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Globular Clusters at Low and High Redshift

Denis Burgarella

Globular clusters form homogeneous populations of stars. On the one hand, because initial conditions are homogeneous within one cluster but vary from cluster to cluster, their study can shed light on stellar evolution processes. On the other hand, globular clusters contain the oldest known stellar population in galaxies. The study of the characteristics of globular cluster systems is one way to understand parent galaxy formation and early evolution. Unfortunately, a direct observation of the time when globular clusters and galaxies formed is still out of reach for today's telescopes, but this remains a major goal.

Globular clusters (GCs) are nearly spherical stellar systems of 10^4 to 10^6 stars orbiting around the center of the Milky Way (*1*). At first sight, the mass contained in our GC system (GCS) seems negligible compared to the rest of the galaxy. If we add up the total mass of the more than 100 known GCs, it only amounts to about 2% of the halo mass (*2*). The characteristic that makes this population so crucial resides in the age of the stars, the halo GCs contain the oldest known stars formed as part of the galaxy formation process (*2*). The study of GCS can therefore place constraints on the formation of the GCs and thereby on the formation of the Milky Way.

Extending these studies to extragalactic GCS has been difficult and only the closest ones in the local group of galaxies (such as M31 and M33) have been well studied (*3–5*). The Hubble Space Telescope (HST) and large, ground-based telescopes are extending the observing capabilities, routinely as far as the Virgo galaxy cluster (*6, 7*) and with more difficulties, to the Coma galaxy cluster (*8*). Star clusters are presently forming in galaxies, such as the magellanic clouds (*9, 10*), but they are probably less massive than the Milky Way GCs. Astronomers wonder whether young clusters similar to the Milky Way GCs are currently forming in other galaxies (*11*). If they actually do, a good place to look is in merging/interacting galaxies. Although not completely accepted (*12*), young GCs have probably been discovered by HST around the colliding galaxies NGC4038 and NGC4039 ("the Antennae") (*13*). A number of other young GCs have been found around other merging/interacting galaxies and spectroscopic observations seem to confirm this hypothesis (*14*). If we account for the difference in age, their characteristics are similar to the old GCs of our galaxy (*15*). The following chapter of this story will be to directly observe the formation of the GCs in order to understand how today's normal galaxies like the Milky Way formed.

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The Main Sequence Turn-Off and Globular Cluster Age in the Local Group

The color-magnitude diagram (CMD) of a GC is the observational counterpart of the Hertzsprung-Russell diagram (HRD) (*16*). It is similar to a book where one can read the history of the GC. For a given GC, the location of a star in the HRD depends on its luminosity, L, and its effective temperature, T_{eff}, which in turn depends on parameters such as the evolutionary stage, the mass, the radius, and the chemical abundances of the star. The observable values corresponding to the L and T_{eff} are the magnitude (*17*) and the difference between two given magnitudes, called the color. The stars are not located at random on the CMD, rather it is like an instantaneous picture of a GC where every phase of the stellar evolution lies within a specific area usually called a sequence or a branch. The amount and quality of information gathered depends on the GC's distance and the conditions of observation such as the telescope, the detectors, the site of the telescope, and so on. In order to correctly interpret a GC's CMD, we need to (i) assume an initial mass function (IMF), $\Phi(M)$, with its characteristics, the slope α, the minimum mass, M_{min}, and the maximum mass, M_{max}, and (ii) simulate the evolution of a star and find out where it should be in the CMD after a given time Δt. The IMF is defined as the number, N, of zero-age MS (ZAMS) stars formed between M_{min} and M_{max} whose mass M_{star} is in the mass range [M_{star}, M_{star} + dM], and C is a normalization constant:

