14 Variable Stars

Stars with changing magnitudes are called *variables* (Fig. 14.1). Variations in the brightness of stars were first noted in Europe at the end of the 16th century, when *Tycho Brahe's supernova* lit up (1572) and the regular light variation of the star *o* Ceti (Mira) was observed (1596). The number of known variables has grown steadily as observational precision has improved (Fig. 14.2). The most recent catalogues contain about 40,000 stars known or suspected to be variable.

Strictly speaking, all stars are variable. As was seen in Chap. 12, the structure and brightness of a star change as it evolves. Although these changes are usually slow, some evolutionary phases may be extremely rapid. In certain evolutionary stages, there will also be periodic variations, for example pulsations of the outer layers of a star.

Small variations in stellar brightness are also caused by hot and cool spots on a star's surface, appearing and disappearing as it rotates about its axis. The luminosity of the Sun changes slightly because of the sunspots. Probably there are similar spots on almost all stars.

Initially stellar brightnesses were determined visually by comparing stars near each other. Later on, comparisons were made on photographic plates. At present the most accurate observations are made photoelectrically or using a CCD camera. The magnitude variation as a function of time is called the *lightcurve* of a star (Fig. 14.3). From it one obtains the *amplitude* of the magnitude variation and its *period*, if the variation is periodic.

The basic reference catalogue of variable stars is the *General Catalogue of Variable Stars* by the Soviet astronomer *Boris Vasilyevich Kukarkin*. New, supplemented editions appear at times; the fourth edition published in 1985–1987, edited by P.N. Kholopov, contains about 32,000 variables of the Milky Way galaxy.

14.1 Classification

When a new variable is discovered, it is given a name according to the constellation in which it is located. The name of the first variable in a given constellation is R, followed by the name of the constellation (in the genitive case). The symbol for the second variable is S, and so on, to Z. After these, the two-letter symbols RR, RS, ... to ZZ are used, and then AA to QZ (omitting I). This is only enough for 334 variables, a number that has long been exceeded in most constellations. The numbering therefore continues: V335, V336, etc. (V stands for variable). For some stars the established Greek letter symbol has been kept, although they have later been found to be variable (e.g. δ Cephei).

The classification of variables is based on the shape of the lightcurve, and on the spectral class and observed radial motions. The spectrum may also contain dark absorption lines from material around the star. Observations can be made outside the optical region as well. Thus the radio emission of some variables (e.g. flare stars) increases strongly, simultaneously with their optical brightness. Examples of radio and X-ray vari-

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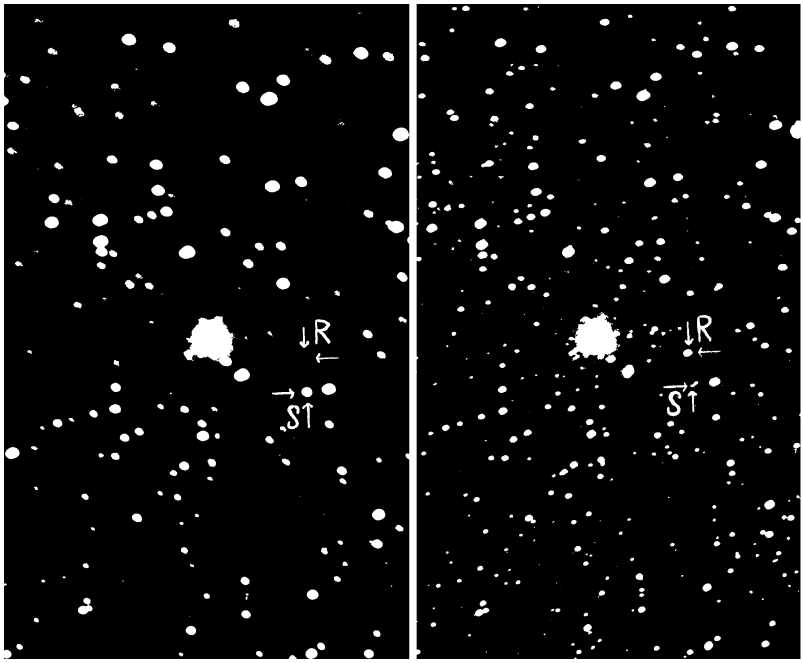


Fig. 14.1 The variables are stars changing in brightness. Two variables in Scorpius, R and S Sco. (Photograph Yerkes Observatory)

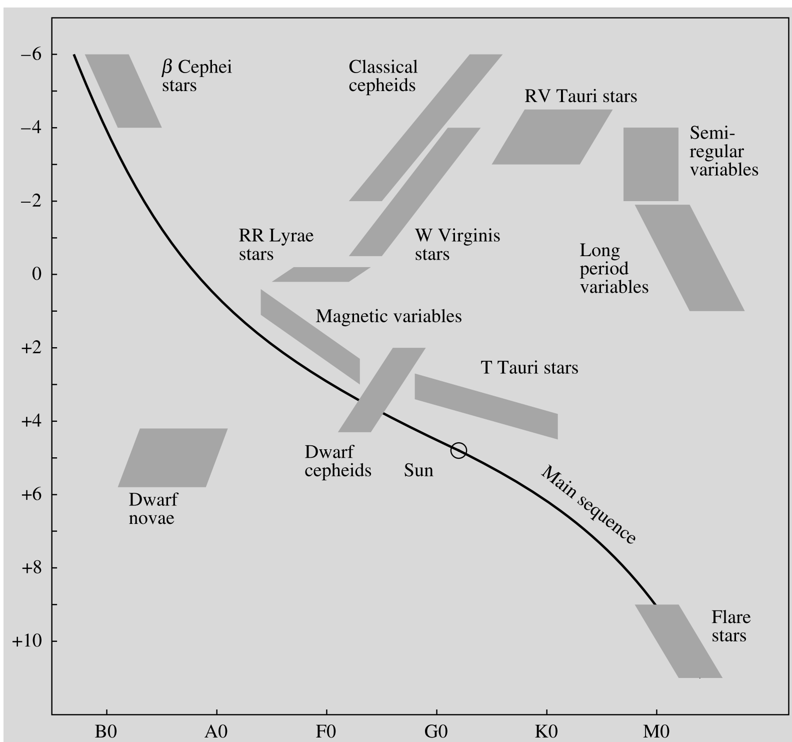


Fig. 14.2 The location of variables in the HR diagram

ables are the radio and X-ray pulsars, and the X-ray bursters.

Variables are usually divided into three main types: *pulsating*, *eruptive* and *eclipsing variables*.

