eyes, or moderate instruments, might employ their time to excellent advantage. It holds out a sure promise of rich discovery, and is one in which astronomers in established observatories are almost of necessity precluded from taking a part by the nature of the observations required. Catalogues of the comparative brightness of the stars in each constellation have been constructed by Sir William Herschel, with the express object of facilitating these researches.

These words are still true today. We must remember, though, that many eminent scientists of a century or two ago were amateurs by our definition. William Herschel was a good example. So too were John Goodricke (1764–86) and Edward Pigott (1753(?)–1825), two well-to-do Yorkshire gentlemen who made

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a special study of variable stars. Pigott is credited with the discovery of the variability of η Aquilae in 1784, of R Coronae Borealis in 1795, and of R Scuti in 1796. Goodricke is credited with the discovery of the variability of δ Cephei and β Lyrae in 1784, and of the periodicity of β Persei (Algol) in 1782–1783 (though the latter was apparently discovered independently by a German farmer named Palitzch, who had an interest in astronomy). Together, Goodricke and Pigott also proposed that the variability of Algol might be caused by eclipses (but by a planet!). Goodricke, a deaf mute, died at the untimely age of 21, and Pigott, after the death of his friend, gradually gave up astronomy, but, during the brief period of their collaboration, 'the Yorkshire astronomers' laid the foundations for the study of variable stars as a branch of astronomy.

1.3 Systematic visual observations

Throughout the nineteenth century, variable stars continued to be observed. In 1786, Pigott had listed 12 definite variables and 39 suspected ones. By about 1850, F. W. A. Argelander (1799–1875) listed 18 definite variables and numerous suspected ones. Furthermore, many of the definite variables had good light curves (plots of brightness *versus* time) thanks to the techniques of measurement which William Herschel had devised and which Argelander had refined. Argelander's work marks another high point in the study of variable stars because, through his compilation of the *Bonner Durchmusterung* catalogue and charts, he made hundreds of thousands of visual measurements of the brightnesses of stars, providing magnitudes for comparison stars and discovering many new suspected variables in the process.

Not the least of Argelander's contributions was his well-known appeal to 'friends of astronomy'. It appears at the end of an article in Schumacher's *Astronomisches Jahrbuch* for 1844, in which Argelander discusses the history, importance, methods of study, and idiosyncracies of variable stars:

> Could we be aided in this matter by the cooperation of a goodly number of amateurs, we would perhaps in a few years be able to discover laws in these apparent irregularities, and then in a short time accomplish more than in all the 60 years which have passed since their discovery.
>
> Therefore do I lay these hitherto sorely neglected variables most pressingly on the heart of all lovers of the starry heavens. May you become so grateful for the pleasure which has so often rewarded your looking upward, which has constantly been offered you anew, that you will contribute your little mite towards the more exact knowledge of

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> these stars! May you increase your enjoyment by combining the useful and the pleasant, while you perform an important part towards the increase of human knowledge, and help to investigate the eternal laws which announce in endless distance the almightly power and wisdom of the Creator! Let no one, who feels the desire and the strength to reach this goal, be deterred by the words of this paper. The observations may seem long and difficult on paper, but are in execution very simple, and may be so modified by each one's individuality as to become his own, and will become so bound up with his own experiences that, unconsciously as it were, they will soon be as essentials. As elsewhere, so the old saying holds here, 'Well begun is half done', and I am thoroughly convinced that whoever carries on these observations for a few weeks, will find so much interest therein that he will never cease. I have one request, which is this, that the observations shall be made known each year. Observations buried in a desk are no observations. Should they be entrusted to me for reduction, or even for publication, I will undertake it with joy and thanks, and will also answer all questions with care and with the greatest pleasure.*

Argelander's appeal did not go unheeded. The Variable Star Section of the British Astronomical Association was founded in 1890, and has been active ever since. In America, the study of variable stars was supported especially by E. C. Pickering (1846–1919) at the Harvard College Observatory. In 1882, Pickering had published *A Plan for Securing Observations of Variable Stars*, pointing out, among other things, that such work might especially appeal 'to women'. In 1911, the American Association of Variable Star Observers (AAVSO) was founded in Cambridge, Massachusetts. Originally, it was very closely associated with the Harvard College Observatory. Now, though some links remain, the AAVSO is an independent, international association, receiving hundreds of thousands of observations each year from members and associates around the world. The study of variable stars has indeed been a fruitful area of astronomy for women, in part because Pickering encouraged and hired women astronomers (albeit at low salaries). Henrietta Leavitt, Margaret Mayall, Cecilia Payne-Gaposhkin, and Helen Sawyer Hogg are among many examples.