$$\Phi(M) = dN/dM = CM^{-\alpha} \quad (1)$$

Classically one uses the number of objects between log M_{star} and log M_{star} + dlog M. In agreement with Salpeter (*18*) who found $\alpha = 2.35$, the value of the slope α is in the range 2 to 2.5 in the Local Group of Galaxies (*19*). Concerning the limiting masses, on the one hand, M_{max} seems to vary with local physical conditions from about 30 $M_\odot$ in several starburst galaxies (*20*) up to masses of 150 $M_\odot$ in the Large Magellanic Clouds (*21*). There is general agreement from photometric and spectroscopic work for M_{max} to be about 60 to 100 $M_\odot$ (*22–25*). However, the number of massive stars may be underestimated, a non-negligible fraction of newly formed massive stars, at the time they appear from the clouds where they are born, are not ZAMS stars anymore (*26*). As a consequence, the slope of the IMF is likely to be flatter than measured. On the other hand, there is agreement (*27*) on the mass which initiates the onset of H burning to be around 0.08 $M_\odot$ under optimal conditions. That mass does not seem to be dependent on the metallicity (*28*), M_{min} ~ 0.07 to 0.08 $M_\odot$ for $Z = Z_\odot$ and 0.09 to 0.10 $M_\odot$ for Z = 0 (*29*). However, the IMF in active regions of star formation may be weighted toward more massive stars (*30*), which translates in a turnover around 3 to 10 $M_\odot$. This phenomenon may be explained by the longer formation time for low-mass stars, which would lead to the disruption of low-mass condensing protostellar clouds by supernovae and cosmic rays (*31*).

Assuming, for a star of M_{star}, that the core mass (M_c) where the H-ignition *T* is reached amounts to $M_c = 0.1\ M_{star}$, this mass M_c of H is burned to produce He. The time τ(MS) spent by a star on the MS can be estimated with the following formula:

$$\tau(\mathrm{MS}) = (\eta\, X\, M_c\, c^2)/L \sim 10^2 \, (M_{star}/M_\odot)(L_\odot/L) \text{ years} \quad (2)$$

where η is the efficiency (about 0.7% of the original mass involved in the ^{4}He fusion) and X is about 0.75. We can now make use of the relation $L \sim M^{3.2}$ predicted by the simple homology models (*32*). The observed exponent is about 3.2 over the whole mass range which gives:

$$\tau(\mathrm{MS}) \sim 10^{10}(M_{star}/M_\odot)^{-2.2} \text{ years} \quad (3)$$

Of course, the real MS lifetime depends on several other parameters such as the abundances of atoms other than H, the type of nuclear reactions, convection, and pressure, but the main result is that τ(MS) is a decreasing function of the initial mass; more massive stars exhaust their H fuel supply faster than less massive stars do. As a consequence, massive stars move away from the MS faster than less massive stars. At a given age *t* of a homogeneous stellar population, all the stars more massive than a threshold mass M_t have evolved off the MS toward the low-*T* giant branch and more evolved stars while stars with $M_{star} < M_t$ still lie on the MS. This means that the MS stops at a point in the CMD corresponding to M_t which is called the turn-off (TO). This TO will move toward fainter and less massive stars as time passes (Fig. 1). This locus is important because the position of the TO for a homogeneous population provides an estimate of *t*. For young clusters only the more massive stars have evolved off the MS and the TO is located on the upper MS while for older ones it is in the lower MS. In brief, the position of the TO moves toward less massive and less luminous stars with time (Fig. 1). For the galactic GCs, the stars more massive than about 0.8 $M_\odot$ are no longer on the MS. Because GCs are certainly formed by a coeval population of stars, if we know the mass of TO stars for a given cluster, we would have an estimate of the date of the formation of the GCs (*33*). It has long been thought (*34*) that globular clusters are fossil remnants of the protogalactic era. From a global analysis of the spatial distributions, kinematics and metallicities of a large sample of GCs, it was shown 12 years ago (*35*) that at least two GC populations coexist in our galaxy: (i) a metal-poor, slowly rotating population with a spherical distribution in the halo and (ii) a metal-rich, rapidly rotating population in the disk with a highly flattened distribution. Part of the metal-rich observed GCs probably belongs to the bulge but the number is likely to be relatively small due to an important amount of gas and dust in these regions which absorbs the visible light and prevents us from seeing the central Galactic GCs at these wavelengths. The question of the bulge population of clusters is not clear (*36*). Did they form early, that is as part of the same continuous process that gave birth to the halo GCs (*37*) or can one invoke an early merging of a satellite galaxy (*38, 39*)? Even for the halo population of clusters, a debate exists concerning the formation time scale of the halo, the two extreme estimates being a few times 10^8 years for a rapid free-fall collapse (*40*) to a few Gyr for a scenario where protogalactic fragments collide, form stars and clusters before giving up its gas content to the galactic disk (*41*). Some evidence can be found suggesting that the halo can be divided into two subpopulations, an old coeval population in the inner halo and a younger population in the outer halo (*42*). Studying the GCSs of the galaxy will increase our understanding of the formation and early evolution of the galaxy.

