Variable Stars

Stars vary in many ways and for many reasons. Broad categories of variation include stars that pulsate, fluoresce, become veiled, are disturbed by companions, erupt, explode and even change their spots. Variations may be episodic, irregular, semi-regular or periodic. A separate wide class comprises the extrinsic variables such as eclipsing and tidally distorted binaries and gravitationally lensed stars, whose variations result from changing aspect, but here we survey the intrinsic variables.

The first recognized variable stars were novae and supernovae ('new' stars), with some very old records being astrophysically useful, chiefly because they fix the accurate date of a stellar explosion. Although the ancient accounts are obscure and fragmentary and do not recognize modern distinctions (such as nova versus supernova), the type of event may still be discernible. For example, a supernova can be visible for 6 months or even longer, whereas ordinary novae are prominent for a matter of weeks, so a nearby nova can mimic a distant supernova in brightness but is typically a much briefer event. Observations of exploding stars go back to several centuries BC with records of some objects from two or more places, and would go back further if not for library burnings. The records were kept by imperial astrologers in China (later in Japan and Korea) as the 'new' stars were considered important omens. Today's telescopic observations provide good statistics of novae, but useful statistics of the infrequent supernovae in our Galaxy rely on the old records. Events observed in other galaxies have demonstrated enormous differences in scale between supernovae and novae. Theory has shown those differences to be far greater than optical observations indicate, as supernovae release the vast bulk of their energy in invisible forms.

Except for novae, stars were regarded as constant until the mid to late 1600s, when the first non-eruptive variables were recognized. Most notable was the pulsating red giant o Ceti (Mira, the Wonderful) with its $\approx 330^d$ large-amplitude variations. An appearance and disappearance of Mira had been noticed by D Fabricius in 1596, but was taken to be a nova. The early histories of intrinsic and extrinsic variables are inextricably linked, as ideas about causes emerged only slowly over several centuries. Systematic recording replaced casual notes over the 1700s, with the improved records leading to further discoveries. Thus θ Serpentis was conclusively shown to be variable by E Pigott, confirming G Montanari's suspicions of a century earlier, and J Goodricke found periodic variation in δ Cephei, the prototype of *Cepheid variables*, and in the eclipsing binary β Lyrae. The improved records also led to some success in identifying variation mechanisms. Speculation of the late 1700s cycled among eclipses, moving and transient spots on rotating stars, and rotating distorted stars. All of these phenomena commonly occur, but early assignments to particular stars were usually wrong. Pulsation was advocated only much later. Algol was (correctly) said to eclipse by Pigott and Goodricke, but both later favored other ideas. Curiously, the eclipse hypothesis of Algol was cast into disrepute by discovery of variable stars that clearly were not eclipsing binaries, apparently from a wish to have all variables follow a single theory. Spots on rotating stars were very popular in the 1700s and 1800s, even for Mira, and have now returned for RS Canum Venaticorum, W Ursae Majoris, FK Comae and BY Draconis type binaries. As late as *c*. 1930, pulsating star velocity curves were fitted in terms of orbital parameters, even when there was little or no doubt about their pulsational origin. A common finding was that the orbit of a star's unseen (and non-existent) companion was actually inside the observed star. The orbit parameters would be printed anyway after a comment or two on the unphysical situation and the need to fit something. Although the reality of pulsation for Long Period Variables (LPVs) and Cepheids was not seriously disputed, there was much uncertainty in sorting true pulsators from a miscellany of competing phenomena. Most authors simply avoided explicit mention of pulsation while discussing effects that scarcely could be due to anything else, with an occasional remark that velocity variations might not really be due to line of sight motion of any kind. The popularity of pulsation was undeniable in the 1920s and 1930s, however, when up to 10% of *Astrophysical Journal* papers concerned Cepheids and related stars—remarkably high for one subject. Nearly all contributions were observational at that time, although major theoretical advances had already been made by A Ritter in the 1870s and 1880s and by A S Eddington in the 1920s. Full acceptance of spectroscopy's implications for the pulsation hypothesis took nearly a half century (*c*. 1890–1935), yet many kinds of pulsating stars were eventually recognized as a direct consequence of the radial velocity and temperature changes discovered spectroscopically. Not only the existence of radial motion, but its phasing compared with that of light curves, is a crucial discriminant among models.

Realization that large numbers of variable stars exist was slow to develop until the breakthrough of photography. Only ≈10 non-exploding variables were known in the early 1800s, but the permanent records in photographic plates quickly extended the list into the hundreds between 1850 and 1900. Systematic photographic surveys in the 1900s at Harvard, Bamberg, Leiden and other observatories raised catalog listings into the tens of thousands. Recent automated gravitational lens surveys with electronic detectors have produced light curves of thousands of variables as a by-product of the surveys' primary objective, thereby substantially increasing the discovery rate. The *General Catalog of Variable Stars* ('GCVS', Kholopov 1984) is a four-volume listing of coordinates, types and other information on 28 211 variables of all kinds, nearly 70% being intrinsic variables. A companion catalog of *New Suspected Variables* ('NSV', Kholopov 1982) contains 14 811 stars of uncertain status.

