Glossary

Accretion disc  A disc of material that flows onto a star or other compact object under the influence of gravity. Because the material arriving at the object carries angular momentum it rarely flows directly towards. Instead, friction causes the material to lose energy as it orbits the object, causing it to move ever inwards.

Asymptotic giant branch (AGB) star  An aging low or intermediate mass giant star that has consumed the hydrogen then helium in its core. Energy now comes from alternating waves of hydrogen and helium fusion, as strong stellar winds remove much of its mass. It is the loss of mass that ultimately destroys these stars.

AGB-Manqué star  A low mass and somewhat hotter giant star with a meager layer of hydrogen surrounding its degenerate carbon-oxygen core. Like more conventional AGB stars energy is produced by helium fusion in a shell that alternates with hydrogen fusion further out. AGB Manqué stars are believed to originate when red giant stars lose most of their outer hydrogen-rich layers earlier in their lives.

Angular momentum  A property of matter that is moving in a broadly circular path. Momentum is a product of the mass and its velocity (speed and direction) and, like energy, is always conserved.

Anti-correlation  When one property or variable changes in the opposite way to another. For example the more cigarettes you smoke the shorter your average lifespan will be. In globular clusters the more oxygen a star has the less sodium it has, and vice versa.
Be stars  A type of intermediate or relatively massive star of spectral class B that is surrounded by a disc of material. These stars rotate much more rapidly than the Sun, and several are known to be shaped more like a disc (or the chocolate Minstrel) Some of these stars are very young and still accreting matter, but the majority are losing mass in a broad disc that surrounds the equator of the star. Some Be stars are known as Shell stars.

Beta (β) Cephei stars  Fairly massive stars that pulsate with a short period measured in minutes to hours. Pulsations appear to be driven by alternating waves of ionization and recombination of iron (loss and gain of many of their electrons).

Blue Straggler star  A star produced by the collision of two or more other stars. The straggler is still on the main sequence after all of its siblings have become red giants. When these stars finally leave the main sequence they become first yellow stragglers, then red straggler stars (below).

Cataclysmic variable  A binary system consisting of a low mass, hydrogen-burning star and a white dwarf. The white dwarf acquires material from its low mass companion. In the process the system emits bursts of energy either from the disc or from the surface of the white dwarf.

CNO cycles  In fairly massive stars energy is produced by hydrogen fusion that involves the addition of hydrogen nuclei in fours to a carbon seed nucleus. After four nuclei have been added, the product oxygen nucleus breaks back down to release the original carbon nucleus and a helium nucleus. The process releases energy at a far higher rate than the pp-chains that power low mass stars like the Sun.

Conduction (of energy)  Energy transfer between particles through collisions between them. In typical stars the relevant particles are usually electrons.

Convection  The transport of energy through the bulk motion of a gas or other fluid. Hot material is less dense and rises; cold material is denser than its surroundings and sinks.

Crossing time  The time it takes a star to move under the influence of gravity through a cluster from one side to another. The
crossing time effectively sets the probability that two stars will productively encounter one another during their main sequence lives and merge or interact. The crossing time is very important in young clusters where collisions between massive stars could allow unusually massive stars to form. In older clusters it sets the time for lower mass star to have encounters which could lead to Type Ia supernovae.

**Cusp** A particular distribution of stars within a cluster—typically an old globular cluster where the density of stars rises nearly continuously to the very centre of the cluster instead of rising to a plateau near the cluster core.

**Disc shocking** A term describing the effect of a spiral galaxy disc on a globular cluster passing through it. The gravitational pull of the disc accelerates the stars in different directions as the cluster punches through the disc. This causes the stars to move faster relative to each other, which in turn causes the cluster to expand.

**Excretion disc** A disc of material that is expanding away from a star. Be stars typically show this (above) but they may also form when two stars are spiraling in on one another. The outward movement of material in the disc balances the loss of angular momentum (above) of the two inward migrating stars.

**Extended clusters** Faint and ancient clusters that have been seen in the halos of nearby galaxies but not the Milky Way. These have diameters similar or somewhat larger than typical globular clusters but appear to have similar masses. The half-mass radius (see below) is typically 3–5 times that of a globular cluster.

**Evaporation (of clusters)** The eventual dissolution of a cluster of stars under the combined effect of the pull of surrounding stars and nebulae and the combined motion of the stars within the cluster. Stars acquire enough energy to reach the gravitational edge of the cluster where the pull of the cluster as a whole matches that of the surrounding galaxy. The process is equivalent to water evaporating from a pan of hot water where the particles have acquired sufficient energy to break the binds that link them to the rest of the liquid in the pan.
Faint fuzzy  Another type of newly discovered cluster with similar nearly identical properties to extended clusters. These have been spotted in the outskirts of neighboring galaxies but not ours.

