Introduction

1.1 Motivation

The aim of this book is to describe the connection between the physics and evolution of relatively nearby luminous hot stars and more distant starburst phenomena occurring all the way to cosmological distances. There have been recent significant advances in our knowledge concerning hot stars and their contribution to highly energetic star formation episodes. The Hubble Space Telescope (HST) and Spitzer in particular have provided many new insights into these areas. Recent observations of the near infrared regions have also greatly aided our view of star formation processes. This book is aimed at those extragalactic astronomers who would be interested in hot star astrophysics and those stellar astrophysicists concerned with galaxy evolution. It would be of use in graduate astrophysics courses at a level suitable for advanced students. This monograph will be one of the first of its kind in spanning the connection from the astrophysics of hot stars to that of newly forming galaxies.

1.2 Observed properties

The Hertzsprung–Russell diagram

What are stars? They are fully gaseous, ionized, gravitationally bound entities, emitting large amounts of radiation over many wavelengths. In normal stars, the gas is in hydrostatic pressure equilibrium under the ideal gas law equation of state. It is held in balance against the inward forces of gravity by the outward pressure of radiation generated from nuclear reactions in the stellar interior (or from gravitational contraction adjustments). By using the phrase “luminous hot stars” we mean to describe those massive ones that inhabit the upper left-hand portion of the Hertzsprung–Russell (H-R) diagram. This fundamental empirical relationship, known for nearly one hundred years, plots stellar absolute magnitude along the ordinate. The brightness is plotted increasing upward, thus the value of the magnitude becomes smaller and even negative in those peculiar units so familiar to astronomers. The H-R diagram has as its horizontal axis the stellar color (or spectral type) such that the value along the abscissa increases going from hotter to cooler stars, bluer to redder objects, “earlier” to “later” spectral types, from left to right. Most stars are found in a relatively narrow band reaching from the lower right (faint and cool) to the upper left (bright and hot). This is called the main sequence (MS) and stars along it are often referred to as dwarfs, with an appropriate color prefix such as red, yellow, or blue. Stars above and to the right of the MS are called giants or supergiants, dependent on their distance from it, also with color prefixes.
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Stars near to but below the MS are called sub dwarfs. Finally, on an H-R diagram of nearby stars a few are found well below the MS; these are termed white dwarfs (even though they are blue) and they represent the final state of evolution of low and intermediate mass stars.

In more precise physical terminology, the H-R diagram is a plot of stellar luminosity \( L^* \) (emitted energy) upwards versus effective (“surface”) temperature \( T_{\text{eff}} \) increasing right to left. The \( T_{\text{eff}} \) is defined by the equation

\[
L^* = 4\pi R^2_\star \sigma T_{\text{eff}}^4,
\]

where \( R^* \) is the radius of the star from which radiation is emitted and \( \sigma \) is the Stefan–Boltzmann constant. \( L^* \) and \( T_{\text{eff}} \) are parameters which readily lend themselves to estimation.\(^1\)

The important properties of luminous hot stars, that is, their luminosities, \( T_{\text{eff}} \), masses, and chemical compositions will be considered in Chapter 3. Chapter 2 will discuss photometry and spectroscopy of early-type stars. Chapter 4 will describe the observations of stellar winds which are ubiquitous amongst massive stars, plus the physics behind them, which involves radiation pressure. According to a fundamental theorem of stellar structure, the luminosity and temperature of a star are unique properties of its mass and composition. Stellar rotation and magnetic fields introduce perturbations to this relationship, but these factors are usually small compared to the effects of mass, \( M^* \),\(^2\) and composition\(^3\) on the structure.

MS stars utilize nuclear reactions that fuse (“burn”) hydrogen to helium in their central cores, with exothermic energy release. The more massive the star, the more luminous it will be on the MS, with \( L^* \approx M^4 \) for solar-type stars, decreasing to \( L^* \approx M^{2.5} \) for high mass stars. Most stars near the Sun have a similar composition (or abundance, referring to the elements other than hydrogen and helium); thus the MS is relatively narrow. Stars with an initial abundance below solar values will lie on a different MS (the sub dwarfs) and evolve in a quantitatively different manner.