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A reasonably complete list of variable star types with minimal descriptions would exceed available space, but the GCVS devotes five pages to descriptions. It recognizes 88 types of intrinsic variables, including 34 pulsating, 7 rotating, 10 x-ray, 22 eruptive and 15 cataclysmic types (cataclysmic and other eruptive variables are kept distinct). A standard naming convention allows immediate recognition of a star as variable, although some bright variables have only their Bayer names. To begin the sequence, a single capital letter is assigned alphabetically in order of discovery from R to Z, then double letters RR, RS, . . ., RZ, then double letters AA, AB, . . . to AZ, then BB, BC, . . . to BZ, and ultimately to ZZ, followed by the constellation name (e.g. T CrB; ZZ Cet). Letter J is not used. Designations of the form V335 Cygni, V336 Cygni, etc. follow the 334 names of the letter system.

There is great interest in variable stars among amateur astronomers, whose observations are indispensible for professionals. Not only visual brightness estimates but phototube and charge-coupled device (CCD) measures are now made available in large quantities through bulletins, journals and especially the Internet. Variable star organizations include the American Association of Variable Star Observers (AAVSO), the Association Française des Observateurs d'Etoiles Variables (AFOEV), the British Astronomical Association Variable Star Section (BAAVSS), Bundesdeutsche Arbeitsgemeinschaft für Veränderliche Sterne (BAV), the Center for Backyard Astrophysics (CBA), the Hungarian Astronomical Association, International Amateur-Professional Photoelectric Photometry (IAPPP), the Variable Star Group of the Astronomical Society of Southern Australia, Variable Star Network (VSNET), and the Variable Star Section of the Royal Astronomical Society of New Zealand. Information on all these organizations can be found via the Internet. Their imprints on professional astronomy date at least as far back as the 1920s—for example in Joy's use of an AAVSO Mira light curve in the 1926 *Astrophysical Journal*. The role of such organizations is rapidly expanding today. The central professional organization is Commission 27 of the International Astronomical Union.

LPVs and Cepheid variables were not only discovered early but still dominate our catalogs. LPVs are pulsating red giant stars of great luminosity and are thereby rather easy to discover. The name *Mira type* is reserved for the LPVs of larger light amplitudes, although there probably is continuity in the overall class, including Galactic distribution, space velocity and composition as well as light variation. There may also be continuity with 'non-variable' red giants, which probably have some variation. Spectra of LPVs and especially Miras show prominent emission lines that are clearly due to pulsation, as non-variable red giants lack emission lines but otherwise have similar spectra. More specifically, pulsation amplitude correlates with emission line strength. Miras vary by up to 9^m in blue light (a factor of $\approx$4000), but the enormous optical variations are caused by emission being ultra temperature-sensitive, with the optical band lying far to the short-wavelength side of the spectral energy peak. Bolometric amplitudes are similar to those of Cepheids. A problem for spectroscopy, especially prior to modern efficient spectrographs and large telescope apertures, was the faintness of Miras near minimum light. Observations must cover full cycles if much is to be learned about pulsation, and it was only in 1926 that A Joy produced the first complete velocity curve of Mira. The classical Cepheids are highly luminous F and G type pulsating giants and supergiants that vary periodically up to roughly a magnitude. Periods range from a few days to over 100 days. Rather early it was realized that the important relation between period and mean density

$$P\sqrt{\rho} = \text{constant} \qquad (1)$$

applies to Cepheids and several other prominent categories of pulsating stars. The relation exists because a star's dynamical timescale depends on its size and mass, with some dependence on internal structure (thus a different constant for each category). Stars with given HR diagram coordinates have the same size, but not necessarily the same mass and structure, so pulsation periods provide a link to structure and thereby to understanding evolution. The W Virginis stars, members of a very old Galactic population, pulsate with their own $P\sqrt{\rho}$ relation and are understood to be in a later evolutionary stage than classical Cepheids, having lost much of their original envelopes. Thus pulsation is an important evolutionary diagnostic that can even help trace Galactic origins.

In addition to the essentially periodic and roughly periodic classes of pulsating stars, there are giants and supergiants of spectral classes F to M that pulsate irregularly or semi-regularly. Curiously they lie mainly *between* the more regular Cepheids and LPVs in the HR diagram. The less regular and typically redder of these are known as RV Tauri stars, while the somewhat more regular ones are simply called yellow semi-regular variables. Periods, in so far as they can be quantified at all, range from tens to thousands of days, and amplitudes can be up to about four magnitudes. These stars may be interesting in terms of chaos theory, as some show alternating cycles of larger and smaller amplitude that hint of the period doubling seen in the approach to chaos.

Brightness measurement

We have astrophysically useful records of the brightness variations of the supernovae of 1572 and 1604, as observed by T Brahe and others and by J Kepler respectively, despite lack of light detection equipment and even of telescopes 400 years ago. Their usefulness illustrates two points about astronomical brightness measurement. First, although precision requirements are stringent for small variations, they can be relaxed for large variations. Second, in no case can we allow the scale to be wrong, unless mere detection of variability is the only objective. One might expect eye estimates to be quantitatively useless, but

Brahe's and Kepler's light curves demonstrate otherwise. The situation has been saved by the 'secret' advantage of the photometric astronomer—the remarkable long-term constancy of normal stars. Brahe and Kepler recorded their supernovas' magnitudes relative to known stars that, as far as we know, are essentially unchanged in brightness. Modern photoelectric observations of the reference stars have accordingly placed the supernova estimates on an objective scale. Of course the old estimates are subjective, but the largest overall errors are limited by the magnitude spacings of reference stars. An estimation method involving magnitude steps, introduced by F Argelander about 1840, further diminished maximum errors.