Gamma ray burst  A burst of high energy radiation, dominated by gamma rays, released (most likely) when a black hole forms. They are divided into at least three groups: short, long and ultra-long. Short bursts last less than 0.2 s and release harder (higher energy) radiation. These are believed to occur when two neutron stars merge. Long bursts (lasting anything from 0.2 s to several minutes) are softer (less energetic) than short bursts, but appear to happen when the cores of very massive stars implode. Most (maybe all) are associated with the deaths of some but not all Wolf-Rayet stars. Ultra-long bursts are a new discovery, and last for several hours. They may be associated with the implosion of the core of a blue supergiant or luminous blue variable.

Globular cluster  A ball of 100,000 to a few million stars that is roughly 1–200 light years across. The half-mass radius is typically less than 10 light years and usually less than 5. In the Milky Way all globular clusters are more than 8 billion years old (although the Arches cluster may be analogous). In the LMC, SMC and many other galaxies much younger globular clusters (or globular-like clusters) are known with ages measured in as little as a few million years.

Gravothermal collapse  The process through which old star clusters, particularly globular clusters are believed to pass. Stars lose so much energy to neighbors that they fall towards the core of the cluster causing the density of stars to increase rapidly. Various effects then come into play, which prevent the cluster’s total implosion.

Half-light radius  If you look at an image of the cluster it can be divided into an inner and outer region. The half-light radius is the radius of the region from which half the light of the total cluster is emitted. This is a convenient method of determining the bulk property of the cluster including its size and density.

Half-mass radius  Like the half-light radius (above) the half-mass radius is the radius of an imaginary circle around the core of
the cluster that contains half the cluster’s overall mass. For old clusters, where the stars are low in mass, the half mass and half-light radii are effectively the same. In younger clusters, where there may be a skewed distribution of stars of various masses this may not be true.

**High mass X-ray binary (HMXB)** A binary star system where a black hole or neutron star is paired with another star of high mass—typically more than ten times the mass of the Sun. Material from the stellar wind of the more massive stars is captured into a disc around the compact, dark remnant. These systems can be relatively large, measuring several million miles between the two objects.

**Keplerian disc** A disc of material around (for example) a star that rotates in a relatively stable, elliptical orbit around the star. In globular clusters, many have two populations of stars. The most oxygen-rich (and sodium-poor—see anti-correlation, above) typically have Keplerian orbits around the cluster core, meaning that they are broadly elliptical but not one that is extremely different from a circular path.

**Low mass X-ray binary (LMXB)** A small X-ray binary system consisting of a black hole, neutron star or white dwarf that is orbited closely by a low mass companion. Material flows directly from the companion star’s surface onto the compact remnant through an accretion disc.

**Mass segregation** The tendency for stars to separate within a cluster according to their mass. Gravitational interactions between stars cause the heaviest objects to settle towards the centre, while lighter stars are moved towards the outskirts of the cluster.

**Millisecond pulsar** A generally old pulsar that spins at over 100 revolutions per second. These recycled pulsars are spun back up when they accrete material from a nearby companion. Many are partners in low mass X-ray binaries, while others have destroyed their partners and now live alone. The first planets discovered outside the solar system accompany the millisecond pulsar PSR B1257+12.
**Momentum (see angular momentum)**  Momentum is a property of any moving mass. It is calculated by multiplying the mass of the object (in kilograms) by its velocity (in meters per second). When two moving masses encounter one another—either through a direct collision or by interaction through their mutual gravity—momentum is always conserved.

**Nebula**  A cloud of gas and dust. Various types are known including planetary nebulae that are expanding and fluorescing clouds that are formed from dying red giants; molecular clouds are nebulae that contain predominantly molecular (diatomic) hydrogen.

**Neutrino**  A very low mass particle (in the lepton family of particles) emitted during some nuclear reactions. The neutrino balances the change in momentum of the particles involved in the reactions and is an important means through which stars lose energy.

**Nova**  A thermonuclear explosion that occurs on the surface of a white dwarf. Hydrogen, which has been accreted from a neighboring star, ignites and burns through the CNO cycles. During these reactions, unstable nuclei build up which undergo radioactive decay. This, further, heats the layer of burning fuel until burning becomes explosive, lifting the entire layer and part of the underlying dwarf off into space. Shocks within the expanding debris and the disc can generate gamma rays. Novae tend to repeat on timescales measured in thousands of years, but a small subset, called recurrent novae such as RS Ophiuchi, repeat on decadal timescales.

**Open cluster**  A predominantly young cluster of several hundred, to several thousand, stars. There is no longer any hard and fast distinction between open and globular clusters, as many galaxies, including the LMC and SMC, have many large young clusters. A handful of very old open clusters are also known.