Stellar spectroscopy

The gaseous matter that makes up a star has a wide run in properties from the innermost core to the outer regions. Most stars are spherical in shape to a good approximation so there is a simple radial dependence of variables such as the gas density, temperature, and pressure. These decrease outwards monotonically following the perfect gas law such that the star is in hydrostatic equilibrium at every point. While the stellar cores are typically at a few \( 10^7 \)K, the surface temperatures are a few \( 10^3 \) to \( 10^4 \)K. The gas in the interior of a star is highly ionized and quite opaque to radiation. The energy created in the core diffuses slowly (in the Sun \( \approx 10^6 \) years) outward to the surface. The character of the radiation keeps in thermal equilibrium with its surroundings such that the \( \gamma \) rays generated in the core become visible wavelength radiation at the stellar surface.

But what is the “surface” of a gaseous object? This can be thought of as that region of the star from which the emergent radiation escapes (roughly where the continuum opacity is near unity). This “photosphere” is overlain by a slightly lower density and temperature

\(^1\) Typically in units of solar luminosity, \( L_\odot \), where \( L_\odot \approx 4 \times 10^{33} \) erg s\(^{-1}\).

\(^2\) Typically in units of solar masses, \( M_\odot \), where \( M_\odot \approx 2 \times 10^{33} \) g.

\(^3\) Normal stars, including the Sun, are composed mostly of hydrogen (\( X \approx 70\% \), by mass) and helium (\( Y \approx 28\% \)). There is a small admixture (\( Z \approx 2\% \)) of all other elements, often called “metals” by astronomers.
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regime where the line opacity for various relatively abundant elements and ions has dropped to near unity. This cooler “atmosphere” is the source of the absorption line spectra of normal stars. In most stars the geometric depth of the photosphere and atmosphere has some overlap and is small with respect to the stellar radius (hence can be treated as “plane-parallel”). This is the reason that the Sun’s limb appears sharp. Gaseous material exists above a stellar atmosphere but normally its density is so low that it is normally not easily detectable directly (but, e.g., total solar eclipses reveal this material in the Sun, commonly known as a corona).

The characteristics of a stellar spectrum are a function of the properties of the stellar photosphere and atmosphere, which are closely coupled to \( L \) and \( T_{\text{eff}} \) in normal stars. The specific spectral features that will be found depend upon the absolute numbers of ions present (related to the abundance of the element and the ionization state) and the line transition probabilities. As the most common element, lines from hydrogen are visible in most stars and they are prominent in hot stars. Helium lines are readily seen only in the hottest stars, given the relatively high energy needed to excite the lowest electronic level. Generally speaking, only high excitation lines of ions of other elements are observed in hot stars in the optical regions. Ground state lines of hydrogen and helium, along with highly ionized common elements, are found primarily at far UV wavelengths. These outer boundaries of stars provide nearly all the direct observations of their properties. Until the latest or final stages of evolution are reached, the surface composition of stars represents their initial values and not that of the nuclear reactions in the core which otherwise remain hidden from direct view.\(^4\) (Neutrinos from nuclear reactions in the interior of the Sun have been directly detected.)

Classification systems have utilized the appearance and strength of absorption lines and estimation of line ratios to determine their character, or spectral type. The spectral types for normal stars are labeled with the letters O, B, A, F, G, K, and M, in order from the hottest (“earliest”) to the coolest (“latest”). Numerical subtypes distinguish differences within the spectral letters and go from number 0 to 9 (but with a few 0.5 divisions). Astronomers also utilize line widths and other line ratios to determine the atmospheric pressures (related to gas densities, local gravity, hence luminosity). These labels utilize roman numerals I–V, with the latter corresponding to the faintest luminosity class. Line widths are generally narrowest in the most luminous stars while the Balmer (and HeI) lines have Stark-broadened wings in the fainter ones. While five luminosity classes are easily distinguished among cool K and M stars with their wide dispersion in \( M_V \), only I, III, and V are adopted for O type stars which have a more limited \( M_V \) range, as discussed in Chapter 2.