The existence of natural constant brightness standards largely accounts for the accuracy of astronomical photometry, which is typically better than that of laboratory photometry despite the disadvantage of observing through Earth's irregular atmosphere. Astronomers also have an advantage in the temperatures of reference sources, as very hot laboratory standards would vaporize their surroundings, while hot stars have no surroundings to vaporize. Difficulties due to daylight and weather as well as complete blockage of spectral regions are best dealt with by observing from space, although many less severe problems have been minimized through a variety of clever techniques.

The history of star brightness measurement can roughly be divided into an early era of qualitative notes (*c*. 1600 to *c*. 1800), a middle era of quantitative but inaccurate estimation by eye or photography (beginning *c*. 1800 and still somewhat active), and a recent era of accurate quantitative measurement with various electronic detectors (beginning *c*. 1910). Even the early qualitative work was a major improvement on the unplanned occasional notices of preceding times. It made possible the discovery of *periodic* variation and, coupled with long baselines in time, even accurate periods. Thus Goodricke estimated Algol's period in 1784 with an uncertainty of less than a minute out of 2.87 days. Entering the middle era, note that the eye can reliably judge brightness equality between two stars, a point well appreciated and exploited by F W Herschel, J Herschel, Argelander, J Hartmann and K Schwarzschild, but eye estimates of inequality are notoriously subjective. The better visual work accordingly employed a variety of now obsolete ways to reduce the apparent brightness of one star by a known factor so as to equal that of another. Techniques, sometimes applied also to photographic observing, included partial aperture blocking with twin telescopes, extra-focal imaging, tapered neutral filters (wedges), and crossed polarizers. Photographic magnitudes were extracted from diameters of focused images or blackening of unfocused images. The modern definition of astronomical magnitudes, relating magnitude (m) differences to light (l) ratios, $m_1 - m_2 = -2.5\log(l_1/l_2)$, was suggested in 1850 by N Pogson. Simple as it may seem, Pogson's contribution was crucially important, as the quantitative meaning of magnitudes had previously been vague. The new accuracy and increased time lines allowed period *changes* to be measured, with S Newcomb's text of 1884, *Astronomy*, already mentioning period changes for Algol, Mira and β Lyrae. The above-mentioned accuracy tricks work only within small fields, so measurement of actual magnitudes, as opposed to 'local' magnitude differences, received a large boost with the arrival of photoelectric detectors. Invention of the photomultiplier tube in the 1940s especially helped to surmount atmospheric attenuation problems via all-sky photometry, and also greatly improved accuracy of magnitude changes for variable stars. Development of modern standard magnitude systems began when photomultipliers came into widespread use. Examples include the U, B, V, R, I, J, K, L wide-band systems and the *uvby* medium-band systems. A *standard star* has accurately known constant magnitude in one or more standard systems (e.g. γ Oph has $V = 3^m.72$, $B = 3^m.76$), while a *comparison star* has (presumably) constant but not necessarily known magnitude. CCD detectors similar to those in video cameras are now replacing photomultipliers because of their ability to measure many sources simultaneously and thus provide for accurate differential photometry. New practical problems have arisen out of the enormous quantities of data coming from CCD photometry. Advanced computer technology is being applied to storage and distribution problems, in some cases with data collection directly from the detecting equipment. Automatic telescope operation is becoming ever more widespread in many spectral regions, not only in discovery modes (as in extra-Galactic supernova searches) and quick follow-up on γ and x-ray transients, but also in routine observation of known variables. The acronym APT, for Automatic Photometric Telescope, implies remotely operated, programmable instruments that are primarily used for variable star research.

Astrophysical importance of variable stars

The scientific value of variable stars can be seen in two issues—why they vary (theory) and what their variations allow us to measure (observation). The theoretical point connects physical makeup with behavior, while the observational one concerns properties such as size, distance and internal structure that are measurable or estimable because of variation.

Most astronomical distance estimates are based on the *standard candle* method, a comparison of apparent and intrinsic brightness. The extra-Galactic distance scale is an important application, and distances to multiple stars and clusters within our Galaxy also are found from embedded standard candles. The method applies to any stellar group that contains a standard candle and whose diameter is small compared with its distance. Good standard candles are *consistent* (small luminosity range among individuals), *highly luminous* (for observation at great distance) and reliably *recognizable*. Variable stars naturally satisfy the recognition requirement, while some types satisfy the

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other requirements reasonably well and in some cases quite well. Cepheids, being giants and supergiants, can be observed in distant galaxies. Individual Cepheids differ in luminosity by factors up to about 100 and so might seem not to satisfy the consistency requirement, but H Leavitt discovered (*c*. 1905) that Cepheid luminosities are closely related to their directly measurable periods of brightness variation. After calibration, the *period–luminosity (P–L) relation* allows Cepheids to be used as standard candles, although essentially correct calibration required another half-century and is still being refined. However, even faulty early calibrations established distances to galaxies that were correct to an order of magnitude and thereby helped elucidate the nature of the 'spiral nebulae' and the scale of the Universe. Early applications were E Hertzsprung's distance estimate for the Small Magellanic Cloud and H Shapley's work on the extra-Galactic distance scale, following E Hubble's discovery of Cepheids in several galaxies. The distinction between Galactic and extra-Galactic objects was well established by 1925, five years after the famous Shapley–Curtis debates, when Hubble found 11 Cepheids in galaxy NGC 6822 and derived a distance. The Hubble Space Telescope and large ground-based telescopes have recently produced important increases in the Cepheid distance limit. Several kinds of exploding stars have very high luminosity, but Type Ia supernovae are best for recognition and consistency, in addition to being especially luminous. However, even the far less luminous and far less consistent ordinary novae have been used as distance indicators.