If the stars of the clusters can be separated and a CMD can be built (*43*), two kinds of methods exist which may provide age estimates. The first method is to determine the absolute age. The absolute age may be determined by fitting theoretical isochrones to the MS of the GC CMDs (*44*). Except in the best cases, the observational uncertainties (*33*) are large enough (of the order of 25%) showing that it is difficult to be conclusive about the estimated age (*45*). Moreover, some uncertainties, about 15%, are due to the stellar models which also affect the absolute age estimates for GCs (*33*). Observations of GCs at low-galactic latitude are limited by an important contamination of a large number of non-member stars and a large and variable reddening (limiting magnitude and blurring of the CMDs). It was therefore difficult to reach the TO and as a consequence, the disk and bulge systems are still poorly known compared to the halo system. Dating the bulge GCs is crucial to date the formation of the bulge and constrain the different theories. Near-infrared (NIR) observations (*46, 47*) will probably play a key role in the battle to understand the formation of reddened GCs but we also have to use high resolution instruments to separate stars in this dense environment. To date, the best efficiency has been achieved by the Near Infrared Camera and Multi Object Spectrograph (NICMOS) onboard the HST (*36*). Note, however that ground-based instruments equipped with adaptative optics can

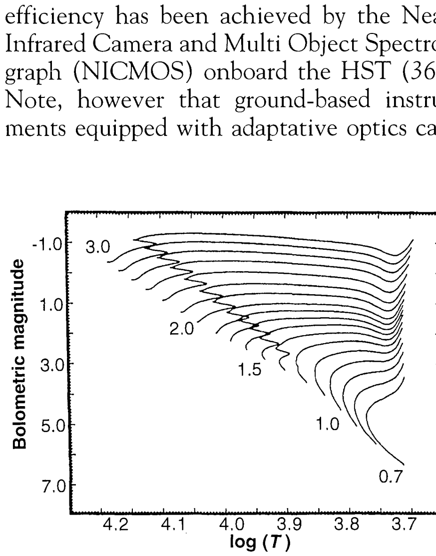

Fig. 1. Position of the main sequence turn-off for different low-metallicity (Z=0.003) stars with masses in the range 0.7 to 3.0 $M_\odot$ (*72*). The turn-off corresponds to the locus in the CMD where stars experience central hydrogen exhaustion. This is the end of the main sequence phase and stars will climb the giant branch. The lines represent the evolution of the stars in the CMD after the zero-age main sequence. The time spent on the MS depends on the mass of the stars. They leave the MS after 0.22, 0.62, 1.36, 3.91, and 25.4 Gyr, respectively, for 3.0, 2.0, 1.5, 1.0, and 0.7 $M_\odot$ stars.