**Pair instability supernova**  A supernova from a star with 130–260 times the mass of the Sun that is powered by the creation of electron-positron pairs. Energetic gamma rays arise in the core of the star as the temperature exceeds 800 million Kelvin. Following Einstein’s dictate, $E=mc^2$, many become electron-
positron pairs, which removes the support from the massive stellar core. This, then, collapses rapidly inwards. In the process carbon and oxygen within the core is fused to iron, releasing sufficient energy to eviscerate the star.

**Pulsational pair instability supernova** In somewhat less massive stars (95–130 times the mass of the Sun), pair instability is not so extreme that the energy released destroys the star. Instead, the shockwave blasts part of the star off into space at a few thousand kilometers per second. This reduces the temperature and rate of nuclear reactions in the core, allowing the star to “relax”. After pulsing the star may become unstable again if sufficient mass remains in its core. These later pulses carry away less mass but have the same total energy so move faster. This causes them to catch up with the first pulse. In doing so, much of the kinetic energy of the second pulse (or subsequent supernova) is released as light, powering a long-lasting, highly luminous display.

**Planetary nebula** An expanding low mass cloud of highly ionized gas that surrounds a very young white dwarf star. The gas originates in the outer layers of a former red giant. Strong stellar winds from the giant blow off its envelope which is then heated and ionized by ultraviolet radiation coming from the now exposed stellar core (the proto-white dwarf). Such nebulae are fairly common but last only a few tens of thousands of years until they disperse into the surrounding space.

**Positron** The antimatter equivalent particle of the electron. Positrons have the same mass but the opposite charge and spin of the electron.

**Primordial binary** A binary system that was formed with the star cluster.

**Radiation (energy transfer by)** The transfer of energy from place to place using electromagnetic radiation, rather than with particle motion.

**Red giant** A cool but highly luminous star that is several tens to a few hundred times the diameter of the Sun. They are typically a few hundred to a few thousand times brighter than the Sun.
Red giants are produced at the end of a star’s main sequence when its core runs out of hydrogen fuel and collapses.

**Red straggler**  A red giant star that lies above the main sequence turn off but is also too luminous to have been formed from the stars that are currently leaving the main sequence. These must be the descendents of blue straggler stars, produced when two or more stars collided and merged while still on the main sequence.

**Red supergiant**  A very large, cool red star with a very high luminosity, over 10,000 times that of the Sun. These are produced when the core of a much more massive star runs out of hydrogen fuel and then collapses.

**Ring cluster**  Odd, ring shaped collections of stars that are a few hundred million years old. These are not known in the Milky Way but are seen in the Magellanic Clouds.

**r-process element**  An element produced by the rapid addition of neutrons to seed elements such as iron. These include the most massive elements in the periodic table. All elements that are more massive than lead-207 are produced through the r-process. The location of the r-process is unclear but almost certainly includes both the environment surrounding young neutron stars in core-collapse supernovae; and also short gamma ray bursts, where two neutron stars collide.

**rp (and p)-processes**  A series of nuclear reactions where (predominantly) unstable proton-rich isotopes of elements are produced. The most likely site for their formation is the surfaces of neutron stars undergoing violent hydrogen fusion (Type I X-ray bursts). Novae may also produce some of these elements (the p-process).

**Sawyer-Hogg classification system**  A system of classifying globular clusters based on their luminosity, distribution and the density of the stars contained.

**sdB star**  A blue sub-dwarf star that appear to be the stripped descendent of red giant stars. Some, but not all are helium burning stars; while many more have too little fuel to do this and will quietly evolve into helium-rich white dwarfs.
Shell star  See Be star.

Sodium-neon cycle  An off-shoot of the CNO cycles where hydrogen is fused into helium. In these reactions, neon picks up four protons, forming first sodium, before the reactions spit the original neon nucleus back out plus the product helium nucleus.

s-Process element  A series of reactions thought to occur most frequently in AGB stars. Here, a steady but slow supply of neutrons is added to smaller, seed nuclei. This builds them up in mass until they reach Lead-207. At this point the rate of radioactive decay exceeds the rate at which further assembly can occur and the process halts. Larger nuclei are made in a similar set of reactions, called the r-process (see above).

Thorne-Żytkow object ( TZO)  A hypothetical object consisting of a red giant or supergiant with a neutron star-core. The two are brought together when the expanding red (super)giant swallows up the neutron star. Such an object may be the source of rp-elements (above). The lower mass TZOs are thought to die when the outer layers are blown off into space. More massive red supergiant TZOs likely die more violently when their cores implode to form black holes. In the accompanying eruption the black hole may betray its formation with an accompanying long GRB (above).

Tidal shocking  (See disc-shocking, above.)

Trumpler classification system  A classification system for open clusters that takes into account the number of stars, their distribution in the cluster and the presence or absence of accompanying nebulosity.