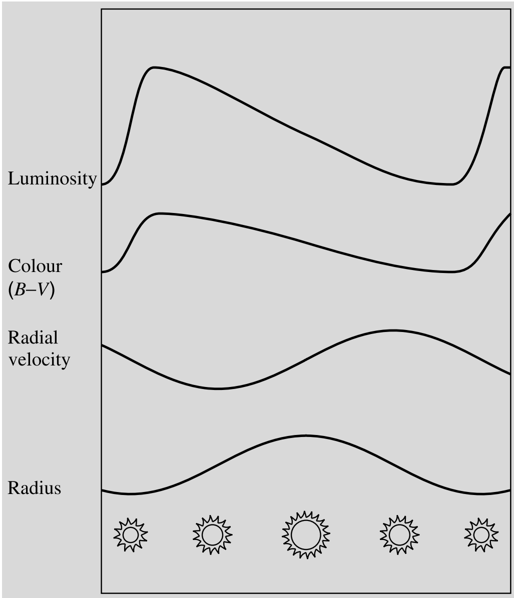


Fig. 14.3 The variation of brightness, colour and size of a cepheid during its pulsation

The eclipsing variables are binary systems in which the components periodically pass in front of each other. In these variables the light variations do not correspond to any physical change in the stars. They have been treated in connection with the binary stars. In the other variables the brightness variations are intrinsic to the stars. In the pulsating variables the variations are due to the expansion and contraction of the outer layers. These variables are giants and supergiants that have reached an unstable stage in their evolution. The eruptive variables are usually faint stars ejecting mass. They are mostly members of close binary systems in which mass is transferred from one component to the other.

In addition a few *rotating variables* are known, where the brightness variations are due to an uneven temperature distribution on the surface, starspots coming into sight when the star rotates. Such stars may be quite common—after all, our Sun is a weak rotating variable. The most prominent group of rotating variables are the magnetic A stars (e.g. the α^2 Canum Venaticorum stars). These stars have strong magnetic fields that may be giving rise to starspots. The periods of rotating variables range from about 1 day to 25 d, and the amplitudes are less than 0.1 mag.

Table 14.1 The main properties of pulsating variables (N, number of stars of the given type in Kukarkin's catalogue, P, pulsation period in days, Δm, pulsation amplitude in magnitudes)

Variable	N	P	Spectrum	Δm
Classical cepheids (δ Cep, W Vir)	800	1–135	F–K I	$\lesssim 2$
RR Lyrae	6100	<1	A–F8	$\lesssim 2$
Dwarf cepheids (δ Scuti)	200	0.05–7	A–F	$\lesssim 1$
β Cephei	90	0.1–0.6	B1–B3 III	$\gtrsim 0.3$
Mira variables	5800	80–1000	M–C	$\gtrsim 2.5$
RV Tauri	120	30–150	G–M	$\lesssim 4$
Semiregular	3400	30–1000	K–C	$\lesssim 4.5$
Irregular	2300	–	K–M	$\lesssim 2$

14.2 Pulsating Variables

The wavelengths of the spectral lines of the pulsating variables change along with the brightness variations (Table 14.1). These changes are due to the Doppler effect, showing that the outer layers of the star are indeed pulsating. The observed gas velocities are in the range of 40–200 km/s.

The period of pulsation corresponds to a *proper frequency* of the star. Just like a tuning fork vibrates with a characteristic frequency when hit, a star has a fundamental frequency of vibration. In addition to the fundamental frequency other frequencies, "overtones", are possible. The observed brightness variation can be understood as a superposition of all these modes of vibration. Around 1920, the English astrophysicist *Sir Arthur Eddington* showed that the period of pulsation P is inversely proportional to the square root of the mean density,

$$P \propto \frac{1}{\sqrt{\rho}}. \quad (14.1)$$

The diameter of the star may double during the pulsation, but usually the changes in size are minor. The main cause of the light variation is the periodic variation of the surface temperature. We have seen in Sect. 5.7 that the luminosity of a star depends sensitively on its effective temperature, $L \propto T_e^4$. Thus a small change in effective temperature leads to a large brightness variation.

Normally a star is in stable hydrostatic equilibrium. If its outer layers expand, the density and temperature decrease. The pressure then becomes smaller and the force of gravity compresses the gas again. However, unless energy can be transferred to the gas motions, these oscillations will be damped.

The flux of radiative energy from the stellar interior could provide a source of energy for the stellar oscillations, if it were preferentially absorbed in regions of higher gas density. Usually this is not the case but in the *ionisation zones*, where hydrogen and helium are partially ionised, the opacity in fact becomes larger when the gas is compressed. If the ionisation zones are at a suitable depth in the atmosphere, the energy absorbed during compression and released during expansion of an ionisation zone can drive an oscillation. Stars with surface temperatures of 6000–9000 K are liable to this instability. The corresponding section of the HR diagram is called the cepheid instability strip.

Cepheids Among the most important pulsating variables are the cepheids, named after δ Cephei (Fig. 14.3). They are population I supergiants (stellar populations are discussed in Sect. 18.2) of spectral class F–K. Their periods are 1–50 days and their amplitudes, 0.1–2.5 magnitudes. The shape of the light curve is regular, showing a fairly rapid brightening, followed by a slower fall off. There is a relationship between the period of a cepheid and its absolute magnitude (i.e. luminosity), discovered in 1912 by *Henrietta Leavitt* from cepheids in the Small Magellanic Cloud. This *period–luminosity relation* (Fig. 14.4) can be used to measure distances of stars and nearby galaxies.

We have already noted that the pulsation period is related to the mean density. On the other hand the size of a star, and hence its mean density, is related to its total luminosity. Thus one can understand why there should be a relation between the period and the luminosity of a pulsating star.

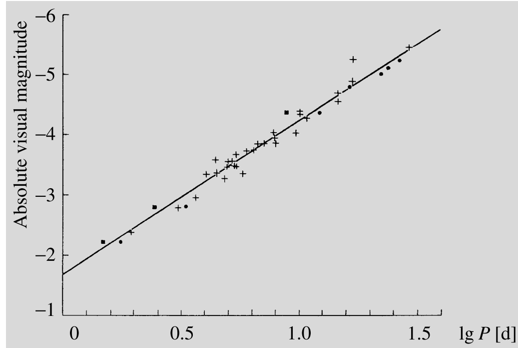


Fig. 14.4 The period–luminosity relation for cepheids. *The black points* and *squares* are theoretically calculated values, *the crosses* and *the straight line* represent the observed relation. (Drawing from Novotny, E. (1973): *Introduction to Stellar Atmospheres and Interiors* (Oxford University Press, New York) p. 359)

The magnitudes M and periods P of classical cepheids are shown in Fig. 14.4. The relation between M and $\log P$ is linear. However, to some extent, the cepheid luminosities also depend on colour: bluer stars are brighter. For accurate distance determinations, this effect needs to be taken into consideration.

