Stars: From Formation to Death

Stars have fascinated humanity since we first looked to the heavens. Beyond the constellations drawn out by past generations and their importance to guide travellers and ships for centuries, stars provide us with a unique chance to explore physical conditions that are impossible to forge on Earth. From their birth in dense molecular clouds to their compact remnants as white dwarfs, neutron stars and black holes, they span a tremendous range in density and temperature. Their interiors are subject to instabilities and turbulence that make them powerful physics laboratories. Many stars are paired in binary (and higher multiple) systems, opening-up studies of new physics. In particular, the growing capabilities to detect gravitational-wave (GW) bursts produced by the coalescence of neutron-star and black-hole binaries has given us a remarkable new window at the crossroads of astrophysics and fundamental physics.

Stars are at the heart of almost all astronomical structures. A large fraction are found to have planetary systems, and precise knowledge of the host stars is critical if we are to accurately characterise the planets. Populations of stars form the building blocks of galaxies. The energy feedback and chemical yield of entire stellar populations are fundamental drivers, and key tracers, of the evolution of galaxies (near and far) and of the Universe itself. Stars are an important tool to map the geometric and dynamical structures of galaxies, with their kinematics revealing the mass distribution that includes a dominating unseen (‘dark matter’) component. At larger distances, stars shape the integrated light and trace active star formation in galaxies, while also providing beacons to anchor the distance scale for cosmological studies.

Tremendous steps have been made over the past century in our understanding of stellar properties, enabled by new observational capabilities and detailed modelling (supported by the growth of computing power). We can now resolve their surfaces, probe their deepest interiors and characterise their evolution better than ever before.

The emergence of multi-messenger (e.g. LIGO-Virgo, KM3NeT) and ‘big data’ astrophysics (e.g. *Gaia,* VRO, LOFAR), combined with the imminent arrival of unprecedented facilities in space (e.g. *JWST*) and on the ground (e.g. VRO, ELT, SKA, CTA), will provide exquisite new constraints on the properties of stars through all of their evolutionary stages. Multi-wavelength observations will allow astronomers to address fundamental questions in modern science, ranging from the nature of the once massive binary systems now detected regularly by the GW experiments, down to the seemingly innocuous low-mass stars that may harbour Earth-like planets. Only with strong observational constraints can we improve stellar models to better understand physical processes across a broad range of scales, from the factors influencing the appearance of our own Solar neighbourhood, back to conditions in the most extreme environments in the early Universe.

Fig. 1: *Artist's concept of two neutron stars at the moment of collision, a catastrophic event probably producing short gamma-ray bursts. (Credit: Dana Berry / SkyWorks Digital, Inc.)*

Some of the key questions regarding the nature of stars and their impact on other areas of contemporary astronomy are presented below, including identification of some of the future facilities needed to address them. They are explored in three stages that stars navigate through their lives: formation and youth, their main-sequence lives and evolution, and their ultimate demise leading to the formation of compact remnants.

Stellar Birth & Youth

Stars spend most of their lifetime on the main sequence, but the physical processes at work during their childhood determine their properties, evolution and eventual fates. Stars form from the interstellar medium in dense molecular clouds. Over a process that lasts but a few million years, they inherit their mass and spin, build their planets, and fire-up their dynamos.

The step-change in studies of Galactic star-formation have been wide-area surveys in the near-IR (UKIRT, VISTA), optical (INT, VST, DECam, *Gaia*), and at longer wavelengths (*Herschel, Spitzer*) for an overarching picture of the gas and dust properties. These have been supported by studies of molecular clouds in the Galaxy and beyond (with e.g. IRAM-30m, APEX, JCMT), revealing the filamentary nature of many structures. Molecular rotational lines trace kinematic components and map the signatures of dynamic chemistry, as well as revealing places where reduced shielding means that some gas is not detected in maps of carbon monoxide.

Key questions to progress the field include:

- How do molecular clumps fragment?
- What effect does the local magnetic field have on collapse?
- How do stars accrete material?

- What sets the upper mass limit of a star?
- Is the initial mass function (IMF) universal?
- What is the relationship of the IMF to the core mass function?
- What sets the initial multiplicity of stars, and how does this impact the IMF?
- How do young stars and their disks set the properties of nascent planetary systems and their early evolution?
- What chemical pathways are important in the production of complex organics?

Multi-wavelength observations of a multitude of star-forming environments (in terms of mass, density, metallicity, etc.) are required to tackle these questions, as outlined below.

Transforming interstellar gas into stellar embryos: challenges & future facilities

Large single-dish facilities (e.g. IRAM-30m, JCMT, LMT) are vital to trace the properties of the extended, low surface-brightness, dense filamentary structures where stars are forming under the combined effects of gravity, magnetic fields and turbulence (complementing mapping with the ALMA Compact Array). However, limited spatial resolution and mapping speed at mm/sub-mm wavelengths with the largest dishes is now motivating study of a large aperture antenna (AtLAST) equipped with highly multiplexed detectors with a large (>1 sq. degree) field and operating at high frequencies.

On smaller spatial scales, the development of ALMA and the JVLA has opened new horizons in tracing the dense, cold structures in the Milky Way and transforming many of the long-standing paradigms of star formation. ALMA's exquisite resolution and sensitivity at mm/sub-mm wavelengths makes it the facility of choice to investigate the close environments of protostars, tracing both the mass accretion processes and the locations where planets form. The planned ALMA upgrades (larger bandwidths, new receivers) will enhance its capabilities to hunt for chemical complexity and the physical interplay at work during the star and planet formation process, including stellar multiplicity.

In the coming years, ALMA and NOEMA will measure the core-mass function and gas dynamics in large samples across a range of environments, and in distant regions where single-dish facilities cannot resolve the characteristic core scales. Alongside this, *JWST* will obtain unprecedented observations of young stellar objects (YSOs) down to planetary mass objects in nearby star-formation regions and in lower-metallicity environments such as the Magellanic Clouds. Variability studies to probe the physics of accretion onto protostars have been significantly advanced with surveys from VISTA (VVV, VVVX), with contributions from other facilities such as JCMT and *XMM-Newton* . The future focus of such time-domain studies will be VRO/LSST (alongside ZTF in the north), complemented by e.g. X-ray studies of T Tauri stars, M dwarfs, and planet-hosting stars.

To understand the chemical content and physics of star-forming gas in the progenitor dense cores requires far-IR observations. Some of the most important gas coolants have transitions in the far-IR (and sub-mm), including lines from [CII], [NII], [OI] and [OIII], as well as transitions from warm molecular gas (H_2O, CO) that are inaccessible from the ground. In particular, far-IR spectroscopy is needed to address the dust properties and chemistry in dense structures and the interstellar medium (ISM), supported by investments in laboratory astrophysics to be sure that we can meaningfully interpret the observed features. Such observations require a large, sensitive far-IR space observatory (e.g. the *Origins Space Telescope* concept). Sensitive X-ray observations (*XRISM, Athena*), when coupled to models built from irradiation laboratory experiements (e.g. large facilities such as SOLEIL), will allow us to probe the crystallinity, composition and size of the dust in the relatively dense (10^{23}/cm^2) interstellar medium (ISM).