The large-amplitude pulsations of Cepheids and related variables can be exploited to measure radii rather directly. Luminosities then follow from combination of the radii with effective temperature (T_{eff}) estimates, so as to provide standard candles. Observed variation is due to separable changes in surface brightness and size. 'Wesselink radii' (after A Wesselink) require three kinds of accurate observations—a radial velocity curve, a light curve and a color index curve (briefly 'color curve'—formed by differencing light curves (in magnitudes) for two effective wavelengths). Color curves of Cepheids resemble their light curves at first glance, having smaller amplitudes and subtly different shapes. Points with given color occur at paired times that are close together near a color maximum or minimum and well separated at intermediate color. The basic idea is that color index is a reliable indicator of T_{eff} and therefore of surface brightness. However, a quantitative relation to predict surface brightness from color is not needed—just the reasonable assumption that when the star returns to a given color it also returns to the 'original' surface brightness. Any change in observable light, l, between those two times is due to changed surface area, so the ratio of radii at the two times is

$$\frac{R_2}{R_1} = \sqrt{\frac{l_2}{l_1}}. \tag{2}$$

The difference of radii follows from an integration between the corresponding points on the radial velocity curve,

$$R_2 - R_1 = \int_{t_1}^{t_2} v_r \, \mathrm{d}t. \tag{3}$$

Now having both ratio and difference, we find the individual radii at the two times. Repeating the procedure for many time pairs, we find the run of R with time. The fundamental assumption that surface brightness is a unique function of color for a given star may not be quite true, but is close enough for useful applications. With actual radii in kilometers and with model stellar atmosphere predictions of surface emission per unit area, a final step computes luminosities. The method is one of the few direct means to find accurate radii of giant stars and to calibrate P–L relations.

Another natural situation to exploit is the existence of variable stars in binaries and multiple star systems, where the variable star and binary star characteristics should be compatible if our evolutionary understanding is correct. For example, the age of a variable should agree with that of its companion(s), and its absolute dimensions and distance may be derivable from observations of the binary or multiple system. Examples include δ Scuti (see below) type members in Y Camelopardalis and AB Cassiopeia, a Cepheid in V350 Sagittarii, and a β Cephei star in 16 Lacertae. It is important to discover more such systems.

There are few probes of stellar interiors so it is important to have a *wide variety* of checks on global and surface properties, and the measures provided by pulsation and other forms of variation are welcome. For example, Cepheid masses can be inferred from both evolutionary and pulsational models, so the comparison either provides a check or sounds an alarm. Light curve and velocity curve details also can be predicted from pulsation models. The help comes where needed, as pulsational instabilities occur primarily in highly evolved stars where structure is complicated and theories are uncertain. Not only stellar structure theories but also equations of state, opacities, and energy generation rates ('laboratory physics' in principle but not in practice) are thereby subject to scrutiny.

On a wide front, galactic evolution is largely understood in terms of population types. For example the *RR Lyrae* type pulsating stars found in globular clusters and spheroidally distributed Galactic populations are not just short-period Cepheids, but have quite different Galactic distribution, motions, history and structure. Insight into RR Lyraes and Cepheids can apply to their non-variable neighbors in the HR diagram. On the observational side of galaxies, certain variable stars can be recognized at large distances and thus serve as population indicators.

Pulsation studies have now broadened into the rapidly developing field of asteroseismology, in which new observing methods and theoretical work on stellar oscillations extract structural information from multiple-frequency small amplitude variations in light and velocity.

Applications to the Sun (helioseismology) are particularly successful because the Sun is spatially resolved and because it has a rich spectrum of oscillations. The directly tapped energy of solar oscillations is that of convective motions in the outer envelope that generate sound waves. Certain other kinds of stars, such as Ap, δ *Scuti* (see below) and especially some white dwarf stars, show intricate oscillations that are clues to their evolutionary states. World-wide observing networks such as the Whole Earth Telescope (WET) allow the long, nearly continuous, coverage needed to separate closely spaced frequencies.

Explosion mechanisms

Nova theories of the early to mid 1900s involved rapid contraction to the white dwarf state or dynamical resonances combined with nuclear reactions. Those theories now seem inapplicable to known kinds of stellar explosions. A modern schematic model that covers many particular categories includes a donor star to provide a supply of gas and an accreting star on which eruptions occur. The flow may be a stream from overspilling a critical lobe or it may be a wind, and the eruptions may be powered by thermonuclear or gravitational energy. Ordinarily the donor is non-degenerate while the accretor is some kind of compact degenerate object, and most commonly a white dwarf star. Neutron star accretors are much rarer, and main sequence donors greatly outnumber evolved donors, but a wide variety of combinations occur. An especially abundant class is that of the *cataclysmic variables* (CVs) where the compact object is a white dwarf, although the white dwarf often cannot be detected directly. In most CVs the companion is a low-mass main sequence star, the orbit period is well under a day, and the entire binary is similar in size to the Sun, and smaller in many cases. CVs are typically old objects as shown by their distribution in the Galaxy, which is in a thicker disk than ordinary Population I stars.