* This translation, by Annie J. Cannon, appears in *Popular Astronomy* for 1912, and in *A Source Book in Astronomy*. Several types of variable stars were particularly well suited to visual observation by amateurs: unpredictable variables of the R CrB, U Gem and nova type, and large-amplitude regular and semi-regular variables such as the long-period or Mira variables.

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1.4 The photographic revolution

Several developments occurred in the late nineteenth century which had a profound effect on the study of variable stars. One was the development of photography. This had begun many years earlier (John Herschel being one of the pioneers), and was first applied to stellar astronomy in 1850, but it was not until about 1880 that emulsions became sensitive enough, and telescope drive systems became accurate enough, for astrophotography to make its full impact. The photographic plate, which could now integrate starlight for up to several hours, could record stars which were far too faint to be seen visually in the telescope. Furthermore, thousands of stars could be recorded on a single plate, making discovery and measurement more efficient. Photography provided a permanent record of star brightness, capable of being checked or re-measured at any time. If a newly discovered variable had been recorded on earlier plates, its previous history could be investigated. Archival collections such as that of the Harvard College Observatory contain a gold mine of information on the past variability of stars – and of more exotic objects such as quasars.

Many observatories embarked on systematic photographic surveys of variable stars, notably Harvard, Heidelberg, Leiden, Sonneberg, and Sternberg. Each observatory accumulated its own collection of variables, with consequent problems of nomenclature. Selected regions of the sky were more closely surveyed: the northern and southern Milky Way, the region of the galactic bulge in Sagittarius, globular clusters, the Magellanic Clouds, and later more distant galaxies such as M31. The number of known variables increased rapidly to over 1000 in 1903, over 2000 in 1907, and over 4000 in 1920. Today, there are tens of thousands of confirmed variables.

1.5 Spectroscopy

The development of astronomical spectroscopy and spectral classification also led to a better understanding of variable stars. Unusual aspects of the spectra of variable stars were noted visually as early as 1850: the absorption bands in the spectra of cool, long-period variables, and the bright emission lines in the spectra of novae and of Be stars such as γ Cassiopeiae. The development of photographic spectroscopy by H. Draper in 1872 led to large-scale projects in spectral classification, notably by Pickering and his associates at the Harvard College Observatory. It became possible to classify variables according to temperature, and later according to luminosity; this enabled astronomers to learn how variable stars compared and fit in with normal stars. This in turn led to improvements in the classification schemes for variable stars. Spectroscopy

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also provided the raw material for deducing the chemical composition of the stars, and the differences in composition between different groups of stars. But it required modern astrophysics to do the interpretation correctly.

1.6 Classification and explanation

The earliest classification scheme dates back nearly two centuries: Pigott divided variables according to the nature of their light curve into novae, long-period variables, and short-period variables. A century later, Pickering devised a more detailed scheme: (Ia) normal novae: primarily nearby ones in our own galaxy; (Ib) novae in nebulae: now known to be primarily supernovae in distant galaxies; (IIa) long-period variables: cool, large-amplitude pulsating variables; (IIb) U Geminorum stars: dwarf novae; (IIc) R Coronae Borealis stars: stars which suddenly and unpredictably decline in brightness; (III) irregular variables: a motley collection; (IVa) short-period variables such as Cepheids and later including the cluster-type or RR Lyrae stars; (IVb) Beta Lyrae type eclipsing variables; and (V) Algol type eclipsing variables.

Pickering's classification scheme contains some hints as to the nature and cause of the variability. Classification and explanation go hand in hand (in principle), and in the late nineteenth and early twentieth centuries, progress was made in understanding the physical nature and the physical processes in variable stars, and in stars in general. This culminated in Arthur S. Eddington's (1882–1944) monumental book *The Internal Constitution of the Stars*.