To directly compare the structures of the cores and gas, as well as the spatial distribution of YSOs (using statistical tools) we need to match the angular resolution from ALMA at IR wavelengths. This requires the angular resolution of the European Extremely Large Telescope (ELT) and its near-IR (MICADO) and mid-IR (METIS) instruments to probe, e.g., the pristine stellar mass function of heavily embedded star-forming regions for a key test of the IMF.

The full reward of ambitious future facilities will only be secured if also supported by significant computational efforts. For example, high-resolution MHD models to obtain predictions from the scales of molecular clouds down to stars and their protoplanetary disks. Only with such comprehensive models, for a range of initial conditions, can we describe the interleaving of different physical processes to determine stellar properties at birth. Future large datasets will also require analysis with data-mining tools and machine-learning techniques to track the fragmentation and evolution of cores, to feed into the theoretical framework within which to interpret the observations. The ISM is dynamic with enrichment from stellar winds and outflows, and evolving temperature, gas state and density, possibly mediated by magnetic fields. The interpretation of observations relies on time-dependent astrochemical models to reflect the evolutionary state of the regions under study.

Moreover, the analysis and interpretation also needs to be supported by efforts to produce the required laboratory data. This is especially important and challenging regarding experiments to constrain dust emissivities and scattering, irradiation experiments in astrophysical ices to set-up the chemical complexity (from stellar environments down to planets), and laser experiments to study the physics occurring in shocks, which may be key to set the ionisation conditions around young stellar jets.

Role of magnetic fields: star-formation, young stars and their disks

The importance of magnetic fields in star formation and early stellar evolution remains unclear. The first complete map of magnetic fields in the Galactic environment came with *Planck*, but we have only recently had the sensitivity to magnetic fields on a variety of size scales. Facilities such as JCMT, SMA and ALMA have produced the first maps of magnetic fields threading from cloud scales down to individual protostellar cores, tracing the importance of magnetic support over orders of magnitude in density, temperature and pressure. These ground-breaking observations have revealed strong hints of a star-formation process where magnetic fields play a key dynamical role in transporting angular momentum from the core to the central star, hence potentially influencing the spin of new-born stars and therefore their internal structure. Moreover, recent interferometric observations of young stars with VLTI-GRAVITY have revealed the presence of accretion funnels, indicating that the strong stellar magnetic field disturbs the disk and controls accretion. It seems clear that magnetic fields play an important role at these small scales in reproducing the properties of both young stars (spin, multiplicity) and their protostellar disks (sizes, dust evolution). Polarised dust emission at thermal-IR and mm wavelengths and observations of scattered light at near-IR wavelengths (e.g. with VLT-SPHERE, VLTI-GRAVITY+) have also provided new insights into dust properties, disk structure and evolution, and planet formation.

In the coming decade, current and future polarimetric facilities (e.g. SPIROU, NOEMA, ALMA, SOFIA, SKA) will be used to provide large surveys of the magnetic fields at disk and envelope scales. A critical gap in our ability to map the magnetic fields of these processes is where the dense medium mediates between the scales probed by these surveys and the *Planck* results. This can be filled by a sub-mm/far-IR large single-dish telescope probing magnetic fields at the typical scales of cores to clouds (e.g. the *Origins* and *Millimetron* concepts).

Despite great progress in the mapping of magnetic fields in star-forming structures in the last decade, a key question remain as of how to probe them in the deeply embedded, warm regions surrounding protostars, and in protoplanetary disks. Putting constraints on magnetic fields at disk and stellar-surface scales is key for example to set strong constraints on MHD models to extract angular momentum and regulate mass-accretion rates during star formation. Measuring the magnetic fields in disks is key to understanding disk-winds and their relationship to early stellar and planetary evolution. Mid-IR polarimetry on large telescopes could help make substantial progress in capturing magnetic fields at work in the warm dust around young stars, but there is no polarimetric capability on *JWST*-MIRI, nor planned for ELT-METIS. Another promising avenue to explore, yet still under-developed, would be to measure (proto-)stellar magnetic fields directly via the Zeeman effect in astrophysical molecules. Circular polarization observations of spectral lines from the near-IR to the millimetre wavelengths can assess the nature and role of magnetic fields in disks and their host stars, allowing breakthroughs regarding their intertwined evolution through the magnetic field that threads them. Mid-IR polarimetry would also provide unique information on the size and shapes of the dust grains populating the youngest disks (from which protoplanets form), complementing *JWST* that will probe the ice composition by absorption spectroscopy at these scales.

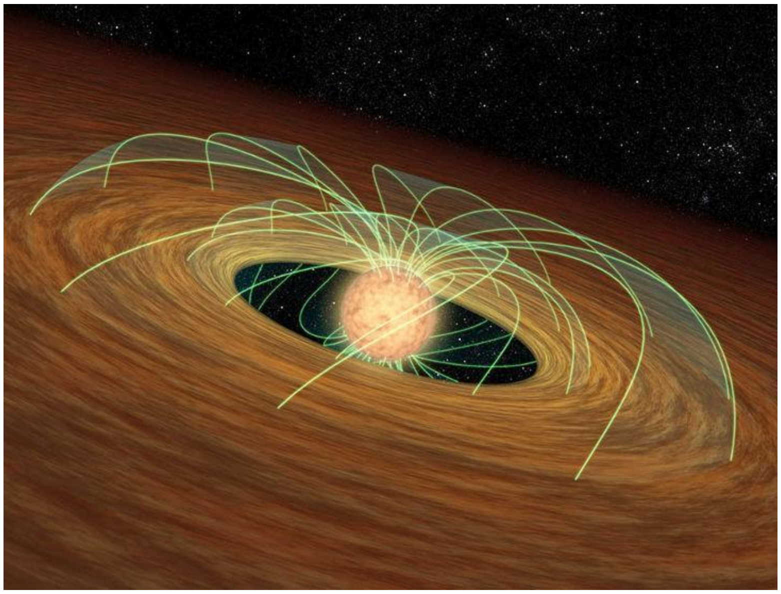

Fig. 2: Artist's concept of a young star connected to its dusty planet-forming disk by magnetic field lines, potentially braking the star's rotation. (Image credit: NASA/JPL-Caltech.)

Star formation in the exoplanet context

Increasing observational evidence suggests that planet formation has already started as early as 1-2 Myr into the star-formation pathway, much earlier than previously thought. For example, disks around T-Tauri stars (and earlier evolutionary stages) observed with ALMA in different star-forming regions show structures suggestive of ready-formed Jupiter-like planets, and may have revealed dust reservoirs that are too small to form the observed population of exoplanets. The study of star-disk systems will be key to our understanding of early planet formation and evolution (see chapter on Planetary Systems), as well as our understanding of the early evolution of pre-main sequence stars.