Three stars in Cygnus with broad emission lines of highly excited elements were first identified by Wolf & Rayet (1867) using a stellar spectroscope. These stars are spectacular in appearance, having strong broad emission lines rather than narrow dark absorption features as nearly all other stars, and the Sun, show. What a sight for the eye: brilliant bright colorful lines superimposed upon a rainbow continuum. These stars later became known as Wolf–Rayet (W-R) stars. It later became apparent that their spectra came in two “flavors”, those with strong lines of helium and nitrogen (WN) and those with strong helium, carbon, and oxygen (WC). Subsequently it was found that some WN stars show hydrogen lines but this element has never been found in WC types.

\(^4\) Exceptions are found for massive stars – see Chapter 5.
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Distribution of stars in our Galaxy

Our Milky Way Galaxy is an extended stellar system containing \( \approx 2 \times 10^{11} \) stars. The overall spatial morphology has been compared to that of a “pair of back-to-back fried eggs”. The slightly flattened central region, or “bulge”, out to a radius of \( \approx 1 \) kpc, contains mostly old stars. A highly extended “disk”, with radius out to about 15 kpc, has a spiral arm structure in its plane and extensive regions of relatively new star formation. The Sun is found at a galacto-centric distance of about 8 kpc. The entire Galaxy is rotating, differentially, with a period at the solar distance of some 200 Myr. Surrounding this flattened system, the source of most of the optical radiation of our Galaxy, is a spherical halo sparsely populated by old stars, with ages \( \approx 12 \times 10^9 \) years (12 Gyr). Recent star formation is found in and near the galactic center, and old stars are also dispersed throughout the disk. See also Chapter 7.

Extragalactic luminous hot stars

Hot stars range in luminosity up to a few \( 10^6 L_\odot \) and are individually detectable on 4-m class telescopes with distances up to 1 Mpc, which includes the extent of the Local Group of galaxies. Classification and spectroscopic analysis of normal stars with their absorption lines is difficult but selected surveys have been published, particularly for the Magellanic Clouds (MCs). W-R stars, with their strong emission line spectra, can easily be detected with narrow emission band imaging in the Local Group. Beyond these distances identification and study of luminous hot stars is challenging but the advent of 8–10 meter ground based telescopes has eased the observing time required. (Individual W-R stars are now being identified in galaxies with distances up to 5 Mpc.) The MC stars sample a range of initial abundances, from solar values to a factor of five smaller. Local Group galaxies have a range of abundances, from somewhat metal-rich values to well below solar metallicity.

It is well known that the details of stellar evolution, particularly for high mass stars having strong winds, depend on the initial composition. Astrophysicists need to continually examine the predictions of stellar evolution models of stars to compare their properties with those of real objects in the sky. Analysis of stellar properties over a wide range of metallicity will enable astronomers to perform stronger tests of stellar evolution theory.

For example, it has been found that there is an observed upper limit to the luminosity of red supergiants (RSGs) using the H-R diagrams of galaxies of the Local Group. This empirical result is now referred to as the Humphreys–Davidson (H-D) limit, following Humphreys & Davidson (1979). The red H-D limit is substantially below that of the hottest main sequence stars. Since massive stars evolve at roughly constant luminosity, the absence of stars in the uppermost right hand corner of the H-R diagram was initially a puzzle. Where are the helium burning stages of the most luminous stars if they are not found in the RSG region? The answer lies in assigning highly luminous hot stars with unique spectral properties, namely W-R stars. Gamov (1943) first suggested that the anomalous composition of W-R stars was the result of nuclear processed material being visible on their surfaces. Evolutionary issues are more thoroughly discussed for single stars in Chapter 5 and close binaries in Chapter 6.

Extensive classification surveys of individual stars, aside from W-R stars, and perhaps the brightest blue supergiants, will be difficult beyond the Local Group until even larger telescopes are available. Spectroscopic analyses will be tedious and direct tests of stellar evolution models more problematic. It is, however, possible to check certain aspects of
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stellar evolution theory using indirect methods, by investigating the collective properties of luminous hot stars.

1.3 Stellar atmospheres

**Astrophysical models**

Astrophysicists construct mathematical and physical models that utilize often incomplete (and possibly incorrect) theory to make predictions about observable phenomena. The astronomer, in turn, makes and analyzes observations to confront the theory so as to help improve it or show what must be discarded. Models can be used to interpret nearly all the aspects of the positions of stars on the H-R diagram. One class of models deals with the physics of the stellar photosphere and atmosphere (treated together). For luminous hot stars, as we shall see in Chapter 4, one must also consider the stellar wind as an integral aspect of that region.