Two centuries ago, Goodricke and Pigott had speculated that the variability of Algol and similar stars might be due to eclipses. A century later, the eclipse hypothesis was firmly established: in 1880, Pickering carried out a mathematical analysis of the orbit based on careful observations of the light curve, and by 1889 the orbital motion was directly observed by H.C. Vogel using astronomical spectroscopy and the Doppler effect. Nevertheless, some eclipsing variables defied explanation and, even today, Goodricke's β Lyrae is one of the most enigmatic objects in the sky. Furthermore, the eclipse hypothesis was often overextended: it was used to explain the Cepheids, long-period variables and even the R Coronae Borealis stars! Ironically, the importance of binarity in explaining the variability of such other types as novae has only recently been appreciated.

In a sense, Goodricke anticipated yet another type of variability. Unable to explain the behaviour of Beta Lyrae under the eclipse hypothesis, he suggested that 'the phaenomenon seemed to be occasioned by a rotation on the star's axis, under a supposition that there are several large dark spots upon its body, and that its axis is inclined to the earth's orbit'. This is precisely the case in the rotating variables discussed later in this book.

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The idea that variability might be due to pulsation was raised (by A. Ritter) as early as 1873, but it was not until the observational studies by Harlow Shapley (1885–1972) and others around 1915, and the concurrent theoretical studies by Eddington, that the pulsational nature of the Cepheids, cluster type variables, and the long-period variables was established. The cause of the pulsation – the thermodynamic effects of hydrogen and helium in the outer layers of the stars – was not firmly established until after 1950.

1.7 Photoelectric photometry: the electronic revolution

Also around 1915, another important technique was added to the arsenal of the variable star astronomer: photoelectric photometry. At first, the technique was insensitive and cumbersome, and could only be applied to the brightest stars. However, through the careful efforts of its first practitioners, Joel Stebbins (1878–1966) and Paul Guthnick (1879–1947), this technique was successfully used to discover the shallow secondary eclipse of Algol (1910), the small light variations in the pulsating Beta Cephei stars (1913), and in the rotating magnetic stars such as α^2 Canum Venaticorum (1914). This technique has since revealed several other new classes of 'microvariables'. It has also enabled small colour variations to be observed. There is a lesson to be learned here: Stebbins and Guthnick were pioneers; they knew the limitations of their technique, and they took great pains to apply it carefully. Nowadays, photoelectric photometry is routine, and its practitioners often apply considerably less care than Stebbins and Guthnick did. The result is often mediocre, inferior data. On the other hand, photoelectric photometers are now simple and inexpensive enough for amateur use. With care, the amateur can now make important contributions to the photoelectric photometry of variable stars, particularly those with unpredictable, irregular or slow variations. This has included the observation of pulsating red giants, RS Canum Venaticorum binaries, and Be stars, as well as the timing of the minima of eclipsing binary stars.

1.8 Consolidation

During the twentieth century, the basic tools of variable star astronomy – visual, photographic and photoelectric photometry, spectroscopy and physical analysis – were gradually refined, and produced a steady stream of important results. To choose a few examples, we might arbitrarily turn to *A Source Book in Astronomy and Astrophysics, 1900–1975*, edited by K.R. Lang and O. Gingerich (Harvard University Press, 1979). It contains excerpts from the 'most important' astronomical papers published during that time. They include:

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'The Measurement of the Light of Stars With a Selenium Photometer, With an Application to the Variations of Algol' by J. Stebbins (1910).

'Periods of 25 Variable Stars in the Small Magellanic Cloud' [discovery of the period luminosity relation] by Henrietta S. Leavitt (1912).

'Novae in Spiral Nebulae' [galaxies] by Heber D. Curtis, George W. Ritchey, and Harlow Shapley (independently in 1917).

'On the Pulsations of a Gaseous Star and the Problem of the Cepheid Variables' by Arthur S. Eddington (1918–1919).

'Cepheids in Spiral Nebulae' by Edwin P. Hubble (1925).

'Novae or Temporary Stars' by Edwin P. Hubble (1928).

'On Supernovae' by Walter Baade and Fritz Zwicky (1934).