The chemical composition and orbits of planets are inherited from the properties of their parent protoplanetary disks, a focus for the coming decade will be large studies of young protostars and their circumstellar material. The chemistry, dust composition, and interaction of disks with their host stars will be scrutinised to assess how planets acquire their mass and composition. Facilities such as *JWST*, JVLA, ALMA ELT, SKA, VLTI (including GRAVITY+), the Europen VLBI Network (EVN) and the ngVLA will have complementary roles in characterizing the star-disk system at the unprecedented scales needed to study exoplanets around main-sequence, solar-type stars in the Milky Way. Combined near-IR to mm observations of disk structures, such as spirals or rings, will allow constraints on the physical properties and chemical evolution of both the gas and dust. The large collecting area and time sensitivity of the next generation of X-ray spectroscopy (e.g. *Athena*) will allow us to observe the detailed atomic lines and probe the magnetic reconnection events between T-Tauri stars and their disks. This is the key to constraining the physico-chemical conditions in planet-hosting disks, as the X-ray ionisation and heating also has significant consequences on the stellar spin, the disk cosmochemistry, and potentially also on planet migration.

Direct imaging of protoplanets at infrared and sub-mm wavelengths will become more common with high spatial resolution observations, with radio emission providing one useful diagnostic of star-planet interactions (e.g. LOFAR, SKA). However, most Earth-like planets may well form at smaller separations (<1au) from their host stars, making them difficult to detect (especially early on). For such systems, only interferometry or indirect signatures of planet-disk-star interactions in time-series observations may reveal their presence.

Another topical area is the study of brown dwarfs and planetary mass objects in Galactic star-forming regions to examine the boundaries and formation mechanisms of these different object classes (e.g. with IR surveys from the ground or space, such as VISTA, *Euclid,* and *JWST,* as well as LOFAR and SKA). For instance, dynamical evolution may lead to mass segregation and with precision photometry, astrometry and spectroscopy we can potentially estimate the number of planetary mass objects in interstellar space.

Stellar Evolution

Stars span a vast range in mass, from brown dwarfs (less than 0.1 M_{Sun}) with just enough hydrogen to begin nuclear fusion, to over 100 M_{Sun}, where they burn through their fuel in just a couple of million years. In the past decades we have studied the physical details of individual stars throughout the Milky Way, out into our neighbouring galaxies (such as the Magellanic Clouds) and even further out into the Local Group of galaxies.

Stars provide us with unique laboratories to address some of the biggest, unanswered questions in modern astrophysics, such as:

- What are the basic constituents of matter?
- What happens to matter in extreme conditions?
- What external factors influence the conditions required for life on planets?

Stellar evolution is a mature subject but there are significant gaps in our understanding that limit our interpretation of the latest observations. Given the broad scope of the topic, it is not possible to be comprehensive in this report; here we highlight four prominent areas of active research in the field that are driving the development of facilities in the coming decade and motivating those beyond.

Stellar atmospheres

The study of stellar atmospheres is required to determine the basic physical properties of stars, such as their temperatures, surface gravities, magnetic fields, radii and chemical composition. Such parameters are generally estimated from analysis of the spectral lines formed at various depths in the atmosphere. Observations at high signal-to-noise and high spectral resolution and from a diverse set of wavelength ranges are required to glean the maximum information from the cores and wings of spectral lines to calibrate stellar models, which can then be used at larger distances and to fainter magnitudes with less optimum observations.

At the same time, modern high-angular resolution techniques such as extreme adaptive optics or interferometry (e.g., at VLT and VLTI) allow astronomers to resolve the stellar surfaces of the larger stars on the sky, revealing the complex atmospheric structures of supergiant stars, as well as their strong and spectacular temporal dependency. Streamlining and further improving these advanced imaging techniques that are pioneered by Europe will allow us to expand existing studies beyond just a handful of objects, and to further time-dependant analyses. These will undoubtedly shed new light into the physical and dynamical properties of stellar surfaces, allowing important observational constraints at the interface between stellar interiors and stellar winds.

Another key goal for atmospheric models is to understand the complex vertical structure of the convective motions and their efficiency in producing the stellar spectra we observe. For instance, M-type dwarfs represent about 70% of the total Galactic population. High-resolution spectroscopy (e.g. ELT-HIRES) will provide robust constraints on 3D magneto-hydrodynamical models of their atmospheres, testing our understanding of convection, magnetism, and the mass-luminosity relation at different metallicities. High-quality spectroscopy will be similarly important for new insights into the impact of rotation, magnetic fields, and chemical enrichment at higher stellar masses.

The physics of stellar interiors

We still have a limited grasp of the fundamental mechanisms in stellar interiors (e.g., convection and transfer of angular momentum), and numerical simulations struggle to reproduce the physical conditions. For example, hydro-magnetic instabilities can appear that drive the system to a turbulent, possibly self-organized state that can account for many of the features we observe in stars, from winds to stellar cycles and flares. High-resolution, multi-dimensional simulations are needed to study these processes from first principles, to arrive at formulations that can be implemented in stellar evolution codes to then follow the full secular evolution of the stars.

Stars also provide us with unique laboratories to study the assembly of the elements by nucleosynthesis. By studying different populations of stars in the Milky Way and other galaxies we can learn about the temporal evolution of chemical abundances of key elements, both from spectroscopy and photometry (where the location of stars in colour-magnitude diagrams is influenced by their internal chemical profiles). Moreover, ongoing underground experiments (e.g., LUNA) are investigating critical nuclear reactions of astrophysical interest for stellar evolution and cosmic nucleosynthesis.

New facilities in the next decade will deliver unprecedented, high-quality datasets of stellar spectra (e.g., 4MOST, WEAVE, MOONS, MSE), magnitudes (e.g., LSST/VRO), and studies of stellar oscillations (e.g., *TESS, PLATO*). These data will potentially lead to fundamental changes in our prescriptions of how stars evolve, for instance:

- Which phenomena most influence surface and interior chemical composition?
- What is the interplay between radiation and convection in stellar interiors?
- How does material mix and diffuse inside the stellar interiors and up to the surface?
- What are the evolutionary timescales across different masses, chemical compositions and evolutionary stages?

The challenge is to derive robust physical prescriptions that explain the observed properties, but analysis of such data is only as good as the available tools and models.

In this context, laboratory astrophysics is the bedrock of stellar research. There remain significant uncertainties in areas such as reaction rates, molecular physics, line opacities, precise wavelengths, PAH characteristics, and more. We also highlight the need for sustained investment in the high-performance and high-throughput computing for theoretical models. Moreover, large-scale distributed computational resources (and cloud computing) have become essential to study and efficiently interpret the tremendous volume of data from the latest space and ground-based surveys.