Generally, radiative processes dominate over collisional processes within hot stars, such that the standard approach of local thermodynamic equilibrium (LTE) within a plane-parallel geometry no longer holds, requiring a more elaborate, computationally demanding approach, known as non-LTE, supplemented with the need to incorporate atomic line opacities. Conversely, for high mass cool supergiants, LTE is valid, but extensive molecular opacities are needed instead. Details are covered in Chapter 3.

**Composition**

The solar photosphere is dominated by hydrogen and helium, with 1–2% by mass in the form of metals, and represents the initial composition of the solar nebula 4.5 Gyr ago. In general, the surface composition of other stars share this characteristic, not that of the nuclear reactions in the core which otherwise remain hidden from our direct view, at least until the latest or final stages of evolution are reached. In the solar case, one exception is that neutrinos from nuclear reactions in the interior of the Sun have been directly detected.

In the case of OB stars, despite their youth, their surfaces may expose partially processed nuclear material, due to internal mixing. This is especially true for red supergiants, where nuclear processed material is dredged up in their convective envelopes. In the extreme cases of W-R stars, a combination of mixing and previous stellar winds reveal fully processed material from H or even He-burning. The evolution of massive stars is considered in Chapter 5.

1.4 Stellar winds

**OB winds**

During their sojourn on the main sequence, the extremes of luminosity and temperature for O and early B stars result in strong stellar winds, sufficient to carry away substantial amounts of material from the star. The existence of winds was first proposed by Beals (1929), with direct signatures established since the first rocket UV missions in the 1960s, which may be parameterized by a velocity and mass-loss rate. The former may be directly measured from observations, whilst the latter relies upon theoretical interpretation. A theoretical framework for winds from hot stars was devised, and developed soon after their detection, involving the driving of outflows via millions of UV spectral lines.
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The critical aspect which distinguishes OB stars from solar type stars is their proximity to the Eddington limit, where radiation pressure balances gravity, plus their high temperature photospheres, where metal species are highly ionized. Mass-loss affects the stellar structure and a substantial modification of the evolution of massive stars occurs, in which the outer hydrogen-rich layers are removed, akin to peeling away the skin of an onion. Once the hydrogen fraction at the surface begins to fall, the star will turn back to hotter effective temperatures on the H-R diagram to become a W-R star. Details are covered in Chapter 5.

Wolf–Rayet winds

Specifically, WN stars have enhanced helium and nitrogen from hydrogen burning (during the CNO H-burning cycle) and WC stars show the products of the triple-$\alpha$ process. In other words, the stellar cores of these stars are partially revealed due to mass-loss, or mixing, in previous and current evolutionary stages. Given their composition anomalies, it is pretty obvious that W-R stars must be highly evolved. W-R stars are intrinsically luminous and found in close association with very massive stars. They are generally over-luminous for their masses, a property shared by other post-MS stars. It is thus natural to associate W-R stars with the late hydrogen and helium burning phases of the most luminous stars since no evolved counterparts appear in the RSG region of the H-R diagram.

The spectra of W-R stars are primarily that of broad emission lines superimposed upon a blue continuum. These come about because W-R stars have very strong stellar winds, the origin of which is tied up in their extremes of luminosity, temperature, and composition. The wind is sufficiently dense that optical depth of unity in the visual continuum arises in the outflowing material. The spectral features are formed even further out and are found primarily in emission. The line and continuum formation regions are, furthermore, geometrically extended compared to the stellar radius and their physical depth in the star is highly wavelength dependent. These topics are presented in more detail in Chapter 4. According to theory, winds from hot stars are intrinsically unstable, such that their outflows are highly structured. Indeed, observations of W-R stars, and most recently OB stars, confirm a clumpy nature. Since the majority of mass-loss diagnostics scale sensitively with density, it is difficult to confidently extract robust values. Structures within their inner envelopes cannot be directly imaged – hot, massive stars are simply too far away.