A major clue into mechanisms and evolution was the inferred presence, via radial velocities and light curves, of white dwarfs in post novae, recurrent novae and nova-like variables in the 1950s to 1960s. Although thermonuclear models had been proposed earlier, ideas for explosions soon focused on accretion-driven surface hydrogen-burning runaways on white dwarfs. CV component masses are difficult to estimate, but the white dwarfs are typically much more massive than their non-degenerate companions. Relatively massive donors should be subject to unstable mass transfer that would radically change the configuration (flow from high to low mass or between comparable mass stars favors instability). Evolved donors (giants and subgiants) have the same problem—for structural reasons they tend to expand, overflow their lobes and transfer gas unstably on a large scale. So the lack of evolved and of relatively massive donor stars is commonly explained by their self-destructive tendencies. However, a CV needs some level of slow mass transfer to fuel its eruptions. A suitable level can be maintained by orbit shrinkage due to magnetic wind braking or gravitational radiation.

Classical novae brighten by 9^m or more over a few days and then decline irregularly over weeks for fast novae or months for slow novae. Symbiotic novae (see below) are much slower (duration $\approx$ decades) than the slowest classical nova and are much wider binaries than the ordinary CVs. The mass donor is typically a giant. For classical novae, more or less standard spectral developments occur, with emission and absorption line episodes and ejecta velocities of the order of 10^3 km s^{-1}, but with a large velocity range among examples. Interpretation is difficult, as the state of the gas is hard to compute and the dynamical situation is intricate, with multiple velocity systems seen at most times. Classical novae have had only one known outburst, but that circumstance is attributed to the short history of observational astronomy. Thus there are also *nova-like variables* that are probably the same as classical novae but have not exploded in (astronomical) historical times. Observations of post-novae find the underlying binaries not markedly changed by their outbursts.

Recurrent novae explode like classical novae but the eruptions are frequent, typically decades apart. Current thinking favors accretors that are close to the white dwarf mass limit, such that only small accretion build-up is needed to start a thermonuclear runaway. Chemical abundances in the ejecta do suggest advanced nuclear processing, as expected for remnants of stellar cores near the edge of collapse.

A computation of simple energetics shows that gravitational energy alone can power a large outburst from a white dwarf for a plausible sudden accretion episode. Objects identified with that mechanism are the *dwarf novae*—CVs that have cyclic outbursts with high repetition rates. Brightenings of up to about five magnitudes are separated by typical intervals of weeks to months and complicated shorter-term behavior includes fast flickering. Ideas to account for the episodes include sudden release of matter from a circumstellar disk (disk instability) and variable supply from the donor star (source instability). Examples are SS Cygni, U Geminorum, Z Camelopardalis and SU Ursae Majoris, each a prototype in a finer classification. Thermonuclear energy may play some role in dwarf novae. Ideas about evolutionary relationships among the several kinds of CVs are under continual revision.

Impressive as they are, CV explosions are small firecrackers compared with supernovae. In contrast to CVs, where the basic configuration remains after an explosion, a supernova event involves the entire star. Supernova mechanisms include thermonuclear incineration of a massive white dwarf star (in a binary) and collapse of an old, dense stellar core to nuclear degeneracy. Other types that are probably much less common have been proposed. The energy release in burning a white dwarf star can be estimated by multiplying a white dwarf mass ($\approx 3 \times 10^{33}$ g) by c^2 and by an efficiency factor

($\approx 10^{-3}$ for helium burning and beyond) to arrive at an energy between 10^{51} and 10^{52} erg, about a million times that of a typical nova. The minimum energy of a core collapse supernova is even much larger and follows from energy conservation in formation of a neutron star, whose gravitational binding energy, E_g, is of order -10^{53} erg. Obviously a positive energy that at least matches E_g must appear in the radiative and material ejecta. The visible radiation amounts to only $\approx 10^{48}$ to 10^{49} erg, and thus is a tiny fraction of the energy budget. Theoretical simulations indicate that nearly all of the energy is carried by neutrinos. The detection of about two dozen neutrinos from supernova 1987a in the Large Magellanic Cloud was a great triumph of supernova theory, as the number observed was the number predicted for a core collapse, within the uncertainties.

Pulsation

Pulsating stars undergo true pulsations (oscillations in size or shape). The pulsations are of the envelope, as the core is static and not directly involved. One could imagine the high-temperature sensitivity of nuclear reactions leading to core pulsations (the ϵ mechanism), but theory predicts that core pulsations will be quickly damped, except for supermassive stars. There are no candidates for core pulsation among the recognized variable stars, except perhaps the bizarre object η Carinae (see below) which may be a supermassive pulsating star. Pulsations grow when there is net conversion of thermal to mechanical energy, so the star is a heat engine. There are zones that *drive* pulsation (net [thermal $\Rightarrow$ mechanical]) and others that *damp* pulsation (net [mechanical $\Rightarrow$ thermal]). Elementary thermodynamics requires net heat injection in the compression stage if heat is to be converted to work so that the engine runs. However, direct injection of heat around maximum compression (as in an ordinary engine) is not the only way. Eddington realized in the 1920s that favorable circumstances could occur if a star is relatively heat-tight when compressed. Rather than thermal energy being inserted, its escape is prevented. This is the famous Eddington *valve* mechanism—a generic means to achieve net driving that covers all specific ways to implement heat-tightness upon compression. Two specific ways are the κ and γ mechanisms. The κ mechanism traps thermal energy by making material in driving zones more opaque upon compression (κ is the usual symbol for opacity). Kramers' Law, $\kappa = \kappa_0\rho/T^{3.5}$, provides roughly correct opacity for given density (ρ) and temperature (T). With ρ and T entered from accurate stellar structure models, it predicts that stellar material becomes *less* opaque upon compression, and indeed most stars do not pulsate. However, actual opacity depends in a complicated way on thermodynamic variables and, although it decreases with compression in most parts of most stars, it *increases* with compression in the driving zones of Cepheids and some other pulsating stars. The γ mechanism operates by increasing the surface density of absorbing particles upon compression. Imagine a thin pulsating shell of gas at its maximum and minimum radii. The number of contained particles is the same whether the shell is large or small but the number per unit area is greatest when the shell is small. Therefore the shell more effectively blocks radiation, or is more heat-tight, when compressed. The γ mechanism always contributes to driving for obvious geometrical reasons, while the κ mechanism can produce either driving or damping.