Stellar winds and chemical enrichment

Stellar winds and outflows are a fundamental process through which stars contribute kinetic energy and chemically-processed material into the interstellar medium. There remains much to learn in our understanding of the mass-loss and winds from stars of all masses. High-resolution numerical simulations are being used to explore the complex physics involved in the dynamical evolution of stars, from low-and intermediate-mass stars on the red giant branch (RGB) and asymptotic giant branch (AGB), up to the physics and evolution of massive OB- and Wolf-Rayet type stars that ultimately explode as supernovae.

In massive stars there remains much to understand regarding the stratification and intensity of stellar winds, particularly at low metallicities. Only with a firm grasp of these properties can we correctly interpret the integrated-light observations of star-forming galaxies in the distant Universe. Multi-wavelength observations from X-rays (e.g. *XMM-Newton, Athena*) to radio (e.g. EVN) are required characterise these outflows, with longer-wavelength studies particularly important for studies in obscured Galactic clusters (e.g. ALMA, SKA, EVN).

Studies in the Magellanic Clouds provide us with a window into the lower-metallicity regime (e.g., the ULLYSES programme with *HST*) but a long-standing goal is for optical and ultraviolet spectroscopy of massive stars in more distant systems, that have closer to primordial abundances (e.g., Sextans A, Leo A, and beyond out to I Zw 18). Increased sensitivity with current facilities will be important to study such populations beyond 1 Mpc (e.g., BlueMUSE, CUBES) but ultimately an ambitious UV/visible space-borne capability is critically required to succeed the *HST*, such as the Large UV/Optical/IR Surveyor (LUVOIR) concept.

Less spectacular but equally important are the contributions from lower-mass RGB and (post-)AGB stars to the ISM. Improving our understanding of their mass loss and winds requires sensitive IR, millimetre and radio observations. Moreover, in the last stages of their lives, as nuclear fuel in their cores is depleted, many stars move into giant or supergiant phases with extended low-surface gravity envelopes and relatively cool surface temperatures. These conditions radically change the characteristics of the stars as the conditions become favourable for the formation of molecules, such as carbon or silicon monoxide, and the condensation of refractory elements into dust. The molecules and dust particles reflect the chemical composition of the stellar envelope and are ejected into the interstellar medium, enriching it in processed materials.

The detailed composition and physical properties of interstellar dust remain uncertain, but it appears that stardust is regenerated in the ISM and reflects the local element abundances. Beyond the properties of the dust itself, a detailed understanding of how dust evolves with the Universe is important in the context of how it affects circumstellar disks and the building blocks of planets. Its properties are also imprinted in interstellar extinction, which impacts nearly all astronomical observations. For instance, dust formed in supernova ejecta may be an important component of the infrared emission seen in high-redshift galaxies, and understanding its composition and how much material condenses into the solid phase at different stages of supernova evolution is the key to interpreting observations. Spectroscopic (and, where possible, spectropolarimetric) measurements of dust emission and absorption features to probe dust properties and their environmental dependence will exploit facilities such as *Spitzer, JWST,* VLT and ELT.

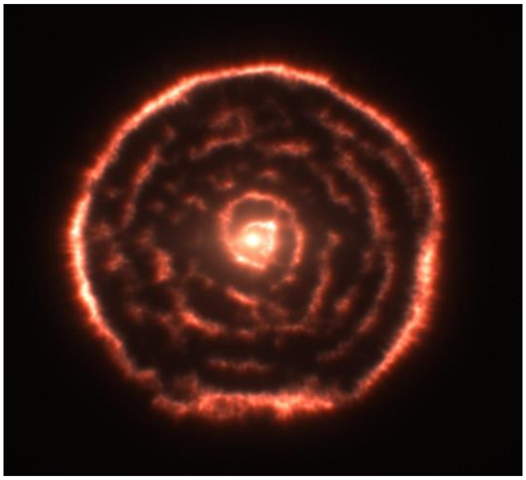

Fig. 3: Observations using the Atacama Large Millimeter/submillimeter Array (ALMA) have revealed an unexpected spiral structure in the material ejected by the old star R Sculptoris. Credit: ALMA (ESO/NOAJ/NRAO)/M. Maercker et al.

Multiplicity

Many low-mass stars, and the majority of stars at least as massive as our Sun, are paired with at least one other star in a binary or a higher-order multiple system. Their orbital properties are remnants of the pairing mechanism during formation and their early dynamical evolution. These multiple systems offer unique diagnostics to precisely measure some of the fundamental properties of stars, such as their masses and sizes. In addition, as a result of the secular expansion of stars as they age, stars in close binaries will exchange mass and angular momentum with their companions and may even merge. This dramatically alters the evolution of both stars, and the nature and properties of their end states. This leads to a plethora of complex physical processes that remain insufficiently understood but that dramatically impact the outcome of stellar models and the predicted properties of entire populations of stars across cosmic time. It is worth noting that while the majority of stars are in multiple systems, most of the studies of exoplanets and exoplanet formation (e.g. via disk studies) are being carried out in single systems, which are not generally representative of the whole population.

Large observational samples of pre-interaction, interacting, and post-interaction binaries across a broad range of mass, age and metallicity are required to map the initial conditions and study the physics of the interaction and characterise its outcome. Such strong observational constraints are needed to phenomenologically connect evolutionary stages within the binary evolution paradigm, as well as to guide the development of models and confront their predictions. Significant multi-epoch photometric, spectroscopic and astrometric observational efforts are needed to characterise their orbital, physical and surface abundance properties. Some of the data will be provided by missions such as *Gaia, TESS* and *PLATO,* but a similar-scale spectroscopic effort in the form of a large-aperture spectroscopic telescope is missing, especially if we are to push the metallicity barrier beyond that of the Milky Way. Interferometric observations (e.g. EVN, VLTI, GRAVITY+) will also be required to directly charaterise stellar and substellar multiple systems in unpredecented detail.

Full integration of multi-messenger astrophysics in the constraints of single and binary evolution will be an important cornerstone of research in the coming decades. Alongside new observations, fundamental theoretical work is required to improve our understanding of the complex physics in binaries, to predict the evolution and final fates of entire populations of stars, and to investigate the interplay between stellar evolution and stellar dynamics in higher-order multiples (e.g. via detailed binary evolution models as well as population-synthesis models that include binary evolution and, possibly, stellar dynamics). At the same time, better predictions are needed regarding the formation channels of compact objects, and their contributions to the stochastic astrophysical background, to properly interpret the large number of GW signals that will be detected by the next generation of GW-interferometers both on (or under) the ground (e.g. Einstein Telescope) and in space (e.g. *LISA*).

Stellar death

The evolution of stars depends primarily on their initial mass, and undergoes a major bifurcation around 8-10 solar masses. Stars with masses above this boundary will end their lives in core-collapse supernovae, leaving behind neutron stars and black holes; those with lower mases have a less violent destiny, and their cores will eventually become white dwarfs. Our understanding of these different classes of compact, extreme objects has grown considerably over the past decade from comprehensive multi-band study of the transient sky and the availability of GW interferometers. We now briefly expand on each of these topics in more detail.