do very well also. Their field of view is generally small but their capabilities will improve in the future. Methods exist involving other features in the CMD in addition to the MS TO such as the visible magnitude difference (*48–51*) $\Delta V = V(\mathrm{TO})\text{-}V(\mathrm{HB})$ between the horizontal branch (HB) and the TO. This index is completely insensitive to the distance modulus, but the problem is the determination of the zero point and the slope of the $MV(\mathrm{HB})$ versus $[\mathrm{Fe/H}] = \log(Z) - \log(Z_\odot)$ relation between the visible absolute magnitude of the HB and the metallicity of the GC (*52, 53*). This latter method is based on the *V* magnitude of the features (vertical method); it is also possible to use the color difference (horizontal method) $\Delta B\text{-}V = (B\text{-}V)_{SGB} - (B\text{-}V)_{TO}$ where $(B\text{-}V)_{SGB}$ is the apparent color of the sub-giant locus and $(B\text{-}V)_{TO}$ is the bluest apparent color of the TO (*49, 54*). For ages in the halo GC range (13 to 17 Gyr), $\Delta B\text{-}V$ is relatively insensitive to variations in metallicity and because we are using color differences within one cluster, the reddening and distance modulus have no impact on the age determination (*55*). The second method is to use relative ages. Relative ages can usually be determined more reliably (typical uncertainty of about 2 Gyr) than absolute ages (*56*). The advantage of this method is that one is only interested in relative positions of the MS TO (and other features of the CMD). This means that not only observational (such as the zero point of the photometry) but also some theoretical (such as abundances and *T* color relations) uncertainties are not affecting the results (*55*). Moreover, using the relative $\Delta B\text{-}V$ implies that the distance modulus and the reddening are parameters that would not need to be estimated (*49*).

Chaboyer (*33*) estimates that the mean absolute age of the oldest GCs are in the range 13 to 17 Gyr; this means that these clusters are older than the oldest stars in the galactic disk (white dwarfs) whose ages lie in the 7.5 to 11 Gyr range. Moreover, observations of the metal-rich bulge GCs, NGC6528 and NGC6553 (*36*), suggest that the two objects are coeval with halo clusters, which would show that the formation of the halo and bulge GCs was nearly simultaneous. From these studies of the Milky Way GCSs it is clear that galactic GCs in the bulge and the halo can be considered as fossils of galaxy formation (*56*). From a sample of 31 galactic GCs Sarajedini (*49*) found an average GC age of 14.6 Gyr with a mean error of 1.8 Gyr and an observed standard deviation of 2.8 Gyr correponding to a full width at half maximum (FWHM) of the age distribution around 5 Gyr. From similar work (*57*) on 39 GCs the mean cluster age is 18 Gyr with an age range of about 5 Gyr. This suggests a prolonged cluster formation and therefore a slow formation of the halo. However, if the distribution of errors in the age are about normal then $\sigma(\mathrm{app})^2 = \sigma(\mathrm{int})^2 + \sigma(\mathrm{obs})^2$ with $\sigma(\mathrm{app})$ being the apparent spread in age, $\sigma(\mathrm{int})$ the intrinsic age spread and $\sigma(\mathrm{obs})$ the spread due to the observational errors. The intrinsic age spread estimate is therefore dependent on the $\sigma(\mathrm{obs})$. If $\sigma(\mathrm{obs})$ is underestimated, the actual age spread may be less than 1 Gyr (*49*). Observational errors are overestimated by some 64% which leads to an intrinsic age spread of the order of 2.5 Gyr. The question is still open and it is certainly too early to draw a definite conclusion (*57*).

