Abstract. The theory of stellar structure and evolution plays a pivotal role in modern astrophysics. Stellar evolution calculations are used to determine the ages and, to a lesser extent, distances of stars, which are critical to our knowledge of the history and structure of galaxies. Moreover, since virtually all chemical elements (except hydrogen) can be synthesized inside stars, knowing the chemical history of the Universe requires understanding stellar evolution. Here, we briefly outline the basic physical processes at work in stellar structures and examine some of the most relevant aspects of the life of stars.

1 Introduction

The study of stars remains a central focus in modern astrophysics, a tradition spanning over five thousand years. Astronomy, possibly the oldest science, originated when early observers gazed at the night sky dominated by stars. Today, stars play important roles across various branches of astronomy. Stars undergo changes at such a gradual pace that they often maintain the same appearance over our lifetimes, and even across the extensive timeline of astronomical observations. Nevertheless, astronomers can infer some fundamental aspects of stellar evolution through careful observations and by applying physical laws and theories to interpret measurements conducted from Earth.

2 Properties of stars

Rather than observing the evolution of an individual star, we can examine a cluster or group of stars. Star clusters offer unique insights into stars’ characteristics since, roughly speaking, all cluster stars originated from the same molecular cloud, at the same time, and with identical composition. Nonetheless, they appear essentially different, showing a variety of star colors and intrinsic brightness (see Figure 1). Generally speaking, the most important physical properties of stars are mass, temperature, luminosity, gravity, age, and chemical composition. Although these parameters are all interconnected, the star’s initial mass primarily determines its evolution, while the chemical composition has a secondary impact. Stars exhibit a broad range of surface temperatures, discernible by their colors. According to Wien’s law, red stars are cool, while blue stars are hotter, with surface temperatures typically ranging from about 3000 to 30000 K. Once the temperature and luminosity are known, the radius of a star can be estimated using the Stefan-Boltzmann law. Stars’ compositions are identified by analyzing the lines in their spectrum, revealing that most stars consist mainly of hydrogen, around 25%
of helium, and up to a few percent of heavier elements. For binary systems, where the stars are gravitationally bound, the masses of the orbiting stars can be determined by combining the inclination angle of the binary orbit, the orbital period, and the separation distance in Kepler’s third law. Most stars have masses ranging from about 0.1 to 30 $M_\odot$. Once a star’s luminosity and temperature are determined, it may be plotted on a Hertzsprung-Russell (H-R) diagram. The majority of stars sit on the main sequence (MS), a diagonal line running from cool, red, dim stars to hot, blue, luminous ones. MS stars follow a mass-luminosity relation, with low-mass stars being less luminous and cooler than high-mass stars. A minority of stars lay above the MS, appearing very luminous but cool. They are identified as red giants. Some stars, known as white dwarfs, are located below the MS, appearing hot but dim.

3 Principles of stellar structure and evolution

Evolutionary processes within stars happen over timescales ranging from millions to billions of years. Although direct observation of most stellar changes during a human lifetime is unfeasible, astronomers employ computational tools to study the lives of stars. This purpose is accomplished by formulating a comprehensive set of differential equations that encapsulate the established physical conditions within a star, accounting for the myriad phenomena governing its temporal evolution. The solution to this set of equations provides internal profiles of various physical properties — temperature, pressure, density, among others — as well as the abundances of ions, atoms, and molecules. Consequently, this allows inferring the temporal evolution of observable quantities, including stellar luminosity, effective temperature, and surface chemical composition [1].

Gravity is the driving force behind stellar evolution, shaping a star’s journey from its birth, when an interstellar gas cloud collapses to form a star, to its eventual death. The other three fundamental forces in physics play pivotal roles in energy production, transfer, and loss, manifested as electromagnetic radiation and/or neutrino emission. For most of their life, stars maintain hydrostatic equilibrium. In this state, an element within a star experiences a gravitational force counterbalanced by a pressure gradient. Stars emit large amounts of energy (mostly in the form of photons) from their surfaces. To sustain their luminosity,
The energy lost through radiation must be replenished within the stellar interiors. The rate of energy transport from the deep interiors to the surface, by radiative transfer, convection, or conduction, depends on the temperature gradient of the stellar structure. Mechanisms responsible for energy transport and generation dictate the star’s evolution as it continually sheds energy to maintain hydrostatic equilibrium, thereby balancing the gravitational force.

In stars, energy stems from two primary sources: the conversion of gravitational potential energy into thermal energy, through a global (macroscopic) contraction, and the thermonuclear reactions that occur within the stellar interiors, where the high temperature and density allow such processes to take place. These two energy-producing mechanisms operate on different timescales. If $\Omega$ is the global gravitational energy of a star and $L$ its average luminosity, then the time needed to radiate away this energy can be expressed as $\Omega / L$. This characteristic timescale is called the Kelvin-Helmholtz timescale. For the Sun, it is about $3 \times 10^7$ years, a time too short to be in agreement with our knowledge of the past history of the Earth. However, when nuclear sources are factored in, a conservative estimate yields a lifetime of about 10 billion years. Consequently, the presence of nuclear sources is essential, not for explaining stellar luminosity, but for explaining the long times over which stars shine. Beyond their energetic role, nuclear reactions are pivotal for stellar nucleosynthesis [2]. The evolution of a star proceeds through a sequence of phases, in which energy is mainly generated by nuclear reactions or by contraction. When a star exhausts its nuclear fuel in the central regions, the core must contract to sustain the necessary luminosity for hydrostatic equilibrium. During these contraction phases, both central temperature and density increase.