Two-body relaxation time  In terms of the death of dense (rich) clusters, including globular clusters, this is perhaps the defining force. The two-body relaxation time is the time it takes a star to change its velocity (its direction) by 90°. Although sounding rather abstract, it defines the number of interactions a star is experiencing on its travels through the cluster. In doing so, the two-body time explains how the velocity of stars becomes randomized through the exchange of momentum between them. In
the process light stars tend to be accelerated outwards as they gain kinetic energy and momentum, while higher mass stars fall inwards. For globular clusters the two-body time is measured in tens to hundreds of millions of years. For an elliptical galaxy, it is far longer than the current age of the universe.

**Type Ia supernova**  An explosion which disrupts a white dwarf in its entirety. These are most likely driven by the white dwarf gaining mass from a companion (or through a collision with another white dwarf) until it approaches and in many cases exceeds the Chandrasekhar mass limit of 1.382 solar masses. It is now apparent that a variety of masses of white dwarf will explode—from 0.9 to nearly double the maximum permitted Chandrasekhar mass, 2.1 solar masses. The variation depends on the type of system in which the white dwarf lives. A few of these supernovae are known as “.Ia” supernovae as they are a tenth as bright as conventional Type Ia events.

**Type II supernova**  A type of supernova where the core of a massive supergiant star implodes to form a neutron star (or more rarely a black hole). The spectrum of the explosion reveals abundant hydrogen from the supergiant’s outer layers. When the light output of the supernova is plotted against time, many Type II supernovae also show a plateau in brightness caused by the steady recombination of hydrogen nuclei with neighboring electrons (Type II-P supernovae).

**Ultra-compact dwarf**  A small galaxy with a diameter more like a globular cluster (2–400 light years). The stellar density is very high but the half-mass radius is larger. Many UCDs appear to be the stripped-down remnants of larger galaxies that have undergone fatal encounters with larger elliptical and spiral galaxies. Like their much larger elliptical cousins some contain supermassive black holes. The small galaxy M32, in Andromeda, is a close relative, but somewhat larger than most UCDs.

**Velocity dispersion**  A measure of the spread in velocity of stars in a cluster. As stars mill around the core of the cluster they have different velocities to one another. This spread is super-imposed upon the velocity of the bulk cluster as it moves through space.
The spread is called the dispersion around the mean velocity of the cluster as a whole.

**Violent relaxation**  A thoroughly messy adventure where a young star cluster, rich in massive stars undergoes a process of “re-alignment”. As massive stars die and expel much of their mass, the distribution of mass changes rapidly, which then violently alters the gravitational field of the cluster. Remaining stars are forced to redistribute themselves within the cluster in order to re-balance the forces acting upon them. In the process any original structure within the cluster is destroyed. The process occurs over the first 5–20 million years as the most massive members of the cluster die.

**Virialization**  The process through which the kinetic energy of every star within a cluster (or a galaxy) becomes randomized. Through two-body encounters, stars exchange kinetic energy and momentum with one another causing the appearance of the system to smooth out.

**White dwarf**  A small, earth-sized star which does not produce any more energy through nuclear reactions. These stars are supported by electron degeneracy—a repulsive effect between electrons confined in very dense environments. They are all the end-products of red giant stars that have completely exhausted their fuel and shed their outermost layers. White dwarfs with less than 44 % the mass of the Sun are made primarily of helium. Those more than a Sun’s mass are mostly made of oxygen, neon and magnesium. Those with intermediary masses (the most abundant currently) are made mostly of carbon and oxygen.

**X-ray binary**  A binary system consisting of a small, dense star, such as a white dwarf, neutron star or black hole, paired with another, more conventional star. See low mass X-ray binary and high-mass X-ray binary.

**X-ray pulsar**  A binary star system where a neutron star is paired with another (usually high mass) star. Material from the companion streams onto the magnetic poles of the neutron star generating a hot spot which emits X-rays. As the neutron star
rotates, this hot spot swings into and out of view, generating apparent pulses in the emission.

**Yellow straggler** A yellow star, often a sub-giant, which lies above the main sequence turn-off of a cluster. These are the descendents of blue straggler stars.
Further Reading

To improve accessibility to the work that this book is based upon, where possible ArXiV preprints (or equivalent) are provided as references.

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Chapter 3—Variable Stars in Clusters


Chapter 4—Globular Cluster Formation


Chapter 5—Open Clusters


Chapter 6—Stellar Soap Operas

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Chapter 7—The Complex Life of Globular Clusters


Chapter 8—One Thousand Rubies in the Sky


Further Reading


Chapter 9—Milkomeda and the Fate of the Milky Way

Stellar Dynamics in Galaxies [www.maths.qmul.ac.uk/~wjs/MTH726U/chap2.pdf](http://www.maths.qmul.ac.uk/~wjs/MTH726U/chap2.pdf)


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