LBV and RSG outflows

There are also episodes of instability observed in which extensive ejection of matter from a hot star takes place during Luminous Blue Variable (LBV) phases, of which $\eta$ Carinae is the most famous example. LBVs are apparently intermediate between the blue supergiant and W-R phases in the evolution of the most massive stars. Furthermore, there may be mixing of material from the helium rich core regions to the hydrogen rich outer parts of the stars, thus affecting the run of chemical composition.

RSGs also possess stellar winds, albeit denser and slower than other evolutionary phases of high mass stars, although there is no robust theoretical framework in their case. Radial pulsations are believed to provide the mechanism for transporting material to sufficient distance that dust grains can form, which permit winds to be driven outward via the intense continuum opacity from such high luminosity stars.
1.5 Evolution of single stars

Main sequence evolution models

Stellar evolution from the point at which hydrogen burning is first initiated can be sketched from stellar structure models – describing the behavior of the star from the core outwards to the photosphere – which are relatively mature. Energy transport from the center to the surface in normal stars is typically convective or radiative, depending on the temperature gradient. In high mass stars, the inner core is convective and the outer envelope is radiative; this situation is reversed in the Sun and low mass stars. While there is energy transport between convective and radiative regions there is no mixing of material between them in classical models. Matter within a convective region is, of course, well mixed.

As a star gradually converts hydrogen to helium in its core the composition changes and the stellar structure readjusts to keep equilibrium. The location of the star in the H-R diagram migrates “slowly’’ to slightly cooler temperatures (for massive stars) or to higher luminosities (for lower mass stars). Only the core mass participates in nuclear reactions unless there is mixing of hydrogen rich material downward from the outer zones of the star. For most stars the core mass fraction is about 10%; for higher mass stars, this is closer to 30%. Once the hydrogen in the core is nearly exhausted, the star very rapidly approaches post-MS evolution and leaves the MS (Chapter 5).

The evolution time for stars on the MS varies inversely as roughly the 3.5th power of the mass (since the fuel supply is proportional to $M_*$ and the rate of using it up proportional to $L_*$). Stars of high stellar mass go through their entire evolution cycle before low mass stars have evolved much at all. Clusters of stars are known in which hundreds to thousands of stars are born at more or less the same time. Cluster evolution on the H-R diagram can readily be understood in terms of this stellar evolution timescale with its inverse dependence on mass. Initially, a cluster will be relatively blue and bright, as the hot stars on the MS dominate the luminosity. The most massive stars will be the first to “peel off” the MS in turn, in order of their mass. The position of the “turn-off” point of a cluster on the H-R diagram, the uppermost part of the MS, is a direct measure of its age. As the cluster evolves, the turn-off point moves to fainter and redder magnitudes along the MS as stars of lower and lower mass evolve away. Clusters are more fully considered in Chapter 7.

Post-main sequence evolution

Once a star begins to run out of hydrogen fuel in its core, the stellar structure changes dramatically to maintain hydrostatic equilibrium and all stars begin to migrate “rapidly” towards the upper right hand portion of the H-R diagram. This is the red supergiant (RSG) region for most high mass stars and the red giant region for low and intermediate mass stars. Although the surface temperatures are becoming cooler, the core temperatures and central densities are inexorably rising. At some point, a zone of material surrounding the now hydrogen-depleted core becomes hot (and dense) enough to support hydrogen fusion, here termed shell hydrogen burning. Eventually the temperature and density in the core are high enough that helium can begin to fuse into carbon (the triple-$\alpha$ process, or helium burning) under controlled conditions (for high and intermediate mass stars) or sporadically (for lower mass objects). The post-MS lifetime is typically about 10% of the MS lifetime for each mass, aside from the most massive stars. While clusters still young enough to contain mostly
massive stars will appear relatively blue, as time goes on the color will be dominated by red supergiants and giants.

Lower mass stars are unable to process nuclear fuel beyond helium burning. This phase occurs as a series of “helium flashes” which not only mix processed material from the core to the surface but also result in rapid movements on the H-R diagram. Intermediate mass stars go through helium burning in a stable manner during the red giant stage, and massive stars do so during a RSG or W-R phase. High mass stars reach core temperatures high enough for further exothermic nuclear reactions to occur, and elements further up the periodic chart are produced in their interiors. All of these post helium burning reactions occur on timescales that are even more rapid than what has gone before. These stages end for low and intermediate mass stars with the ejection of the outer envelope, to be identified as a planetary nebula, and the uncovering of the white dwarf (WD) remnant. High mass stars collapse as their fuel is exhausted and a supernova (SN) results. Details are covered in Chapter 5.