W Virginis Stars In 1952 *Walter Baade* noted that there are in fact two types of cepheids: the classical cepheids and the W Virginis stars. Both types obey a period–luminosity relation, but the W Vir stars of a given period are 1.5 magnitudes fainter than the corresponding classical cepheids. This difference is due to the fact that the classical cepheids are young population I objects, whereas the W Vir stars are old stars of population II. Otherwise, the two classes of variables are similar.

Earlier, the W Vir period–luminosity relation had been used for both types of cepheids. Consequently the calculated distances to classical cepheids were too small. For example, the distance to the Andromeda Galaxy had been based on classical cepheids, since only these were bright enough to be visible at that distance. When the correct period–luminosity relation was used, all extragalactic distances had to be doubled. Distances within the Milky Way did not have to be changed, since their measurements were based on other methods.

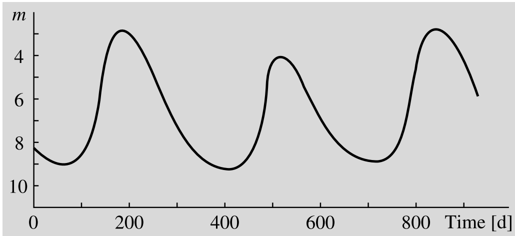


Fig. 14.5 The lightcurve of a long period Mira variable

RR Lyrae Stars The third important class of pulsating variables are the *RR Lyrae stars*. Their brightness variations are smaller than those of the cepheids, usually less than a magnitude. Their periods are also shorter, less than a day. Like the W Vir stars, the RR Lyrae stars are old population II stars. They are very common in the globular star clusters and were therefore previously called cluster variables.

The absolute magnitudes of the RR Lyrae stars are about $M_V = 0.6 \pm 0.3$. They are all of roughly the same age and mass, and thus represent the same evolutionary phase, where helium is just beginning to burn in the core. Since the absolute magnitudes of the RR Lyrae variables are known, they can be used to determine distances to the globular clusters.

Mira Variables (See Fig. 14.5.) The Mira variables (named after Mira Ceti) are supergiants of spectral classes M, S or C, usually with emission lines in their spectrum. They are losing gas in a steady stellar wind. Their periods are normally 100–500 days, and for this reason, they are also sometimes called long period variables. The amplitude of the light variations is typically about 6 magnitudes in the visual region. The period of Mira itself is about 330 days and its diameter is about 2 au. At its brightest, Mira has the magnitude 2–4, but at light minimum, it may be down to 12. The effective temperature of the Mira variables is only about 2000 K. Thus 95 % of their radiation is in the infrared, which means that a very small change in temperature can cause a very large change in visual brightness.

Other Pulsating Variables One additional large group of pulsating stars are the *semiregular* and *irregular variables*. They are supergiants, often very massive young stars with unsteady pulsations in their extended outer layers. If there is some periodicity in the pulsations, these variables are called semiregular; otherwise they are irregular. An example of a semiregular variable is Betelgeuse (α Orionis). The pulsation mechanism of these stars is not well understood, since their outer layers are convective, and the theory of stellar convection is still poorly developed.

In addition to the main types of pulsating variables, there are some smaller separate classes, shown in Fig. 14.2.

The *dwarf cepheid* and the δ Scuti stars, which are sometimes counted as a separate type, are located below the RR Lyrae stars in the cepheid instability strip in the HR diagram. The dwarf cepheids are fainter and more rapidly varying than the classical cepheids. Their light curves often show a beating due to interference between the fundamental frequency and the first overtone.

The *β Cephei* stars are located in a different part of the HR diagram than the other variables. They are hot massive stars, radiating mainly in the ultraviolet. The variations are rapid and of small amplitude. The pulsation mechanism of the β Cephei stars is unknown.

The *RV Tauri* stars lie between the cepheids and the Mira variables in the HR diagram. Their period depends slightly on the luminosity. There are some unexplained features in the light curves of the RV Tauri stars, e.g. the minima are alternately deep and shallow.

14.3 Eruptive Variables

In the eruptive variables there are no regular pulsations. Instead sudden outbursts occur in which material is ejected into space. Nowadays such stars are divided into two main categories, *eruptive* and *cataclysmic variables*. Brightness changes of eruptive variables are caused by sudden eruptions in the chromosphere or corona, the contributions of which are, however, rather small in the stellar scale. These stars are usually surrounded by a gas shell or interstellar matter participating in the eruption. This group includes e.g. *flare stars*, various kinds of *nebular variables*,

Table 14.2 Main properties of eruptive variables (N, number of stars of the given type in Kukarkin's catalogue, Δm, change in brightness in magnitudes. The velocity is the expansion velocity in km/s, based on the Doppler shifts of the spectral lines)

Variable	N	Δm	Velocity
Supernovae	7	$\gtrsim 20$	4000–10,000
Ordinary novae	210	7–18	200–3500
Recurrent novae		$\lesssim 10$	600
Nova-like stars (P Cygni, symbiotic)	80	$\lesssim 2$	30–100
Dwarf novae (SS Cyg = U Gem, ZZ Cam)	330	2–6	(700)
R Coronae Borealis	40	1–9	–
Irregular (nebular variables, T Tau, RW Aur)	1450	$\lesssim 4$	(300)
Flare stars (UV Ceti)	750	$\lesssim 6$	2000

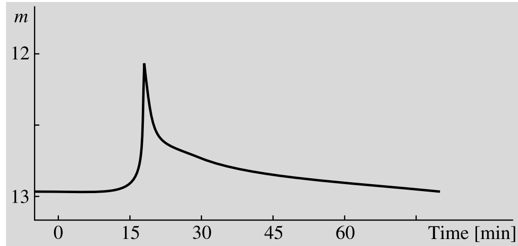


Fig. 14.6 The outbursts of typical flare stars are of short duration

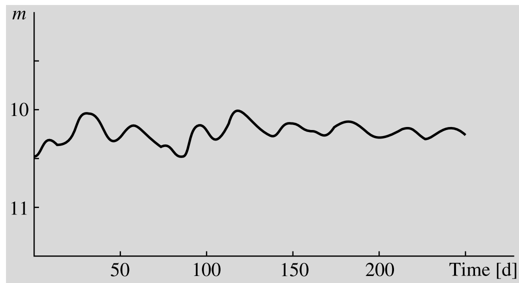


Fig. 14.7 Light curve of a T Tauri variable

and *R Coronae Borealis stars*. Eruptions of the cataclysmic variables are due to nuclear reactions on the stellar surface or interior. Explosions are so violent that they can even destroy the whole star. This group includes *novae* and nova-like stars, *dwarf novae* and *supernovae* (Table 14.2).