The Observation of Newly Formed Globular Clusters

A major objective of modern observational astronomy would be to directly observe galaxies and therefore GCs in formation. Nowadays, not only do we think that most of the GCs are formed in starburst galaxies but the formation of GCs is likely to be an important way of forming stars (*58*). Large populations of extragalactic GCs have been detected farther and farther away (*3, 59*). Harris (*60*) concluded that "massive (globular) clusters [exhibiting young and massive MS stars] will form any time and anywhere a galaxy can accumulate gas clouds the size of super giant molecular clouds (SGMC) (that is, massive, cold, self-gravitating and magnetized clouds)." The ultraviolet (UV) continuum flux of GCs is very intense for ages <100 Myr, but the MS lifetime of massive stars is short and as these stars move off the upper MS, the UV flux decreases and the peak of the spectral energy distribution moves toward IR wavelengths (Figs. 2 and 3). This short-lasting stage is therefore favorable to the detection of young GCs.

Recently, high redshift ($z > 3$) galaxies from ground-based observations (*61*) and HST observations in the Hubble Deep Field (*62*) have been identified. The characteristics of these objects suggest that we are seeing the formation of the spheroidal component of present-day luminous galaxies, that is elliptical galaxies and the bulge of spiral galaxies (*63, 64*). The fact that the star formation rate in ellipticals and spiral bulges has been low since $z \sim 1$ supports the hypothesis that the formation of galactic spheroids cannot be later than this period (*36*). From the study of Galactic GCs located in the bulge and a comparison with halo GCs, it seems that the mean GC age decreases and the age dispersion increases when going toward the galactic center, consistently with a chaotic formation over an extended period of time (*41*). If this trend continues down to the bulge GC population (*65*), these characteristics suggest that the formation of the galaxy may be an inside-out process, which, in turn, implies that the bulge can be a kind of seed which accreted more and more gas-rich clumps around it that later formed the halo.

In relation to these observations, a large number of faint and compact clumps have

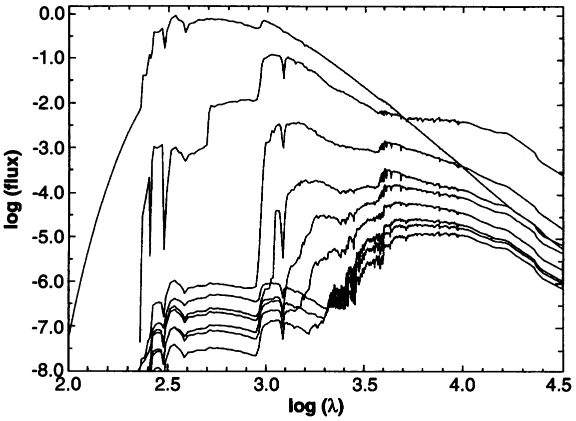

Fig. 2. The evolution of the spectral energy distribution of a stellar population from the top to the bottom 0.001, 0.01, 0.1, 0.5, 1.0, 2.0, 5.0, 10.0, and 15.0 Gyr after an instantaneous burst (*73*). The emission peaks at UV wavelengths 1 Myr after the burst but shifts in the IR wavelengths after 1 Gyr when massive stars evolve off the main sequence. A globular cluster should be more easily detectable in the UV range (rest wavelengths) before the first 100 Myr of its lifetime.

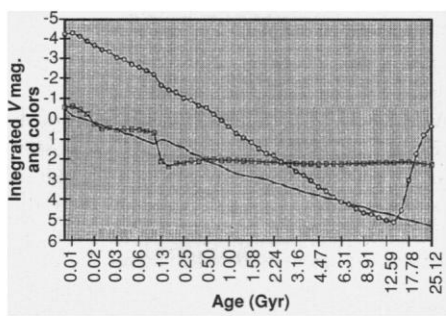

Fig. 3. Absolute *V* magnitude (solid line) and color evolution (circles = UV-V, squares = V-NIR) with time of a single stellar population (*74*). The low-metallicity of the models presented here should be representative of the conditions in the early universe. Whatever the filter used, the magnitude is more intense in the first 100 Myr but this effect is much more important at 155 nm wavelength.