'Rotation Effects, Interstellar Absorption and Certain Dynamical Constants of the Galaxy Determined from Cepheid Variables' by Alfred H. Joy (1939).

'Spectra of Supernovae' by Rudolph Minkowski (1941).

'The Crab Nebula' by Rudolph Minkowski (1942).

'T Tauri Variable Stars' by Alfred H. Joy (1945).

'The Spectra of Two Nebulous Objects near NGC 1999' [Herbig-Haro Objects] by George W. Herbig (1951).

'Studies of Extremely Young Clusters 1. NGC 2264' [Pre-Main Sequence Variables] by Merle F. Walker (1956).

'Binary Stars among Cataclysmic Variables III. Ten Old Novae' by Robert P. Kraft (1964).

'Observations of a Rapidly Pulsating Radio Source' [a pulsar] by Anthony Hewish *et al.* (1968).

This list, though somewhat arbitrary, touches on most of the key areas of variable star astronomy up to 1975, and mentions most of the outstanding contributors to this field. Note the predominance of North American astronomers. This is only partly due to bias: North American astronomers have indeed monopolized the field of observational stellar astronomy for most of the twentieth century. Sadly, the field of stellar astronomy has fallen somewhat out of favour in North America in the late twentieth century, in part because of the lure of fields such as observational and theoretical cosmology.

1.9 The modern age

The last entry on the list above is appropriate in that it introduces one of the many sophisticated new techniques which have been applied to variable

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stars – and all other fields of astronomy – in the last four decades. It is impossible to mention all the results of these techniques here; they will be discussed in detail later in this book.

The discovery of pulsars was probably the most unique and important contribution of radio astronomy to any field of stellar astronomy. Radio telescopes can also probe the interstellar matter around forming stars, as well as the matter ejected from supernovae, novae, and other eruptive stars. The most powerful radio telescope is the Very Large Array (VLA) in New Mexico, USA. An even more powerful facility – the Atacama Large Millimetre Array, to be located in Chile – is currently under construction as a multinational project.

Infrared (IR) astronomy began in the 1920s, using thermocouple detectors. Since then, detectors and telescopes have improved to the point where we can now observe IR radiation from stars such as Cepheids, even in external galaxies. IR telescopes are particularly useful for studying cool variables (which emit most of their energy in the IR) as well as for probing the cool gas and dust around stars, both old and young. IR detectors have become simple and cheap enough to be within the reach of the amateur, and there is particular need for systematic, long-term IR studies of variable stars – studies which can best be carried out at smaller, local observatories. The first major infrared satellite was the *Infrared Astronomical Satellite (IRAS)*, launched in 1983. The *Infrared Space Observatory (ISO)* was launched by the European Space Agency in 1995. NASA's *Space Infrared Telescope Facility (SIRTF)* was launched in 2003, and renamed the *Spitzer Space Telescope* after Lyman Spitzer, an early 'champion' of the concept of space telescopes.

Ultraviolet (UV) astronomy must be carried out from above the atmosphere, because the ozone layer absorbs all wavelengths shorter than 3000 Å. The first rocket observations were made in 1955, but UV astronomy truly blossomed with the launch of UV satellites: *Orbiting Astronomical Observatory 2* in 1968, *Orbiting Astronomical Observatory 3 ('Copernicus')* and the European Space Research Organization's *TDI* in 1972, and the *International Ultraviolet Explorer (IUE)* in 1978. The IUE was the 'workhorse' of UV astronomy, producing thousands of astronomical research papers in its long and productive life. The *Extreme Ultraviolet Explorer (EUVE)* was launched in 1992, and the *Far Ultraviolet Spectroscopic Explorer (FUSE)* in 1999. Two ultraviolet experiments – *ASTRO 1 and 2* – were flown on the Space Shuttle in 1990 and 1995. These UV satellites and experiments have been especially effective in studying hot stars (such as the Be stars) and hot gas (such as the chromospheres of 'active' stars and the discs of gas around the dense components of close binary systems).

X-ray astronomy must likewise be carried out from above the atmosphere, and has likewise been revolutionized by the launch of satellites, particularly *UHURU* in 1970 and the *High Energy Astrophysical Observatory B ('Einstein')* in 1978.

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