Flare Stars The *flare* or *UV Ceti stars* are dwarf stars of spectral class M. They are young stars, mostly found in young star clusters and associations. At irregular intervals there are flare outbursts on the surface of the stars similar to those on the Sun. The flares are related to disturbances in the surface magnetic fields. The energy of the outbursts of the flare stars is apparently about the same as in solar flares, but because the stars are much fainter than the Sun, a flare can cause a brightening by up to 4–5 magnitudes. A flare lights up in a few seconds and then fades away in a few minutes (Fig. 14.6). The same star may flare several times in one day. The optical flare is accompanied by a radio outburst, like in the Sun. In fact, the flare stars were the first stars to be detected as radio sources.

Nebular Variables In connection with bright and dark interstellar clouds e.g. in the constellations of Orion, Taurus and Auriga, there are variable stars. The *T Tauri stars* are the most interesting of them. These stars are newly formed or just contracting towards the main sequence. The brightness variations of the T Tauri stars are irregular (Fig. 14.7). Their spectra contain bright emission lines, formed in the stellar chromosphere, and forbidden lines, which can only be formed at extremely low densities. The spectral lines also show that matter is streaming out from the stars.

Since the T Tauri stars are situated inside dense gas clouds, they are difficult to observe. However, this situation has improved with the development of radio and infrared techniques.

Stars in the process of formation may change in brightness very rapidly. For example, in 1937, FU Orionis brightened by 6 magnitudes. This star is a strong source of infrared radiation, which shows that it is still enveloped by large quantities of interstellar dust and gas. A similar brightening by six magnitudes was observed in 1969 in V1057 Cygni (Fig. 14.8). Before its brightening, it was an irregular T Tauri variable; since then, it has remained a fairly constant tenth-magnitude AB star.

Stars of the *R Coronae Borealis* type have “inverse nova” light curves. Their brightness may drop by almost ten magnitudes and stay low for years, before the star brightens to its normal luminosity. For example, R CrB itself is of magnitude 5.8, but may fade to 14.8 magnitudes. Figure 14.9 shows its recent decline, based on observations by Finnish and French amateurs. The R CrB stars are rich in carbon and the decline is produced when the carbon condenses into a circumstellar dust shell.

One very interesting variable is η *Carinae* (Fig. 14.10). At present it is a six magnitude star surrounded by a thick, extensive envelope of dust and gas. In the early 19th century η Carinae was the second brightest star in the sky after Sirius. Around the middle of the century it rapidly dimmed to magnitude 8, but during the 20th century it has brightened somewhat. η Carinae is a so called bright blue variable. Its mass is estimated to be of the order of 100 solar masses. The circumstellar dust cloud is the brightest infrared source in the sky outside the solar system. The energy radiated by η Carinae is absorbed by the nebula and re-radiated at infrared wavelengths. The exact reason for the enormous brightness variations is not known. It is believed that the stability of the star is disturbed by the radiation pressure of the huge energy produced by a very massive star. When the nucleus will collapse at the end of the lifespan of the star, η Carinae will explode as a supernova.

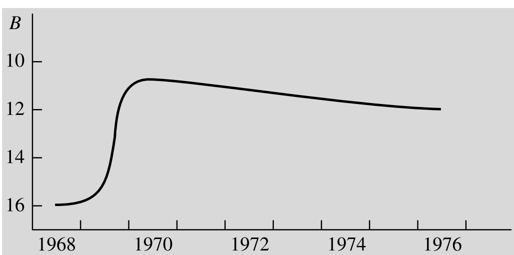


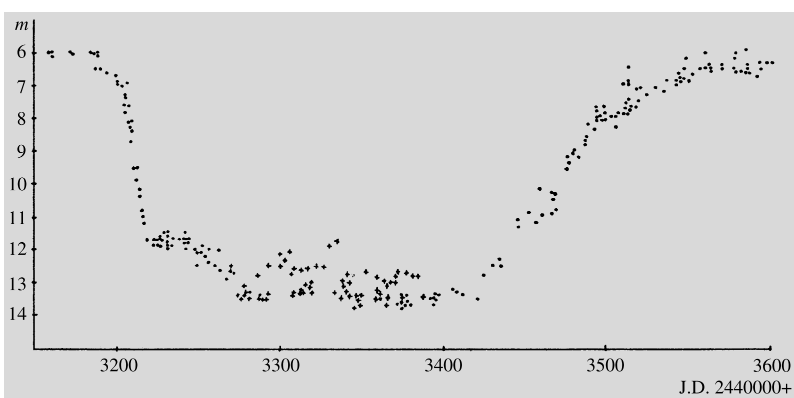
Fig. 14.8 In 1969–1970, the star V1057 Cygni brightened by almost 6 magnitudes

Novae One of the best known types of eruptive variables are the *novae*. They are classified into several subtypes: *ordinary novae*, *recurrent novae* and *nova-like variables*. The *dwarf novae* (Fig. 14.11) are nova-like rather frequently eruptive stars; although the lightcurves are similar to those of novae, the mechanism is different.

The outbursts of all novae are rapid. Within a day or two the brightness rises to a maximum, which may be 7–16 magnitudes brighter than the normal luminosity. This is followed by a gradual decline, which may go on for months or years. The light curve of a typical nova is shown in Fig. 14.13. This light curve of Nova Cygni 1975 has been composed from hundreds of observations, mostly by amateurs.

In recurrent novae, the brightening is somewhat less than 10 magnitudes and in dwarf novae, 2–6 magnitudes. In both types there are repeated outbursts. For recurrent novae the time between outbursts is a few decades and for the dwarf novae 20–600 days. The interval depends on the strength of the outburst: the stronger the outburst, the longer the time until the next one. The bright-

Fig. 14.9 The decline of R Coronae Borealis in 1977–1978; observations by Finnish and French amateur astronomers. (Kellomäki, Tähdet ja Avaruus 5/1978)