been discovered (66) at $z \sim 2.4$, that is closer to us than the possible early galaxies previously discussed. These objects may be spheroidal systems where 10^9 to 10^{10} $M_\odot$ were processed into stars. Even if the most massive stars (O and early B stars) are no longer on the MS, the dominant stellar population (late B and early A stars) and less massive stars still burn H in their core. These clumps are smaller than the bulges of spiral galaxies but much larger than GCs. These objects could be the building blocks in the bottom-up hierarchical models that would eventually merge to form present-day galaxies. According to these hierarchical scenarios of galaxy formation, the smallest objects would be the first ones to form and would eventually merge to form more massive ones. Given the low efficiency of cluster formation (56, 67) from SGMC, the gas clouds at the origin of the 10^5 to 10^6 $M_\odot$ clusters have to be in the 10^8 to 10^9 $M_\odot$ range. That mass is of the order of today's gas-rich compact galaxies like IZw18 and comparable to possible original fragments (41). In this picture and in agreement with previous work (56, 65) we can speculate that the actual building blocks that would eventually form the galaxies are smaller than the compact clumps previously discovered (66). The bulge would have been built by the collisions and mergings of 10^9 to 10^{10} $M_\odot$ of gas with an efficient star formation rate and metal enrichment (which can explain how the bulge can be at the same time older and more metal-rich). In a second phase, this process continued in the inner halo, but decreases quickly in this region while lasting about 3 to 4 Gyr in the outer halo.

Most of the light from young galaxies comes from the youngest and more massive stars on the MS and the bulk of their radiation is emitted in the UV wavelength (68). If dust formed efficiently and quickly, the extinction should be high and the major contribution would be from the heated dust in the far IR redshifted in the submillimeter range (69). However, star formation regions seem to remain largely unobscured by dust throughout much of the galaxy formation (61, 62). In this latter case (Fig. 4), the MS UV-emitted light at z is redshifted in the near IR (70). Due to the atmosphere and the relatively high Earth T, current or planned ground-based large telescope sensitivities (even for the 8-m class VLT or Keck, for instance) are too low to detect highly redshifted newly born GCs. The HST is not able to detect these objects because of the high background level beyond the critical 2-μm wavelength and the limited size (2.4 m) of the primary mirror. A large (4 to 8 m) space-borne cooled telescope would be a key tool for detecting this first generation of MS stars. Such a mission called Next Generation Space Telescope (NGST) is now under study (71).

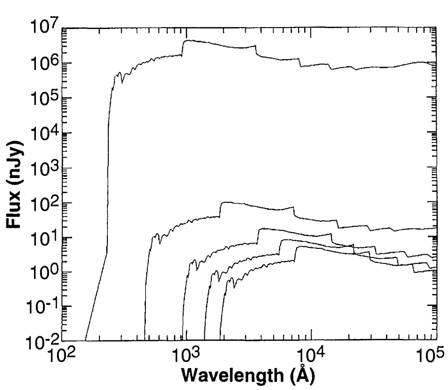

Fig. 4. From top to bottom, the redshifted (Ωo = 1 and Ho = 65 km s^{-1} Mpc^{-1}) observed spectrum of a low-metallicity (Z = 0.004) young (1 Myr) globular cluster (10^6 $M_\odot$) in the Coma cluster at z = 0.02, and at increasing distances of z = 1, 3, 5, and 7. The sensitivities of large telescopes of the 8-m class are in the 0.2 to 0.3 Jy (1 Jansky = 10^{-26} W m^{-2} Hz^{-1}) range at visible and near infrared wavelengths, The HST/NICMOS sensitivity increases from 0.1 Jy at 1 μm to 1 Jy at 2 μm. The predicted imaging performances of the NGST is around 1 to 5 nJy below 5 μm and would allow us to detect early globular clusters as far as z = 7.