White dwarfs

White dwarfs are Earth-sized stellar embers in which the pressure of degenerate electrons balances gravity. Because of their short lifetimes, most A/F-type stars formed throughout the history of the Galaxy have already evolved into white dwarfs. As such, white dwarfs play an important role across a variety of areas in astrophysics (including exo-planets, as discussed in the chapter on planetary systems). Key questions include:

- What are the progenitors of type Ia supernovae?
- What is the Galactic low-frequency GW background?
- What is the ultimate fate of planetary systems orbiting stellar remants?

Stellar evolution & fundamental physics

Homogeneous samples of white dwarfs with accurate physical parameters are essential to constrain and calibrate stellar evolution theory, e.g. mass loss on the asymptotic giant branch (important for the initial-to-final mass relation), internal rotation profiles and loss of angular momentum, and fundamental nuclear reaction rates, as well as having important implications for stellar population synthesis and galaxy evolution theory. Given their well-constrained cooling ages, white dwarfs can be used to estimate the age of the Galactic disc, open clusters and globular clusters, and can potentially trace variations in the Galactic star-formation rate.

Given their extreme densities, white dwarfs also provide excellent cosmic laboratories for the behaviour of matter under extreme conditions, including non-ideal plasma effects, first-order phase transitions, and detailed atomic physics in magnetic fields that are many orders of magnitude beyond capabilities on Earth.

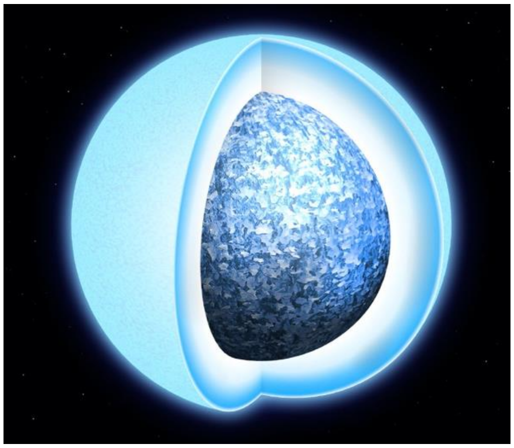

Fig. 4: White dwarfs no longer undergo nuclear fusion, hence their luminosity is powered by their thermal energy content. Eventually their cores will crystalise, releasing latent heat. Photometry and astrometry from the Gaia mission has provided direct observational evidence for this part of this first-order phase transition.
Credit: Mark Garlick/University of Warwick.

White dwarfs in binaries: progenitors of SNIa & low-frequency GW sources

A significant fraction of local white dwarfs are members of binaries, providing a benchmark population to investigate complex interactions. White dwarf binaries are the progenitors of type Ia supernovae - the cosmic distance beacons that led to the discovery of dark energy – but the details of the evolutionary paths leading to these thermonuclear explosions are still poorly understood. Short-period double white dwarf binaries are powerful emitters of low-frequency GWs but we do not know their space density and period distribution very well, and such systems may well define the Galactic background level for the *LISA* mission. Finally, white dwarfs with precise cooling ages in wide binaries can also be used to calibrate main-sequence ages.

White dwarf science over the next decade

White dwarfs are intrinsically faint and difficult to distinguish from more distant main-sequence stars with similar colours. Most known white dwarfs were identified as ultraviolet-excess objects and are young (<1Gyr) and hot (Teff>10,000K), and are not representative of the Galactic population as a whole. *Gaia* DR2 and eDR3 finally provided the parallaxes needed to break the degeneracy between nearby white dwarfs and background main-sequence stars, enabling assembly of the first unbiased all-sky magnitude-limited (G≈20) sample of 260,000 white dwarf candidates.

While the *Gaia* data are sufficient to identify white dwarfs with high confidence, follow-up spectroscopy is required to determine their physical properties (temperature, gravity, composition, magnetic-field strength, multiplicity) and derive their fundamental properties (mass, cooling age, progenitor mass). Multi-object spectroscopic surveys are key to this follow-up, e.g. ongoing surveys with SDSS-V and DESI and in the future with 4MOST, WEAVE, MSE. Multi-epoch spectroscopy is also critical to identify a large, representative sample of short-period double white dwarf binaries. This sample will both guide the development of accurate theoretical models of SN Ia progenitors, as well as establish a suite of calibration targets for the *LISA* mission.

Finally, pushing deeper than *Gaia*, VRO will identify several million white dwarfs, in particular extending the population of cooler and older white dwarfs to a larger volume that will provide new insights into the history of the Galactic star-formation rate.

Neutron stars

Neutron stars are born in the core-collapse supernovae of massive stars, as well as via accretion-induced collapse and binary mergers. They are unique laboratories to study the most extreme phases of matter. We can probe the extremes of gravity and electromagnetism, and the strong and weak interactions in regimes that we have no prospect of exploring on Earth.

The neutron-star population is dominated by radio pulsars, but also includes several extreme and puzzling subclasses such as magnetars, X-ray dim isolated objects, accreting systems with a large variety of companion stars, and more. Nearly 3000 neutron stars are now known in different systems and environments: isolated or in binaries, in twins of double neutron stars, in the Galactic disk, in globular clusters, and in other nearby galaxies. Their extreme gravitational, rotational and magnetic energy are fuel for the diverse emissions from neutron stars, which encompass all multi-messenger tracers: electromagnetic waves, cosmic rays, neutrinos, and GWs. We therefore require a multidisciplinary effort that spans from particle and nuclear physics to astrophysics, from experiment to theory, and from the electromagnetic spectrum to GWs.

Outstanding questions on the nature of neutron stars include:

- What is the equation of state that relates the pressure and density in their interior?
- How do their strong magnetic fields form at birth? How are they ordered in a dipolar field component?
- What are the progenitor stars of the different neutron-star classes?
- Which neutron stars are formed via accretion-induced collapse or binary mergers?
- How do pulsar winds interact with the local environment to form powerful pulsar wind nebulae and accelerate particles up to TeV energies?
- How is their radio emission produced?
- How do they accrete material from companion stars and produce outflows?

Magnetars

This small group of X-ray (and sometimes also radio) pulsars are among the most puzzling neutron stars. Their strong X-ray emission is too high and variable to be fed by rotational energy alone (as in typical radio pulsars) and with no evidence for a companion star that could be contributing via accretion. They are the most strongly magnetized neutron stars, where there fields may form via a dynamo action in the fast-rotating proto-neutron star, via magnetorotational instabilities within the highly convective stellar core or, alternatively, they could be remant fossil fields from a highly magnetic massive star progenitor (with ~1kGauss).