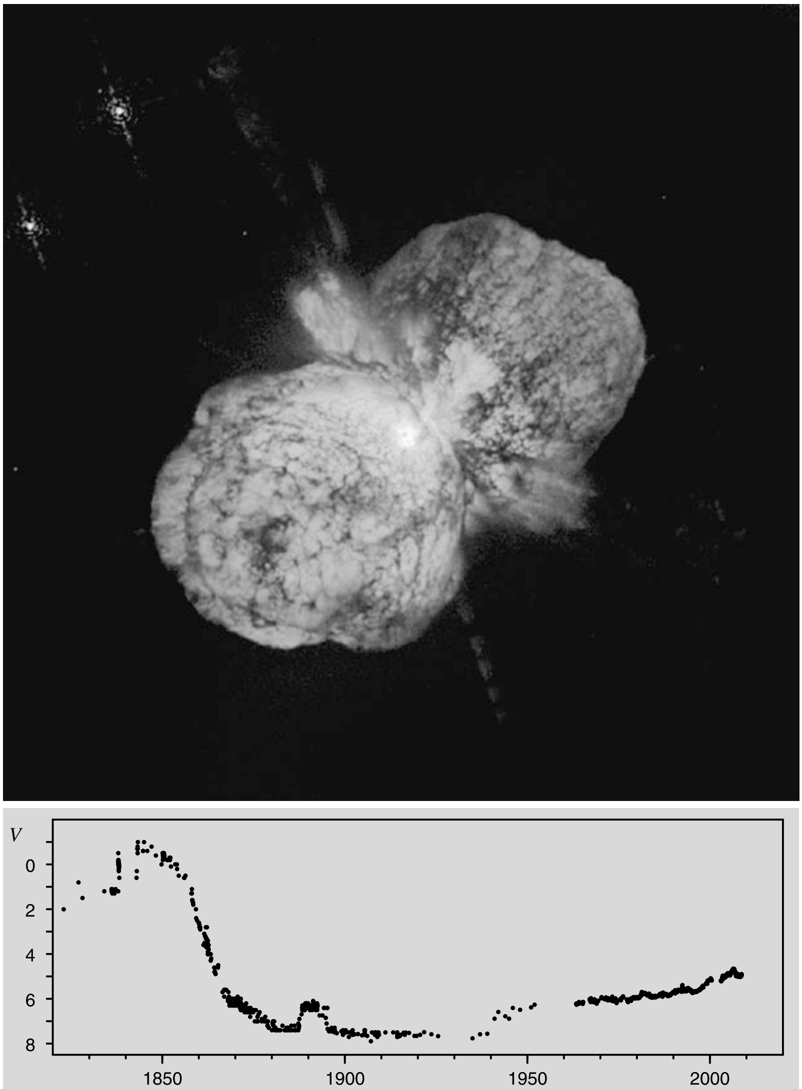


Fig. 14.10 In the 19th century, η Carinae was one of the brightest stars in the sky; since then it has dimmed considerably. In an outburst in 1843 the star ejected an expanding nebula, which has been called "Homunculus". The Hubble photograph has been printed negative, to show finer details in the bipolar outflow. (Photograph NASA/HST/University of Minnesota)

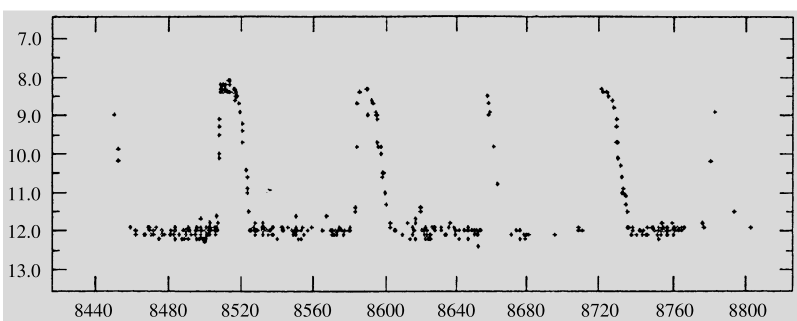


Fig. 14.11 The light curve of the dwarf nova SS Cygni in the beginning of 1966. (Drawing by Martti Perälä is based on observations by Nordic amateurs)

ening in magnitudes is roughly proportional to the logarithm of the recharging interval. It is possible that ordinary novae obey the same relationship. However, their amplitude is so much larger

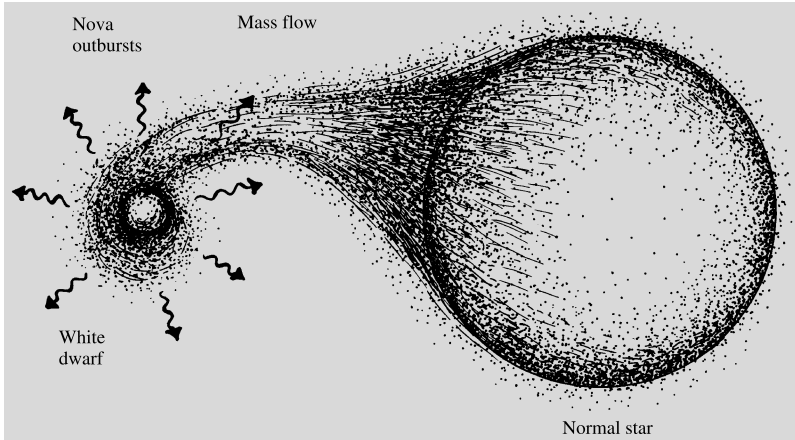


Fig. 14.12 The novae are thought to be white dwarfs accreting matter from a nearby companion star. At times, nuclear reactions burning the accreted hydrogen are ignited, and this is seen as the flare-up of a nova

that the time between outbursts should be thousands or millions of years.

Observations have shown all novae and dwarf novae to be members of close binary systems. One component of the system is a normal star and the other is a white dwarf surrounded by a gas ring. (The evolution of close binary systems was considered in Sect. 12.6, where it was seen how this kind of system might have been formed.) The normal star fills its Roche surface, and material from it streams over to the white dwarf. When enough mass has collected on the surface of the white dwarf, the hydrogen is explosively ignited and the outer shell is ejected. The brightness of the star grows rapidly. As the ejected shell expands, the temperature of the star drops and the luminosity gradually decreases. However, the outburst does not stop the mass transfer from the companion star, and gradually the white dwarf accretes new material for the next explosion (Fig. 14.12).

The emission and absorption lines from the expanding gas shell can be observed in the spectrum of a nova. The Doppler shifts correspond to an expansion velocity of about 1000 km/s. As the gas shell disperses, its spectrum becomes that of a typical diffuse emission nebula. The expanding shell around a nova can also sometimes be directly seen in photographs.

In dwarf novae the energy does not come from nuclear reactions but mainly from the potential energy of the matter falling into the white dwarf. An eruption occurs when the density of the accretion disk formed by the matter flowing from the companion star exceeds a certain critical limit, becomes unstable and is strongly heated.

A considerable fraction of the novae in our Galaxy are hidden by interstellar clouds and their number is therefore difficult to estimate. In the Andromeda Galaxy, observations indicate 25–30 nova explosions per year. The number of dwarf novae is much larger. In addition there are nova-like variables, which share many of the properties of novae, such as emission lines from circumstellar gas and rapid brightness variations. These variables, some of which are called *symbiotic stars*, are close binaries with mass transfer. Gas streaming from the primary hits a gas disk around the secondary in a hot spot, but there are no nova outbursts.

The supersoft stars (SSS) are a somewhat peculiar subclass of cataclysmic variables. Their X-ray radiation is much stronger and much softer, i.e. has longer wavelength, than that of the ordinary cataclysmic variables. In the SSS objects the component losing mass is more massive than the compact star (white dwarf), in contrast with ordinary interacting binaries. Therefore the mass transfer is an unstable self sustained process transferring more material to the surface of the white dwarf than in the normal cataclysmic variables. On the surface of the white dwarf a continuous fusion reaction resembling nova eruptions is producing a lot of soft X-ray radiation. Due to their unstable character the SSS objects are short lived and therefore relatively rare.