It is expected that for single stars there ought to be a mass above which all stars will evolve to the W-R stage as sufficient mass-loss and/or mixing during blue supergiant phases will have occurred. There is some empirical evidence that this occurs at around 25–30 $M_\odot$ for solar composition. The initial stellar mass corresponding to the H-D limit for RSG lies close to this value, according to stellar models with mass-loss and rotational mixing (e.g., Meynet & Maeder 2003). This suggests that within a limited mass range some single W-R stars might be post-RSG stars. For close binaries, the critical mass for production of a W-R star might be lower. Binary star evolution will be discussed in Chapter 6.

Eventually all stars will run out of fuel or will no longer have the right conditions for further nuclear reactions to occur. In the case of low and intermediate mass stars the stellar cores have already reached a regime in which the ideal gas law no longer applies. Instead, their temperatures and densities are such that electron degeneracy governs the equation of state. These cores, when uncovered, are called white dwarfs, with typically 0.6 $M_\odot$. There is an upper limit to the mass of a white dwarf, the Chandrasekhar limit, of about 1.4 $M_\odot$. Type Ia supernovae occur when a white dwarf exceeds the Chandrasekhar limit, as a result of accretion from a binary or the merger of two sufficiently massive white dwarfs. As such, Type Ia SN may be used as standard candles, from which observations of distant SN indicate the presence of a cosmological constant (Perlmutter et al. 1999).

When high mass stars run out of fuel they collapse under the influence of gravity; electron degeneracy in the core is not stable. This collapse triggers an SN explosion which ends in a stable configuration such as a neutron star or a black hole. These kinds of supernovae are now assigned labels of type II, Ib or Ic. A small fraction of the rare type Ic supernovae whose cores produce black holes also experience one flavor of gamma ray burst (GRB) explosion. Intermediate and low mass stars will end in the white dwarf configuration. The dividing main-sequence mass for these separate end points according to the models is at about 8 $M_\odot$. We will take this as a convenient definition for luminous stars: those with initial masses larger than 8 $M_\odot$, irrespective of their subsequent evolution. On the main sequence, this mass corresponds (following, e.g., Schaller et al. 1992) to a few $10^3 L_\odot$. The (effective) temperature for this mass and luminosity is around $T_{\text{eff}} \sim 19000$ K on the main sequence. Stars of 8 $M_\odot$ live about $5 \times 10^7$ years (50 Myr) during their hydrogen burning stages. The
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largest mass stars \((\approx 100 M_\odot)\) live a few Myr years (their core mass fractions are near 30\%, rather than 10\%).

The end points of stellar evolution, the white dwarf, neutron star, and black hole state, are permanent and their timescales are not counted when one is considering the lifetime of the stellar object. A small fraction of extremely massive stars at very low metallicities may end their lives with a direct collapse to a black hole, without an accompanying supernova explosion, or leave no remnant behind via a hypothetical pair-instability SN. Additional details concerning star death for massive stars will be considered in Chapter 5.

1.6 Binaries

**Binary fraction**

Most, but probably not all stars are formed in binary systems. Binary detection is primarily from systematic spectroscopic observations taken over periods of days to years in which periodic Doppler shifts can be identified. This method, which is distance independent, has even been successfully used to search for duplicity of stars in nearby galaxies. The shorter the period, the larger the velocity range and the easier it is to find double stars. Binaries with periods longer than a decade or so, however, are difficult to identify with this method. A few binaries have been first detected by eclipses in which the light (from the combined system) diminishes in a periodic manner. This photometric method is also distance independent, but requires that the observers are aligned very close the orbital plane of the binary system.

Relatively nearby binaries can be identified if proper motion measures indicate a periodic motion in the sky. This led to the discovery of the binary nature of Sirius, with a period of about 30 years. Eventually the secondary was observed in the glare of the primary and found to be an under-luminous star, now realized to be a white dwarf. If star separations are sufficient, nearby binaries can be detected from their double nature on the plane of the sky. Periods in these cases are typically tens of years, or more. This type of detection is also highly distance dependent and is only suitable for relatively nearby stars.