Driving will be weak if the main driving zones are too close to the surface (high) or too deep inside the star (low), and net damping will arrest pulsation. In the high case, the problem is insufficient density in the driving zones so that too little matter contributes to driving. In the low case, the driving zones lie in the nearly adiabatic interior where, although there is plenty of mass, each gram makes only a small contribution. Because driving is associated with ionization zones of the abundant elements H and He, net driving zones will be high in relatively hot (blue) stars and low in relatively cool (red) stars. Thus we have a roughly vertical *instability strip* in the HR diagram where Cepheids are found. However, its red and blue borders are not well defined and many non-pulsating stars lie within the strip. The instability strip extends down to and below the main sequence and includes the little-evolved or mildly evolved δ Scuti and related variables with their typical periods of hours. It then continues to the region of the pulsating white dwarfs (ZZ Ceti stars).

Several major distinctions characterize stellar pulsations. To begin, there are radial pulsations that preserve a star's figure (shape) but change its volume, and non-radial pulsations that preserve volume but vary the figure. An example of radial pulsation could be the expansion and contraction of a balloon under cyclically changing external pressure. A small-amplitude example of the non-radial case is provided by the tidal distortions of the Earth and its oceans. A large-amplitude example would be the oscillations of a disturbed water globule. A more formal description of the contrasting behavior is in terms of a vector field. In radial pulsation, the displacement vectors of local matter elements pass back and forth through zero length but maintain fixed alignments along local radii. Non-radial pulsation is more complicated, with the vectors cyclically changing both length and direction. Of course, real pulsations need not be purely radial or non-radial but can involve both volume and figure changes. However, many realistic situations approximate these idealized types.

Another distinction involves fundamental and overtone pulsation. The situation is conceptually the same as for a flexible string with one fixed and one free end, where the free end is the analog of a pulsating star's surface. The string can have a fundamental oscillation, with a node only at the fixed end, and also overtone oscillations with 1, 2, 3,. . ., n additional nodes. At a given instant, adjacent internode regions have opposite motions (up versus down), and of course there is no motion at the nodes. Similarly a pulsating star can have fundamental and overtone pulsations, with extra nodes for the overtones. For a uniform string the nodes will be equally spaced, but a star has inwardly increasing density, with the consequence that node spacings are not even approximately equal and must be computed. Fundamental and overtone pulsations can coexist and, accordingly, some unusual stars show beat phenomena.

Still another distinction is among pulsation *modes*, i.e. possible ways to pulsate. The large amplitude radial pulsations of Cepheid and RR Lyr type variables are in *pressure* modes (p-modes), so called because they involve large local pressure variations. Both radial and non-radial p-mode pulsations can occur. *Gravity* modes (g-modes) involve global oscillations about a hydrostatic level surface and are necessarily non-radial. They have much smaller pressure variations than do p-modes. Of course, energy can feed from one mode to another and between fundamental and overtones.

No one kind of pulsation analysis serves all purposes. As in other areas, success in computing detailed behavior does not guarantee understanding. The general phenomenon is highly nonlinear and one might expect maximum insight to follow from all-encompassing computations, but much insight has been gained from linear analyses in which only infinitesimal pulsations are studied. For example, the period of a simple oscillating system such as a pendulum is the same for all swing amplitudes, which suggests that linear analysis of infinitesimal pulsations may provide essential results on possible periods of pulsating stars. N Baker realized that outcome by restricting attention to a single mass shell—the One Zone model. However, pulsating stars are complicated structures with many (thermally and mechanically) coupled zones, so quantitative predictions of periods need complete models. To view the problem the opposite way, a full nonlinear computation should settle into a correct period, but will not identify all possible periods found from linear theory. Although linear analysis leads to insight on several fronts, it deals only with infinitesimal pulsations and therefore cannot produce complete models for comparison with observations. Possible pulsation modes and overtones are identified through linear analysis, with detailed behavior at finite amplitude examined via nonlinear analysis, including possible interactions of fundamental and overtones. Similarly, growth and decay rates of small-amplitude pulsations can be investigated via linear analysis, but rates for large pulsations and final saturation amplitudes are matters for nonlinear analysis. Of course, specific light and velocity curve features can be modeled only with full nonlinear computations.