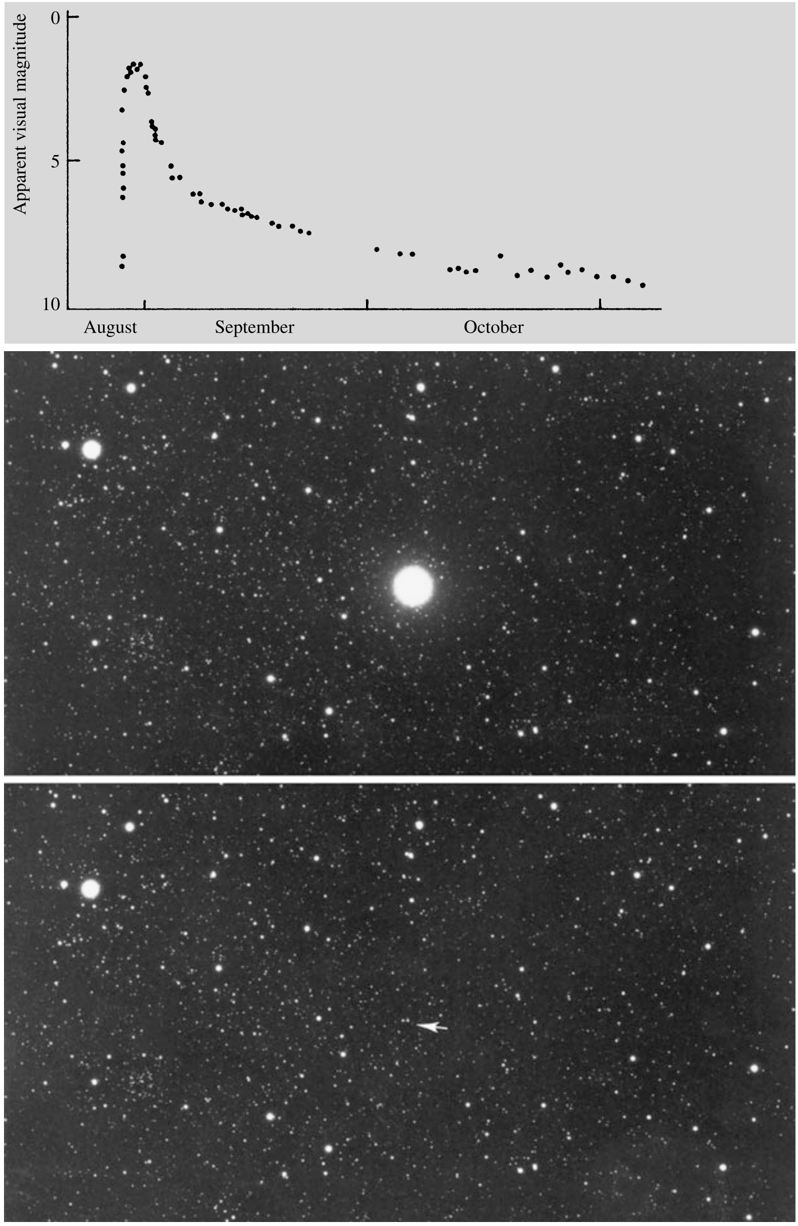


Fig. 14.13 In 1975 a new variable, Nova Cygni or V1500 Cygni, was discovered in Cygnus. In *the upper photograph* the nova is at its brightest (about 2 magnitudes), and in *the lower photograph* it has faded to magnitude 15. (Photographs Lick Observatory)

14.4 Supernovae

Explosions of stars as supernovae are among the most energetic phenomena of the universe. Within a couple of weeks the star becomes so bright that its luminosity corresponds to over a billion Suns or a whole small galaxy. Thus they can be observed even at cosmological distances, and they are useful standard candles for measuring the dimensions of the universe and cosmological quantities. Supernovae are also important sources of heavy elements. Most elements heavier than iron have originated in supernova explosions.

The maximum is followed by a slow decay, and the nearest supernovae can be observed still years after the explosion. In the explosion a gas shell expanding with a velocity of thousands of

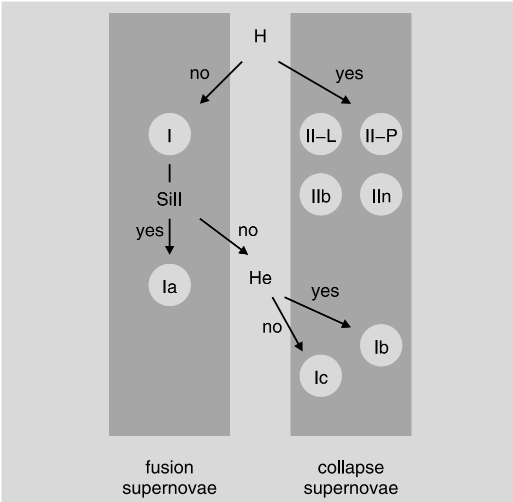


Fig. 14.14 The type of a supernova can be deduced from different spectral lines in its spectrum and the shape of its lightcurve

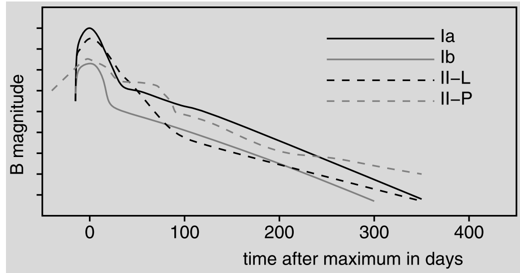


Fig. 14.15 Typical shapes of the lightcurves of different supernovae

kilometres per second is ejected. Over 200 of such supernova remnants have been discovered in the Milky Way. Their ages vary from a few hundred to tens of thousands of years.

At least six supernova explosions have been observed in the Milky Way. Best known are the "guest star" seen in China in 1054 (whose remnant is the Crab nebula), Tycho Brahe's supernova in 1572 and Kepler's supernova in 1604. On the basis of observations of other Sb–Sc-type spiral galaxies, the interval between supernova explosions in the Milky Way is predicted to be about 50 years. Some will be hidden by obscuring material, especially near the centre of the galaxy. In particularly dusty starburst galaxies almost all supernovae remain undetected due to the extinction of the dust. Still the 400 years' interval since the last observed supernova in the Milky Way is unusually long.

Supernovae in other galaxies are detected quite frequently. For example, both in 2006 and 2007 over 500 new supernovae were found. In the near future the number will increase rapidly thanks to new all sky surveys.