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Type II Supernovae SN 1987A and SN 1993J

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The optical and ultraviolet emission from the type II supernova SN 1987A is currently powered by the radioactive decay of titanium-44. In contrast, the emission from SN 1993J is dominated by radiation from the interaction of the supernova shock wave with a dense, stellar wind released before the explosion. The dense wind around SN 1987A was displaced by the fast wind from the compact progenitor star, and the interaction of the supernova with dense gas is now being detected at x-ray and radio wavelengths. The expected neutron stars or black holes at the centers of these supernovae are not yet significant power sources.

Supernovae are cataclysmic stellar explosions that are accompanied by bright visual displays. The designation type II is used for supernovae that have hydrogen lines in their optical spectra, and type I is for those that do not. Type II supernovae have massive star progenitors, stars with masses $\gtrsim 8$ $M_\odot$, where $M_\odot$ is our sun's mass. The observational evidence is that type II supernovae are associated with regions of massive star formation. Calculations show that massive stars form a dense iron core that eventually collapses; the collapsing matter releases its gravitational binding energy in the form of neutrino emission. If a small fraction of the gravitational binding energy of the central core can be deposited in the central regions of the star, something very much like a type II supernova ensues. Models of explosions set off inside a massive star at the end of its life give results that agree with observations of the supernovae, including their light and spectral evolution (*1*).

The nearby supernova SN 1987A (*2*) in the Large Magellanic Cloud (LMC) provided confirmation of the basic picture of core collapse (*3*). The 19 neutrinos that were detected from this event were consistent with the approximately thermal radiation of neutrinos from the outer regions of a proto–neutron star. The fact that neutrinos were detected for 10 s shows that a proto–neutron star existed for at least that time because the formation of a black hole would have cut off the neutrino emission sooner. Although the neutrino observations of SN 1987A confirmed core collapse, they did not shed light on how 1% of the neutrino energy (about 10^{44} J) was deposited in the star to drive the explosion. This topic has been the subject of recent theoretical calculations, with an emphasis on neutrino-driven convection, but the results remain controversial (*4*).

At a distance of about 165,000 light-years, SN 1987A is extraordinarily close; most of the dozens of supernovae discovered every year are in galaxies tens of millions of light-years away. Because of their high intrinsic luminosity (about a billion times that of the sun for tens of days), it is possible to obtain spectra that give the spectral energy distribution and profiles of spectral lines for the distant supernovae. The energy distribution can be related to the angular size of the supernova. The line profiles yield the gas velocities and thus the linear size. The combination of these quantities yields the distance to the supernova, which, together with the redshift to the parent galaxy, gives the Hubble constant, or expansion rate of the universe. This method does not depend on uniform properties of the supernovae, but only on the physics of line and continuum formation in the spectra of individual supernovae. The method is best suited for the type II supernovae because their lines have less blending than those of type I supernovae and they are close to thermal equilibrium. A recent application of this method to type II supernovae yielded a Hubble constant of 73 ± 7 km s^{-1} Mpc^{-1} (*5*) [where 1 parsec (pc) = 3.26 light-years].

Here, I review developments in our observations and understanding of type II supernovae during the last 5 years. The emphasis is on the relatively nearby type II supernovae SN 1987A, in the LMC, and SN 1993J, in the galaxy M81. It is by detailed study of nearby events that we have learned the most about the range of physical processes relevant to supernovae. These processes include shock-wave heating, radioactive heating, and power from a central compact object. The two supernovae do have some nonstandard properties, but the same basic physical mechanisms are expected to operate in all type II supernovae.

SN 1987A and Its Surroundings

At an age of 10 years, SN 1987A has yielded some of its secrets, but a number of mysteries remain. Because of its proximity, we have an unprecedented view of the surroundings of a type II supernova (SN). The radioactive debris of SN 1987A, expanding with velocities up to several thousand kilometers per second, is at the center of several elliptical rings (*6*) (Fig. 1). The nebulosity is slowly moving gas that is the product of mass-loss processes before the SN. The emitting gas is relatively dense [up to 3×10^4 particles per cubic centimeter (*7*)] and was probably dark before the SN. It was

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