A wealth of observed phenomena in pulsating stars remain only partly understood or have only recently been understood, including light versus velocity phase lags that are characteristic of a given class, unusual surface abundances, changing velocity amplitudes and multiple periodicity. Magnetic fields, fast rotation and binary companions are clearly present in some cases, but their roles in pulsation are not usually obvious. Specific driving mechanisms may not be clear. An active testing ground for pulsation theory is provided by the *β Cephei stars*, a class sometimes called the β Canis Majoris stars, although current usage seems to have settled on the name β Cephei. These stars have remarkably short pulsation periods of order $0.^{d}2$, with about half being doubly periodic and thereby showing beat behavior in light and velocity. Many RR Lyr and δ Sct stars also are doubly periodic, but the two periods of a β Cep star can differ by as little as 1%. The prototype β Cephei (not itself doubly periodic) is strongly magnetic and at least a triple system, with weak B-emission (Be) characteristics. A phenomenon that must occur but is difficult to model is that of dynamical tides in eccentric and/or asynchronous binaries, which can be regarded as forced non-radial pulsations. Like ocean waves, such tides are largely stochastic so that prediction is mainly limited to statistical behavior. Several supergiants with neutron star companions show the expected fluctuations in light and velocity, including GP Velorum = Vela X1 and V884 Scorpii, but quantitative matches with tidal theory remain unrealized.

Other variation mechanisms

While eruptive and pulsating stars vary due to a variety of dynamical, thermal and cyclic instabilities that are more or less understood, or at least largely identified, variations in many categories are caused by instabilities that are not so well understood, by random events and by random drifts in conditions. Some of these stars live on the border between intrinsic and extrinsic variables. For example, RS CVn, BY Dra and W UMa binaries can be heavily covered by magnetic spots, similar to sunspots. The agent understood to produce such spots is dynamo action in a fast-rotating convective envelope, so cool stars that have convective envelopes are likely candidates—if they spin fast. The RS CVns, BY Dras, and W UMas naturally spin fast because they are tidally locked close binaries, but FK Com and a small number of similar stars are fast spinning *single* giants! Their fast rotation currently is attributed to their being recently merged ex-binary systems, with the binary orbital angular momentum now existing as spin angular momentum. Spot-modulated stars are extrinsic variables in that they vary on the orbital time scale because of changing aspect of their spots. However, the spots grow, decline and move, so they are intrinsic variables on longer time-scales.

Accretion tends to be highly irregular and causes not only modest brightness fluctuations in active binaries, but variations of up to several magnitudes in newly formed stars that accrete from their surroundings (T Tauri stars). Much of the luminosity of T Tauris and related stars is from the accretion process. Young objects of the FU Orionis type have brightening episodes of up to five magnitudes on a time-scale of decades to centuries. Outflows are associated with accretion but are not well understood at present. Some classical T Tau stars are surrounded by circumstellar disks that have been imaged in the infrared, with spectroscopic and imaging evidence

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of bipolar outflows. Accretion onto white dwarfs not only leads to circumstances that eventually produce nova explosions but also directly converts gravitational energy to more tangible forms, as seen above for dwarf novae. Even an occasional non-degenerate binary such as V361 Lyrae has a hot spot where high-speed gas impacts one of the stars, having flowed in a well defined stream from the other. Variable flows produce variable spot luminosities and thus another kind of intrinsic–extrinsic variable. In post novae and dwarf novae, the hot spot is on a disk surrounding the stream's target star. Most exploding stars show variability between outbursts in their 'quiescent' light curves. A common seat of variation is the hot spot as it flickers by $0.^{m}1$ to $0.^{m}2$ on a time scale of minutes, due to irregular inflow. Usually the hot spot itself, rather than either star or the overall disk, is the brightest light source in the binary. X-ray binaries whose accreting objects are neutron stars have accretion power at least 30 times their thermonuclear power (for H burning; more than 100 times for He burning), so the promptly released energy is about the same whether the material burns or not. However, large thermonuclear bursts can occur on neutron stars if substantial amounts of fuel accumulate, providing the sources known as x-ray bursters, where helium is the fuel. As a group, x-ray binaries are variable in all spectral regions, from radio to gamma, although most individuals are detected only in restricted ranges. There are two essentially disjoint classes on greatly different scales, low-mass x-ray binaries (LMXBs) and high-mass x-ray binaries (HMXBs). At first inspection, LMXBs and HMXBs have little in common except that they contain neutron stars, and even a sketch of ideas about their origins would exceed available space. Configurations are such that HMXBs accrete mainly via winds from their blue supergiant companions and many pulse in x-rays, while LMXBs accrete mainly via lobe overflow and very few pulse. LMXBs bear a remarkable similarity to CVs, including absolute dimensions, with the notable difference being that a neutron star replaces the CV's white dwarf. It has been noted that some LMXBs may form from CVs in rare cases of accretion beyond the white dwarf mass limit.

Still another kind of intrinsic–extrinsic hybrid is the *symbiotic star*, where ultraviolet radiation from the environs of a small, hot accretor interacts with the wind, extended atmosphere or chromosphere of a red giant companion. Fluctuations in UV radiation and in wind flow lead to intrinsically variable fluorescence modulated by orbital aspect effects, sometimes including eclipses. Orbit periods are long compared with most variable binaries, being typically hundreds of days or more. Because of observational difficulties, the defining characteristics of the class are necessarily superficial—the accreting objects are not usually directly observed and may be as diverse as neutron stars, white dwarfs and main sequence stars. Extreme examples of symbiotics include *symbiotic novae* that have outbursts by brightness factors of order 100 and are believed to contain white dwarf accretors. Unlike CVs, a symbiotic nova can be in outburst for decades. The mechanism usually assumed is a thermonuclear surface flash on the accretor followed by slow cooling. These objects are often called slow novae but differ radically from the CVs with the same name, so 'symbiotic nova' should consistently be applied. Examples of symbiotic novae include PU Vulpeculae, RR Telescopii and V1329 Cygni.