Earlier supernovae were divided just to two main categories, I and II, based on whether their spectra showed evidence of hydrogen. Later these main classes have been divided into several subclasses depending on other spectral features and their lightcurves (Figs. 14.14, 14.15 and 14.16).

Type Ia supernovae are recognised by the silicon absorption line (615 nm), which is strong in the spectra of young novae. It is thought that these supernovae originate in binaries, at least a billion years old, consisting of a white dwarf and its companion. In such a close binary material can flow from the companion to the white dwarf until it mass exceeds the limit (about $1.4M_\odot$). Then the pressure of the degenerate of the electron gas inside the white dwarf cannot overcome the gravitation and star will collapse. Increase of the density and temperature will ignite an explosive fusion reaction that can destroy the white dwarf. The kinetic energy released in the process is of the order of 10^{44} J causing part of the gas to expand even at a velocity of $0.1c$. The origin of the radiation energy (around 10^{42} J) is the fission of the radioactive nickel isotope 56 created in the explosion (typically about $0.5M_\odot$) into radioactive cobalt and further into stable iron. The more nickel is produced in the explosion the brighter the supernova shines at its maximum; the absolute magnitude will reach -19–-20. The shape of the lightcurve depends on the brightness of the supernova: the brighter the supernova the broader the top of the lightcurve. Therefore the maximum brightness of a typer Ia supernova can be determined precisely from its lightcurve. This way they can be used as standard candles to determine dimensions of the universe and cosmological parameters (Chap. 20).

In Chap. 12 we discussed the final stages of stellar evolution and how the collapse of a massive star will lead to an explosion. It is believed

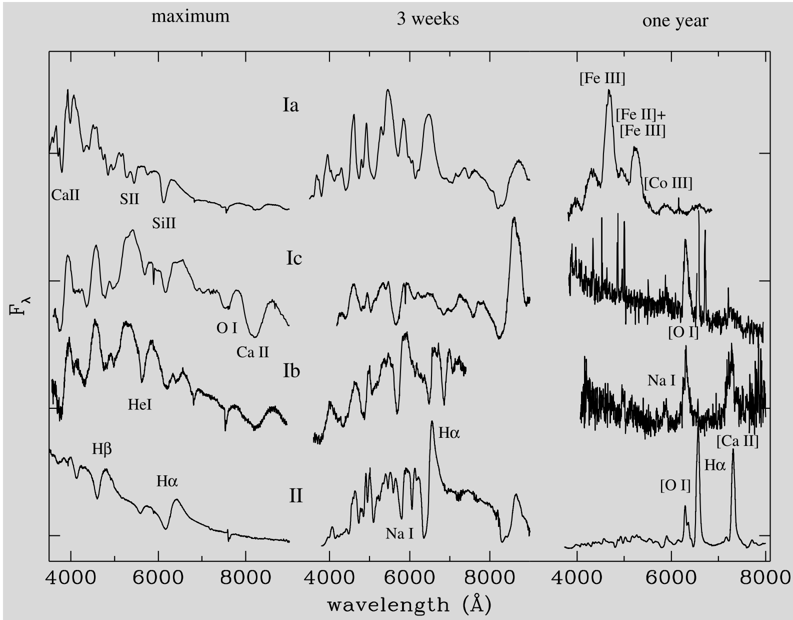


Fig. 14.16 Spectra of different types of supernovae at the maximum, three weeks after the maximum and after one year. (Turatto: Supernovae and Gamma-Ray Bursters, ed. K. Weiler, Lecture Notes in Physics, vol. 598, pp. 21–36)

that all supernovae except type Ia are caused by the collapse of massive and short lived stars. At the end of its lifespan such a star has an iron core that will collapse under its own gravity after exceeding the Chandrasekhar limit. In the stellar core the matter will reach the density of atomic nuclei and the outer layers bounce back sending an outbound shock wave. The process creates a huge number of neutrinos. Since they interact only weakly with the outer layers of the star they rush to the surrounding space. The remaining core may become a neutron star or, in the case of a very massive star, a black hole. Most of the released energy (about 99 %) escapes with the neutrinos. The outer layers of the star receive a kinetic energy of about 10^{44} J, part of which may be released as radiation when the expanding matter hits the material surrounding the star and later the interstellar matter. Typically the supernova itself emits radiation about 10^{42} J within a few months after the explosion, reaching an absolute magnitude between −16 and −20 at the maximum. Later the brightness is sustained by the fission of the radioactive nickel 56, born in the explosion, to other elements just as in the case of the type Ia supernovae.

If the spectrum of a supernova does not contain strong hydrogen or silicon lines its type is either Ib or Ic. The type Ib supernovae are recognised by strong helium lines that are not present in the spectra of type Ic. These supernovae originate in stars that don't have any more hydrogen in their outer layer. The stars exploding as type Ic supernovae have also lost their outer layer of helium. Such stars that have lost their outer layers are called Wolf–Rayet stars.

All type II supernovae have hydrogen lines in their spectra. They are divided into main types II-P and II-L based on the flat (plateau) and linear shape of the lightcurve. Recently several stars that later exploded as supernovae have been identified in high resolution pictures taken e.g. by the Hubble space telescope and the VLT telescope before the explosion (Fig. 14.17). These observations have shown that the more common type II-P supernovae originate in red supergiant stars as predicted by theories of stellar evolution. Initially the masses of such stars have been at least 8 solar masses. Smaller stars are not believed to explode in a collapse. They end up as white dwarfs after more quiescent evolution.

Type IIn supernovae are recognised by their hydrogen emission lines that are much narrower than in the spectra of other supernovae. The lines originate in the matter around the star. The spectra of young type IIn supernovae have hydrogen lines, which, however, disappear in a few weeks, and afterwards the spectrum resembles the type Ib spectra. It is assumed that these supernovae were originally massive stars that still had a small amount of hydrogen in their outer layer before the explosion. Thus they are intermedia between the types II and Ib. The observed properties and types of supernovae depend on the properties of their progenitors, and hence individual supernovae can of intermediate types. Hence it makes more sense to classify supernovae according to the explosion mechanism simply to two different types, *thermonuclear* and *core collapse* supernovae. About 30 % of the supernovae found in nearby galaxies are thermonuclear and the remaining 70 % core collapse supernovae.