The emission from magnetars is thought to be powered by the decay and the instability of their strong magnetic fields. As well as persistent X-ray emission, magnetars emit peculiar flares and outbursts on several timescales (from fractions of a second to years) emitting large amounts of energy (10^{40}-10^{46} erg; the most energetic Galactic events after supernova explosions). These flares are caused by large-scale rearrangements of their twisted magnetic field, either accompanied or triggered by neutron-star crust movements (similar to stellar quakes). These extreme neutron stars are believed to be strongly related to some of the transient objects discussed below, namely super-luminous supernovae, gamma-ray bursts (GRBs) showing plateaus in their afterglows, and fast radio bursts.

Physics of accretion & fundamental physics

The accretion of matter from a companion star onto a neutron star (or a black-hole) produces X-ray luminous systems that are observable at extragalactic distances in some cases. We know several thousand high- and low-mass X-ray binaries in the Milky Way, the Magellanic Clouds and beyond. Some of these binaries are spun-up to extremely short spin periods (of milliseconds) by the accretion. Understanding how such neutron stars are spun-up and how fast they rotate, gives immediate constraints on the neutron star equation of state. The possibility of detecting continuous GWs from such systems also depends on the maximal spin that can be reached and the deformation of the neutron star. To address such topics we need high-sensitivity telescopes such as *XMM-Newton, Chandra,* and the significant gain in X-ray capabilities that *Athena* will provide. Alerts from all-sky monitors and high-cadence monitoring (e.g. *Swift/XRT* in X-rays, MeerKAT in the radio) are also critical.

Rotationally-powered pulsars (particularly those with millisecond periods) also provide us with exceptionally precise astronomical clocks that can serve as unique laboratories for tests of fundamental physics. For instance, the ‘pulsar timing array’ is a set of pulsars used as a Galactic-scale interferometer to look for GWs from binary supermassive black holes and the centre of galaxies, neatly complementing efforts from ground-based GW detectors (and *LISA* in the future). Pulsar-timing arrays depend on high-cadence measurements with radio telescopes such as Nançay, Effelsberg, MeerKAT, GBT and FAST. Unveiling the total Galactic population of radio pulsars (anticpated to be in the tens of thousands of sources) will be significantly progressed by the SKA (and in the shorter term by MeerKAT and FAST). An exciting question here is whether we can find examples of sub-millsecond pulsars, that would provide even more exquisite constraints on neutron-star structure, or pulsar – black hole binary systems that would enable unprecedented tests of general relatively. At the same time, low-frequency pulsar searches (e.g. LOFAR) and targeted high-frequency searches (e.g. MeerKAT searches of the Galactic bulge and centre) can help us achieve a less biased view of the Galactic pulsar population.

Pulsar wind nebulae

Neutron stars lose the bulk of their rotational energy via pulsar winds. These are ultra-relativistic outflows of electrons and positrons for which we have few constraints at present. These winds impact the local environment and are eventually halted by the ISM (and the blast wave of the supernova remnant shock that earlier generated the pulsar) or by a more dramatic interaction with a close binary companion. These mechanisms yield different classes of nebulae, which can provide insights into the formation of their pulsars, the electrodynamics of the magnetized rotators, how the magnetospheres generate the wind, the acceleration of leptons up to very high energies (and their energy distribution), and how these impact on the surrounding ISM. Pulsars and their wind nebulae allow study of plasma-field interaction processes in conditions far beyond what is achievable in the lab. In this context, neutron stars and their environments will be the largest source class for next-generation facilities such as the CTA and SKA.

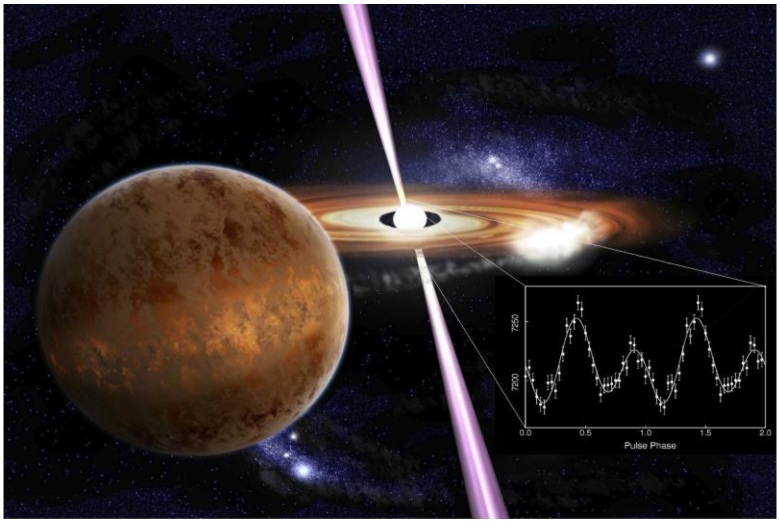

Fig. 4: Artist's impression of PSR J1023+0038, a binary system composed of a neutron star that tears matter from a companion star with the formation of an accretion disk, and emits pulses of visible light. Credit: https://nathaliedegenaar.files.wordpress.com/

Stellar- and intermediate-mass black holes

Stars more massive than ~20 solar masses are thought to collapse to black holes when exhausting their nuclear fuel. In such massive objects not even the neutron degeneracy pressure and strong force that sustains neutron stars can counteract the gravitational forces and nothing can halt the collapse. This process is expected to give birth to one of the most intriguing astrophysical objects: a black hole.

Black hole theories flourished in the 1960s and the first astrophysical example of such an object (Cygnus X-1) was identified in 1971 from the observation of a large amount of X-rays from a star orbiting an invisible compact object. The X-rays are from gas stripped from the star and heated to high temperatures while spiraling onto the hidden object, which was later estimated to have a mass greater than five solar masses, thus ruling out a neutron star. Since the discovery of Cygnus X-1, several similar accreting but otherwise invisible objects (with masses between 5 and 20 solar masses) in binaries have been observed in the galaxy, which are considered as stellar-mass black holes. However, the limited number of detections over several decades leaves many questions:

- Are these objects really the black holes described by general relativity?
- How common are they, and how do they form?
- Do intermediate-mass black holes exist beyond the stellar mass range?
- Is there a mass gap between neutron stars and black holes (and within BHs)?

The pioneering GW results from LIGO and Virgo have finally provided some answers to these questions. Compact binaries of neutron stars or black holes emit gravitational distortions that can be detected by GW interferometers when they merge to form a bigger black hole. The detections of more than 50 merging compact binaries to date have transformed the field. Merging black holes are found to be quite common and span a wide range of masses. We have now detected black holes as massive as 160 solar masses, some of which challenge the standard proposed formation channels for such objects. Studies of the gravitational waveforms have allowed spectacular tests of general relativity in the strong-field regime, thus far confirming theoretical predictions.