Variable polarization can result from scattering by circumstellar gas, but really spectacular variable polarization is seen in CVs that contain accreting white dwarfs with extremely strong magnetic fields. These are the *polars*, or AM Her binaries, where cyclotron radiation in an oblique rotator produces strong circular polarization over a wide range of wavelength, including optical light. Polars also are moderately strong x-ray sources and natural laboratories for studying hydrodynamic flows under combined gravitational and magnetic fields, with variable light and polarization as diagnostics. *Intermediate polars* have magnetic fields that are intense but somewhat below those of polars. Examples of intermediate polars are EX Hydrae and GK Persei.

Fluctuations in stellar winds can generate small-scale emission line and continuum variation, particularly where winds are strong. Most *Wolf–Rayet* (W–R) stars accordingly vary by a few hundredths of a magnitude. A W–R star is the highly evolved residue of a very massive star that has lost much of its envelope so as to expose hot inner regions. Often there is an evolved close companion with its own strong wind, so that wind–wind interactions cause further variation.

Intermittent veiling is a very unusual variation mechanism and a major diagnostic of circumstellar conditions and interior structure in certain (usually giant) stars. In veiled stars we find intrinsic and extrinsic variation combined, as clouds come and go while changing aspect controls their influence on light curves. Hydrodynamic flow in a mass transferring binary can lead to concentrations of partially opaque material being projected onto the face of one or both stars, so that light curves can help map circumstellar gas. An example is AX Monocerotis. Particularly spectacular examples of veiling are the *R Coronae Borealis stars*—extremely carbon rich and hydrogen deficient (apparently single) supergiants that are veiled by carbon particles at irregular times, with brightness drops by factors of up to about 1000. These pulsating stars eject clouds of gas whose carbon condenses to soot when sufficiently far from the hot photosphere, with clouds that happen to lie on the line of sight producing the veiling. Pulsational characteristics, together with the strange abundances, provide strong constraints on possible evolutionary histories of R CrB stars. Given that only a few dozen are known, R CrBs must either represent a very brief stage of normal evolution or products of an unusual formation process such as a merger.

Large evolutionary changes over the brief history of observational astrophysics are extremely unusual. Perhaps the most spectacular example is FG Sagittae, which has evolved from the small, hot exciting star of a planetary nebula into a pulsating R CrB type red giant in only a century, with decade to decade developments. Whether FG Sge is typical as a progenitor of R CrBs is an open issue at present.

Flares are brief local eruptions, prominent in both continuum light and lines, from the chromospheres of magnetically active stars. The *UV Ceti* or *flare stars* are low-mass main sequence stars with unusually high levels of chromospheric activity. Flares are much hotter than red dwarf photospheres, so the brightening in magnitudes is highly wavelength dependent, increasing strongly into the ultraviolet. As with spot-modulated stars, rotation in a deep convective envelope generates strong dynamo action, with UV Cet stars being especially fast rotators. Flare activity is at least statistically a sign of youth, since red dwarf rotation decreases with age.

Stars described as variable are traditionally those that vary in brightness, especially over broad spectral regions. However, several kinds of *spectrum variables* vary most notably in spectral details, with behavior that can be as interesting as in the more obvious variables. For example, strong variable magnetic fields are involved in spectral variations of Ap and Am stars (Ap = peculiar stars of spectral type A; Am = metallic line stars of spectral type A). Stars that lose matter via powerful and unsteady winds, such as those of spectral type Of, show variable emission lines with great Doppler broadening. Stars of type Be (*B emission stars*) were among the first to draw special attention as spectroscopically interesting in the 1800s, and continue to stimulate hypotheses, observations, and controversy. The emission lines of Be stars are usually ascribed to circumstellar equatorial rings associated with centrifugal ejection of matter, but circumstances leading to that situation are not widely agreed upon. Even the basic point of whether binary nature is essential or irrelevant to Be behavior remains at issue.

Unique objects

Much of the fascination of variable star astrophysics is provided by unique objects that may result from anomalous formation, short effective lifetime or selection effects. A few examples may give some of the flavor.

Most recognized causes of variation, including pulsation, gas dynamic interactions and rotation phenomena, have been proposed for the spectacular and mysterious η Carinae. Especially notable are its great luminosity and enormous swings in apparent magnitude over centuries, including an interval in the 1840s when it approached Sirius in brightness. It is usually regarded as a supermassive star with mass above (and perhaps far above) 60 solar masses, and therefore a candidate for core pulsation via unstable thermonuclear burning. Speculation that it is a binary is supported by recent high resolution imaging of a bipolar nebula that must have been ejected in η Car's great outburst of *c*. 1840 and by discovery of 5.5 year spectroscopic and photometric periodicities. Understanding of η Car is rapidly developing but still rudimentary.

The recurrent nova T Corona Borealis has the basic red star–blue star binary morphology of novae, but with a red giant in place of the usual main sequence red star and an orbit period (228^d) typical of symbiotic novae. However, it can scarcely be called a symbiotic nova, as the outbursts last not for decades but only for weeks. T CrB has no known siblings, but does have a rich and extensive literature.

And then there are the pulsating WHITE DWARF stars, the DUSTY CIRCUMSTELLAR DISKS, the QUASIPERIODIC OSCILLATIONS IN X-RAY BINARY STARS, the incredible SS433 and HERCULES X-1, . . ., but wait—those are other articles. No brief synopsis could do them justice. So turn to those articles—your instrumentation is a comfortable chair and a cup of hot chocolate. Enjoy.

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