4 The life of a star

A star is a self-gravitating object originating from a cold molecular gas cloud, composed of hydrogen, helium, and trace amounts of heavier elements, collectively referred to as metals. The process begins when the cloud is disturbed from equilibrium, perhaps by a passing shock wave. Gravity takes over as the cloud collapses, converting gravitational potential energy into kinetic energy (heat). This collapse increases temperature and density. When the core temperature exceeds several million degrees, nuclear fusion initiates, transforming hydrogen into helium. Thermonuclear reactions then provide non-gravitational energy, countering further collapse and giving birth to a star.

Objects forming with a mass less than about $0.1 \, M_\odot$ do have not sufficient mass to compress them enough to undergo hydrogen fusion and slowly cool down. Such low-mass stars are very dim and are called brown dwarfs. Contrarily, stars with higher masses successfully trigger hydrogen fusion through either the pp chain or the CNO cycle [3]. Both reaction chains transform four protons into a helium nucleus, along with the production of two positrons and two electron neutrinos, with a total energy release of 26.731 MeV. Once hydrogen fusion sets in, stars enter the MS phase, the longest evolutionary stage where central hydrogen transforms into helium, with more massive stars having shorter evolutionary timescales due to their higher temperature and brightness. H-burning efficiency depends on temperature, with the energy generation rate by the pp chain being $\epsilon_{\text{pp}} \propto T^4$ and $\epsilon_{\text{CNO}} \propto T^{18}$ for the CNO cycle[2]. This leads the pp chain to dominate the energy production in lower main sequence (LMS) stars and the CNO cycle in upper main sequence (UMS) stars ($M \gtrsim 1.1 \text{ – } 1.3 \, M_\odot$). As a consequence, LMS stars result in a radiative core and a cold, opaque, and convective outer envelope, while UMS stars have a radiative envelope and a convective inner core due to efficient H-burning.

After the central hydrogen burning phase, stars enter a stage where hydrogen is burned in a shell surrounding a central inert helium core. During this phase, known as the Sub Giant Branch (SGB) phase, the stellar envelope expands and cools down, causing the star to
shift towards the red side of the HR-diagram (refer to Figure 2), until reaches the base of the red giant branch (RGB). Throughout the SGB and RGB evolution, the He core steadily accumulates mass, as fresh helium is deposited by the outward-moving H-burning shell. Consequently, the surface luminosity increases. Since throughout the MS evolution, the burning core undergoes slight contraction and temperature increase, H-burning now primarily occurs through the CNO cycle, since it is more temperature-sensitive than the pp chain. Along the RGB phase, mass loss processes are also effective, diminishing the mass of the convective envelope. If the initial mass is \( M \lesssim 2.3 \, M_\odot \), the star develops a partially degenerate He core, delaying central helium ignition until a critical mass of approximately \( 0.5 \, M_\odot \) is reached at the RGB tip. At this point, He burning is triggered within the core, resulting in a helium flash. This process lifts the electron degeneracy, marking the beginning of a phase characterized by quiescent core-He burning. Stars more massive than \( \sim 2.3 \, M_\odot \) (the exact value depends on the chemical composition) avoid the formation of degenerate cores, triggering He-burning in the core in a non-explosive way. During this phase, the star exhibits significantly lower luminosity and higher effective temperature compared to the RGB tip. Throughout this central He-burning phase, the H-burning shell remains active. Given the large temperature dependence of the triple-\( \alpha \) reaction \( (\epsilon_{3\alpha} \propto T^{40}) \), convection is established in the He core. Helium burning produces carbon and oxygen in the core, through the triple-\( \alpha \) and the \( ^{12}\text{C}(\alpha, \gamma)^{16}\text{O} \) reactions. Following the core-He burning phase, a carbon-oxygen (C-O) core is thus formed. From this point on, the evolution of a star significantly diverges for massive stars and low-and intermediate-mass stars.

For low- and intermediate-mass stars, up to approximately \( 8 \, M_\odot \), the C-O core becomes degenerate and contracts until He burning is established in a shell around the core. The star now has two active burning shells and starts climbing along the asymptotic giant branch (AGB). Throughout the AGB evolution, shell-H and shell-He burning never operate simultaneously; instead, they alternate, generating huge amounts of nuclear energy through a series of He-shell flashes, known as thermal pulses (TPs). During the TP-AGB phase, the star hosts intense mixing and nucleosynthesis phenomena which enrich the envelope with the products of He burning. As the evolution progresses, the strong mass loss gradually reduces the envelope mass. The ejected gas and dust significantly contribute to the chemical enrichment of the Universe. AGB stars are actually considered to be major manufacturers of carbon,
nitrogen, and of elements heavier than iron [6]. When the envelope is virtually all eroded, the star then enters its post-AGB phase, moving towards a higher effective temperature while maintaining a constant luminosity. Following a brief transient phase as the central star of a planetary nebula, the star ends its life as a cooling white dwarf.

Stars with masses exceeding approximately $8 \, M_\odot$ attain a sufficiently high temperature in their cores to undergo carbon ignition. More massive stars may undergo further ignition and burn fuels heavier than carbon (neon, oxygen, and silicon) until an iron core forms, leading to a collapse and triggering a supernova explosion. Massive stars are the most important contributor to the enrichment of the interstellar medium with alpha-elements like O, Mg, Si, S, and Ca and heavy elements from Fe to Sr [7]. For these stars, mass loss through stellar winds becomes significant throughout all evolution phases, including the MS, causing left-right excursions and loops in the HR diagram (see Figure 3). After the explosion of a supernova either a neutron star or a black may be left, mainly depending on the initial mass of the star.

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