It is still early days for the GW field however. In the next few years the ground-based detector network (including LIGO, Virgo, LIGO-India, and KAGRA) will reach design sensitivities, detecting hundreds of such objects per year up to large cosmological distances. By the end of the 2030s, third-generation detectors (the Einstein Telescope in Europe and Cosmic Explorer in the US) will allow us to see black-hole binaries essentially everywhere in the Universe. This will allow us to reconstruct their origin in connection with stellar and binary evolution and, hopefully, to answer (some of) the questions outlined above. For example, detection of nearby binaries at high signal-to-noise will allow us to probe the ringing modes of the newly formed black holes, which carry the fingerprint of its geometrical structure, thus allowing tests of general relativity with unprecedented precision. The improved sensitivity of the new instruments will enable objects up to several thousand solar masses to be observed, testing the existence of intermediate-mass black holes. In short, our journey in the understanding of astrophysical black holes has just started and the future promises to be rich with new discoveries.

Stellar death and the transient extra-galactic sky

Our understanding of the violent and explosive Universe has been revolutionised in the last decade with the development of time domain sky surveys. Wide-field photographic sky surveys were replaced with multi-colour optical and near-infrared digital coverage of the whole sky. These surveys are now on repeat and have opened up the time domain for exploration. A series of wide-field surveys with 20cm to 2m telescopes covering most of the visible sky every few nights have discovered a remarkable diversity in how stars explode and die. Until 2010, our understanding of the transient sky was dominated by the normal supernova populations of type Ia from white dwarfs, type II from massive, hydrogen-rich supergiants and the type Ibc from massive stars that have been stripped of their hydrogen envelopes. GRBs were characterised into short and long, with the long events securely associated with energetic supernovae, potentially from Wolf-Rayet stellar progenitors. The tremendously bright afterglows of GRBs (with some at $z > 6$) allow the high redshift Universe to be probed through absorption line systems and identification of their host galaxies.

The novel optical surveys and rapid, multi-wavelength follow-up have discovered super-luminous supernovae, which are 100 times more luminous than normal core-collapse supernovae and seem to be predominately produced in very low metallicity galaxies (perhaps from ultra-massive stellar progenitors). Candidates for pair-instability supernovae have been discovered, along with very faint and fast transients that do not yet have an accepted explanation. The debate around the progenitor systems of type Ia supernovae (white dwarfs exploding due to a merger event or accretion from a companion) has widened to question whether the white dwarf really is of Chandrasekhar mass and how the wide diversity in thermonuclear explosions can be explained. Several transients with relativistic outflows, but no GRBs have been found and have been associated with prompt black hole formation. Moreover, in 2017, the first kilonova was found, resulting from the merger of two neutron stars that produced the strong gravitational-wave signal GW170817. This produced a short, faint GRB, non-thermal emission from the X-ray to radio and a kilonova powered by the radioactive decay of heavy elements.

The next decade will explore this rich discovery space, with a key facility being the Rubin Observatory that will start operations in 2023. Its Legacy Survey of Space and Time

(LSST) will be the deepest, most precise, wide-band survey of the sky ever undertaken, and repeat observations and rapid analysis will produce a stream of transient alerts. LSST combined with CTA, LOFAR, SKA, the upgraded LIGO-Virgo-KAGRA network and ultimately *Athena,* will define the future of transient discoveries, and motivate significant optical/IR follow-up with telescopes of all sizes (from small-to-medium class telescopes up to the ELT) and at other wavelengths (e.g. *HST, XMM-Newton, THESEUS* concept).

In the coming years we will be able to use supernovae as precision cosmology probes to measure dark matter and dark energy parameters over a larger volume than previously possible. The physics and diversity of stellar explosions will be unveiled across a wide-range of redshifts and host galaxy environments. Indeed, the statistical samples of transient events with precision photometry will be unprecedented, and combining the LSST alerts with multi-wavelength and multi-messenger signals will be very powerful. For instance, radio and high-energy emission probes shock physics and how stellar progenitors evolved in the last few years of their lives, while also revealing relativistic jets.

Finding the electromagnetic counterparts to GWs will constrain the equation of state of nuclear matter in neutron stars, uncover the source of the heaviest elements and probe black hole and magnetar formation. Sources with both GWs and an electromagnetic signal can then be used for both cosmology (direct measurement of the Hubble constant) and fundamental physics (the equivalence principle, velocity of gravitational waves and modified gravity) with novel methods.

Following their discovery just over a decade ago, the physical origin(s) of fast radio bursts (FRBs) is also a very active topic in the study of astrophysical transients. They are seen to originate in other galaxies (some quite distant) but these incredibly luminous radio flashes are shorter than the blink of an eye and the underlying engine that could power them is still a mystery. There is increasing evidence that highly-magnetised neutron stars could be the sources, but many questions remain. For instance, repeating and apparently one-off FRBs have been discovered – are these produced by same the type of source? Giant flares from magnetars could explain the one-off events, but the periodic activity level of some repeating FRBs could indicate a binary orbit.

Regardless of their physical origins, FRBs have already been shown to be unique probes for extragalactic astrophysics and cosmology as their observed radio waves undergo propagation effects due to the magnetic and ionised material they pass through. This allows us to detect the otherwise invisible gas and magnetic fields within and between galaxies. Wide-field radio telescopes like CHIME/FRB are now detecting multiple FRBs per day, and radio interferometers like the EVN, ASKAP and VLA are capable of providing the (milli-)arcsecond localisation that is needed to robustly associate them with a host galaxy.

Precision Stellar Physics

Our understanding of stellar physics and the accuracy with which we can model stars has now become a limiting factor in other fields. This arises because the computational models used to predict stellar properties as a function of time necessarily focus on limited aspects or have to simplify the relevant physics to obtain the required temporal resolution. These models are used to predict the observed properties of stars at different epochs and environments, to then study the properties of, e.g., exoplanets, galaxies, and the transient Universe. We briefly highlight two topical areas in this regard.

Interpretations of exoplanet observations

Missions such as *TESS*, *CHEOPS*, *JWST* and *PLATO*, together with the ELT, will push the limits of planet detection and characterisation. However, disentangling the planetary and stellar signals is often limited by our ability to accurately model the properties of the host star. The stellar component gives important context for the planetary studies, e.g. age estimates for the systems. Moreover, with the maturing of exoplanet atmosphere spectroscopy, comparing planetary atmospheric abundances with the surface composition of the host star is now a reality. This will provide powerful constraints on planet-formation models, but only assuming we are able to confidently recover a unique set of initial conditions from stellar and planetary models.

Observational cosmology

The tension between estimates of the Hubble constant (H_0) from the near and far universe has survived intense scrutiny. The results can potentially be reconciled by invoking new physics in the standard (ΛCDM) cosmological model, but this extraordinary step would require remarkable trust in the measurements. Improving our knowledge of the stellar standard candles used in late-universe H_0 measurements, combined with better observations, will be critical to either reinforce or disprove the tension.