A plot of the frequency of binaries as a function of period reveals a broad maximum at about a week, for massive stars, with a long tail towards longer periods. The shape and length of the tail would tell us whether or not all massive stars are binaries, but the detection methods described above are inadequate to fully describe the long period distribution function.

**Massive binaries**

The study of massive binaries provides the most robust method for measuring stellar mass, for which instances of up to \(80 M_\odot\) have been derived, although the upper limit to the mass of stars may be a factor of two higher. Accurate values for high mass stars are very difficult to establish in general. Close massive binaries, each possessing stellar winds, lead to a wind–wind interaction, details of which are studied by complex hydrodynamics.

For sufficiently close massive binaries there may be substantial mass-loss via a “Roche lobe overflow” process in which the initially more massive primary loses material to the less massive secondary star, resulting in evolution quite different from the single star case. Mass transfer may force a white dwarf into a neutron star state and a neutron star can become a black hole. Various exotic products may result, including high mass X-ray binaries, binary pulsars or OB runaways. A second, intrinsically fainter flavor of GRBs appears to be the result of merging neutron stars or a neutron star and black hole merger.
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1.7 Birth of massive stars and star clusters

Pre-main sequence evolution

Most massive stars in our Galaxy are born within clusters formed during the collapse of giant molecular clouds (GMCs), containing substantial amounts of gas and dust. Within the Milky Way, these are closely confined to the galactic plane. Some massive stars form from lower mass molecular clouds that lead to small clusters, which may or may not be gravitationally bound, such as the Orion nebula (Trapezium) cluster. The dust obscuration at optical wavelengths has made direct observations of massive star birth difficult in many cases, but IR observations are beginning to pierce the veil and reveal the underlying stars. The interaction of the luminous star with the gas and dust of the birth environment can be observed at IR, mm, and cm wavelengths. For luminous hot stars the intensity and hardness of the radiation and the presence of stellar winds complicate the formation processes. The stellar radiation heats and dissipates the dust, dissociates the molecular gas, and ionizes the local hydrogen. The stellar wind blows material outwards, contributing to shocks and jets in the surroundings.

Star birth is not yet well understood in detail and is one of the outstanding unsolved problems in stellar astrophysics. The basic framework appears to be as follows (e.g., Shu et al. 1987): a molecular cloud collapses under the force of self-gravity, or from an external pressure force (i.e., a nearby supernova). The cloud fragments into smaller units of stellar mass, which can be identified as protostellar objects. Each object will undergo a core collapse on a rapid dynamical timescale. Given that the angular momentum of the parent cloud will be conserved, the centrifugal forces will steadily increase as each protostar continues to shrink. At some point these forces will begin to balance gravity in equatorial regions and the stellar object takes on the geometry of a spherical core and a disk-like envelope. Some of the disk material will continue to accrete onto the stellar core and some will be lost to the system. Material can also be ejected perpendicular to the disk in the form of jets. The central star is now described as a Young Stellar Object (YSO), which can be undergoing further contraction.

The energy source during the collapse and contraction phases is from gravitational potential energy. Contraction continues and the core temperature continues to heat and grow denser. Eventually, the light elements in the core such as deuterium and lithium are able to undergo nuclear reactions with hydrogen, providing a new energy source and slowing the gravitational contraction. Light element burning does not last very long as these elements are low in abundance. In any event, the core temperature and density continue upwards until hydrogen burning commences and the star begins its MS lifetime.\(^5\)

The buried star with an accretion disk supporting the YSO phase has a timescale that is independent of the nuclear turn-on timescales and could well be longer. For massive stars, the YSO phase could well exist after the star arrives on the ZAMS and for some portion of the MS lifetime. The first observational evidence of massive star formation represents the hot core phase, followed by the detection of Lyman continuum photon production at radio wavelengths during the ultracompact (or hypercompact) HII region phase. Only later will the star become optically visible, as it clears its natal environment. The birth of massive objects will be the topic of Chapter 7.

\(^5\) This is called the “zero age main sequence”, or ZAMS.