On February 23, 1987 the first burst of light from a supernova in the Large Magellanic Cloud, the small companion galaxy of the Milky Way, reached the Earth (Fig. 14.18). This supernova,

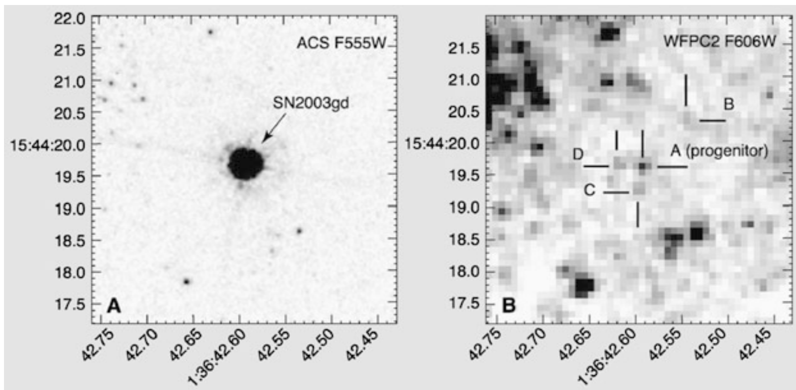


Fig. 14.17 *Left*: The supernova 2003gd of type II-P after the explosion. *Right*: The same region before the explosion. The exploded red supergiant (progenitor) was located in the image taken before the explosion. Both images were taken with the Hubble space telescope. (Smartt et al., 2004, Science, vol. 303, 5657, 499)

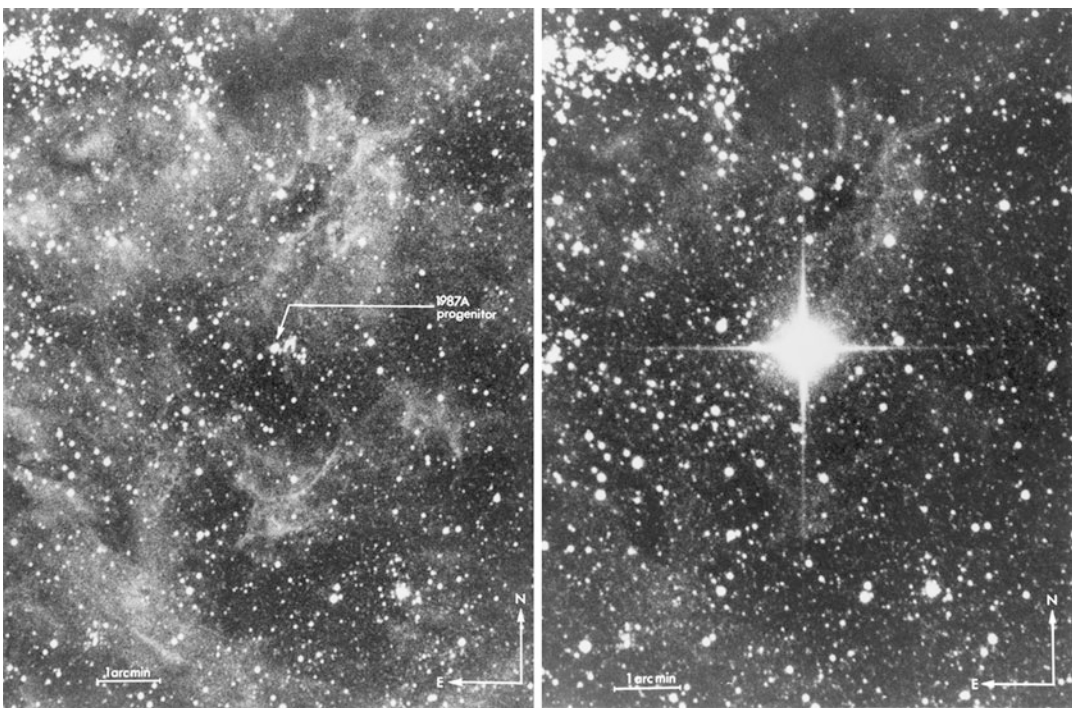


Fig. 14.18 Supernova 1987A in the Large Magellanic Cloud before and after the explosion. (Photographs ESO)

SN 1987A, was of type II, and was the brightest supernova for 383 years. After its first detection, SN 1987A was studied in great detail by all available means. Although the general ideas of Sects. 11.4 and 11.5 on the final stages of stellar evolution have been confirmed, there are complications. Thus e.g. the progenitor star was a blue rather than a red giant as expected, perhaps because of the lower abundance of heavy elements in the Large Magellanic Cloud compared to that in the Milky Way. The collapse of its core released a vast amount of energy as a pulse of neutrinos, which was detected in Japan and the USA. The amount of energy released indicates that the remnant is a neutron star.

14.5 Examples

Example 14.1 The observed period of a cepheid is 20 days and its mean apparent magnitude $m = 20$. From Fig. 14.4, its absolute magnitude is $M \approx -5$. According to (4.12), the distance of the cepheid is

$$\begin{aligned} r &= 10 \times 10^{(m-M)/5} = 10 \times 10^{(20+5)/5} \\ &= 10^6 \text{ pc} = 1 \text{ Mpc}. \end{aligned}$$

Example 14.2 The brightness of a cepheid varies 2 mag. If the effective temperature is 6000 K at the maximum and 5000 K at the minimum, how much does the radius change?

The luminosity varies between

$$L_{max} = 4\pi R_{max}^2 \sigma T_{max}^4,$$
$$L_{min} = 4\pi R_{min}^2 \sigma T_{min}^4.$$

In magnitudes the difference is

$$\begin{aligned} \Delta m &= -2.5 \lg \frac{L_{min}}{L_{max}} = -2.5 \lg \frac{4\pi R_{min}^2 \sigma T_{min}^4}{4\pi R_{max}^2 \sigma T_{max}^4} \\ &= -5 \lg \frac{R_{min}}{R_{max}} - 10 \lg \frac{T_{min}}{T_{max}}. \end{aligned}$$

This gives

$$\begin{aligned} \lg \frac{R_{min}}{R_{max}} &= -0.2\Delta m - 2 \lg \frac{T_{min}}{T_{max}} \\ &= -0.4 - 2 \lg \frac{5000}{6000} = -0.24, \end{aligned}$$

whence

$$\frac{R_{min}}{R_{max}} = 0.57.$$

14.6 Exercises

Exercise 14.1 The absolute visual magnitude of RR Lyrae variables is 0.6 ± 0.3. What is the relative error of distances due to the deviation in the magnitude?

Exercise 14.2 The bolometric magnitude of a long period variable varies by one magnitude. The effective temperature at the maximum is 4500 K.

(a) What is the temperature at the minimum, if the variation is due to temperature change only?
(b) If the temperature remains constant, what is the relative variation in the radius?

Exercise 14.3 In 1983 the radius of the Crab nebula was about $3'$. It is expanding $0.21''$ a year. Radial velocities of 1300 km s^{-1} with respect to the central star have been observed in the nebula.

(a) What is the distance of the nebula, assuming its expansion is symmetric?
(b) A supernova explosion has been observed in the direction of the nebula. Estimate, how long time ago?
(c) What was the apparent magnitude of the supernova, if the absolute magnitude was a typical -18?