Distances are notoriously difficult to estimate in astronomy, and stellar physics provides many useful distance indicators. Precision cosmography uses a distance ladder to measure distances up to the Hubble flow (where galaxy velocities are dominated by the cosmic expansion). The ladder’s first rung and anchors are mostly based on stellar indicators such as eclipsing binaries, RR Lyrae, Cepheids, Miras, tip of the RGB, etc. Exquisite observations have led to distances with 1% or better statistical precision, but the underlying hypothesis of standard candles and their models need to be better than 1%. For instance, can all objects in a given class be reduced to a simple model? In other words, when calibrating a given distance indicator in the Milky Way, to what accuracy is this calibration valid in other galaxies (with e.g. different metallicities)? These effects require dedicated observational experiments and theoretical investigations.

These examples are not exhaustive, but they illustrate how observational advances can push stellar physics to be an ever more accurate tool. Data analysis and models that were designed and validated when the estimated precision was of order 10% cannot be readily applied to data with 1% precision. Future progress in this area will need to include:

- Strong connections between stellar physicists and the communities using their results.
- Careful calibration of the models used to derive stellar parameters (abundances, ages, masses, distances, etc) in future large surveys.
- Development of data-analysis techniques scalable to large surveys that also preserve the accuracy of the underlying models.

The Local Group as a laboratory for galaxy evolution

Resolved stellar populations are a powerful tool to study galaxy evolution. In particular, low-mass stars in galaxies are sufficiently long lived that they allow investigation of star-formation histories and evolution of their host systems over cosmic time. This ‘galaxy archaeology’ is an important complement to studies of (unresolved) galaxies at high redshift. The Milky Way provides us with an unrivalled opportunity to study the formation and history of a large spiral galaxy directly, and the vast dataset from the *Gaia* mission is now transforming our understanding of its structure and kinematics.

A vital complement to *Gaia* is ground-based spectroscopy to provide radial velocities (giving space velocities when combined with *Gaia* proper motions) and chemical abundances. The European astronomical community has invested significantly in new, high-multiplex facilities to provide the required spectroscopy (e.g. WEAVE, MOONS, 4MOST). When combined with the *Gaia* catalogues and precise ages from asteroseismology these will provide new insights into Galactic structure and its chemical evolution and past accretion history. A missing capability is the combination of high spectral resolution (R >40,000) combined with high multiplex (VLT-HRMOS), to provide detailed chemical abundances of a wide range of elements to fully disentangle the populations studied by *Gaia*.

Such Galactic archaeology requires determinations of stellar ages and chemical abundances to high precision to identify different stellar populations. To harness the full diagnostic power of the new spectroscopic surveys, as well as high-precision photometry from other facilities (e.g., VRO, *TESS, PLATO*), automatic reliable data analysis will be critical in the determination of fundamental parameters. Such analysis is also only as good as the stellar models available, reinforcing earlier comments on the continued need to improve our understanding of the internal structure and atmospheric properties of stars.

Within this topic, the identification of very low metallicity stars in the Galaxy provides a fascinating probe of early chemical enrichment. The lowest metallicity stars known display very weak absorption lines in their spectra, indicative of heavy element abundances much lower than the solar values, with iron abundances up to a million times lower in the most extreme examples. Models suggest these abundance patterns may reflect enrichment by a single supernova, providing a unique window into the early evolution of the Universe. To expand our understanding of these tantalising objects we need better sensitivity (e.g. CUBES) and larger samples (e.g., within the WEAVE and 4MOST surveys).

Looking to the future, key parts of the Milky Way (centre, plane) are inaccessible to the optical *Gaia* mission due to interstellar extinction. Future plans for the EVN could potentially use stellar masers to probe the dynamics of the inner Galaxy. Longer term, a near-IR mission similar to *Gaia* would provide the same precision astrometry and photometry to unlock the detailed dynamics and populations of these obscured regions (combined with near-IR spectroscopy from MOONS).

In parallel, we have already begun exploring the broad range of galaxies beyond the Milky Way, both in the Local Group (M31, M33, metal-poor dwarfs) and beyond. Such efforts are at the sensitivity limits of our capabilities, but new facilities such as the *JWST* and ELT will provide us with unrivalled insights into the stellar populations and histories of a diverse range of galaxies. For instance, the sensitivity and spatial resolution of the ELT-HARMONI spectrograph will provide spectroscopy of individual red-giant stars in galaxies at several Mpc, allowing evolved stellar populations to be investigated over a significantly greater range of physical conditions for the first time. Longer-term, a priority in galaxies at >1 Mpc is multi-object spectroscopy with the ELT in the visible (MOSAIC), to address the physical properties of massive stars, and the kinematics and chemical abundances of lower-mass evolved stars across the full spatial extent of their host systems.

Summary

Stellar astrophysics is a diverse and vibrant field, spanning studies of low-mass stars in the local neighbourhood, out to dramatic SNe and GRB explosions of high-mass stars at high redshift. It also underpins a broad swathe of studies in contemporary astronomy from exoplanets to the most distant galaxies at cosmic dawn.

Many of the large facilities under construction by European partners have been strongly influenced by cases from contemporary stellar astronomy. These include (but are not limited to) facilities such as the *JWST*, ELT, VRO/LSST, SKA and *Athena*, as well as new instruments on 4m telescopes (e.g. WEAVE, 4MOST), 8-10m telescopes (e.g. MOONS, CUBES), large interferometers (e.g. VLTI), and new, smaller observatories focussing on time-domain science (e.g. GOTO, BlackGEM).

The immediate priority of the community is to complete the construction of these exciting new facilities and instruments and then deliver on the broad range of stellar science that they will enable. Alongside this, there is a continued need for significant investment in theoretical models (and the relevant tools), laboratory astrophysics and machine-learning/data-mining techniques to be able to draw meaningful conclusions from the rich datasets ahead of us. We also need to continue to invest in existing facilities that have unique capabilities (e.g. ALMA, *XMM-Newton*, *HST, Gaia,* VLT/VLTI, GTC, WHT, TNG) to ensure we have the multi-wavelength and multi-technique observations needed.

The large numbers of transient objects expected to be identified by facilities such as VRO and the GW observatories (and GR bursts etc) will lead to increased demand for follow-up obserations at all wavelengths, with both photometric and spectroscopic instruments. Effective follow-up will make use of the full range of telescope apertures; coordination to ensure optimum use of the available observing time will be a challenge.

Looking to the future there are exciting concepts in development that will provide important capabilities to address the topics outlined in this chapter. These include further development of 8-10m class telescopes (e.g. GRAVITY+, BlueMUSE, HRMOS), new spectroscopic survey facilities (e.g. wider European participation in a project such as MSE), a large single-dish sub-mm facility (e.g AtLAST), and an ambitious new UV/visible/IR space observatory (LUVOIR).

These electromagnetic-oriented facilities, supported with the necessary theoretical and lab work, will allow Europe to keep its leadership in stellar astrophysics. At the same time, the existing bridges between EM, multi-messenger and GW astrophysics need to be strengthened, and even integrated, if we are to grasp the full nature of the evolution of stars and of their end products. In that context, efforts to secure the funding and start the construction of a next-generation, large-scale GW observatory under European leadership should be considered as an additional high priority goal for the decade to come.