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PART I

Introduction

1

An Overview of Star Formation

1.1 Introduction

Within our current understanding of star formation as observed through the lens of molecular astronomy, we can identify the following as the most significant areas of contemporary research: prestellar cores, hot cores and hot corinos, accretion and protoplanetary disks, photodissociation regions, stellar jets, disk winds, outflows, and masers. Of course, these sit within the wider considerations of dense molecular clouds on many scales, from the giant molecular clouds (GMCs) to fragments, filaments, and clumps. In turn, our understanding of molecular clouds depends on our understanding of molecular excitation, energy balance, gas and grain surface reaction kinetics, cosmic ray ionisation, and photochemistries. Some of these facets are more appropriate to low-mass star formation regions (LMSFRs), some to their high-mass equivalents (HMSFRs). While theoretical understanding of low-mass star formation (up to 2 $M_\odot$.) is currently quite well constrained, that of high-mass stars (>10 $M_\odot$) is only now emerging with the help of the latest high-resolution telescopes that offer acutely focused observations as well as deep field surveys of multiple sources at great distances.

All the steps along the way to star formation sit in an evolutionary schema that starts in molecular clouds concentrated particularly in the spiral arms of the disks of galaxies such as our own. However, rates of star formation even in the Milky Way differ in different regions. For example, rates are slower in the Taurus clouds, much more rapid in Orion or W3 or W49. Observations show even more vigorous star formation rates in some external galaxies, such as the 30 Doradus region in our close neighbour the Large Magellanic Cloud (LMC), and in more distant ‘starburst galaxies’ such as NGC 253 or Arp 220.

With few exceptions stars form in clusters, in anything from ten to a million or more in relatively close proximity. A cluster of high-mass stars (an OB association) may occupy a volume of space defined by just a few tens of parsecs early on in its main sequence life, but it will progressively spread to cover a region likely to be hundreds of parsecs wide. OB stars burn out in a few tens of million years, having driven apart their clustered near neighbours through radiation pressure, mechanical turbulence, gas dispersion, and rapid reductions in gravitational stability. They also scatter many lower-mass stars whose formation they will have triggered, although these smaller stars linger to evolve much more slowly. We see such distributions in Orion, Upper Scorpius , and Upper Centaurus-Lupus. These local clusters that are still embedded in their parent molecular cloud cores are obviously at an early stage of evolution, shrouded in dust and often observable only at infrared wavelengths. We will look at surveys of such clusters, as well as the examples of Sgr B2, W43, and Orion BN/KL in the High-Mass Star Formation (HMSF) section. Cluster subgroups such as Orion 1a, 1b, and 1c are clear evidence of the recursive nature of sequential, self-propagating star formation in which the impacts of high-mass stars, expanding HII regions, stellar winds, and occasional supernova explosions lead to widespread gas compression and the triggering of fresh star formation. The Trapezium stars are another familiar example in the visible, along with the Pleiades, which mark the current end of a subgroup sequence of formation and destruction.

At its simplest, the evolutionary sequence for low-mass, solar-type stars proceeds from the diffuse interstellar medium (ISM) to dense cloud to collapsing prestellar core to protostellar envelope and accretion disk, before nuclear ignition and a main sequence lifetime ending in a planetary nebula re-seeding the ISM. In contrast, recent statistical analysis of multiple high-mass star formation regions shows quite clearly how the absence of low- and intermediate-mass stars associated with hot massive proto-cluster cores strongly suggests that high-mass star formation kick-starts the formation of lower mass stars which emerge subsequently. It seems likely that high-mass clusters are triggering the collapse of cold dense prestellar cores, which themselves fragment and engender the binary and multiple stars we observe in two-thirds of solar mass main sequence systems. Let us add a little more detail to that overview, starting for simplicity, if not stellar formation logic, with the low-mass case.

Low-Mass Star Formation (LMSF)

1.2 Diffuse Clouds

The average particle density in the interstellar medium (ISM) is about 1 cm^{-3}. Where the diffuse ISM is in temperature and pressure equilibrium with its surroundings, this neutral hydrogen (HI) gas forms diffuse clouds under gravity

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in which gas particle densities are low (a few tens per cubic centimetre) and temperatures moderate (80–100 K). We can also extend the diffuse cloud classification from the purely atomic to the diffuse, and the translucent, depending on overall column densities, molecular hydrogen to atomic hydrogen ratios, or even some CO (carbon monoxide) abundance. Size and scale vary considerably, but typically these clouds are ~0.5 pc in diameter and ~3 $M_\odot$ in total. They are optically thin to the interstellar radiation field, with column densities correlating with visual extinction A_v ~0.05 magnitude, and it is the penetration of Far Ultraviolet (FUV) radiation that determines their chemistry. The tenuous molecular composition of diffuse clouds is studied at submillimetre wavelengths through absorption (typically ground state lines) against strong background sources, often extragalactic. Even the highest column density clouds show principally diatomic molecules, and just a few triatomics, both neutral and ionised, dominated by the elements of hydrogen, carbon, and oxygen. The precise abundance of the overwhelmingly most common molecule, H_2, is determined by the balance between its accretion, diffusion, and reaction rates on the surfaces of dust grains in competition with the rate of impinging photo-dissociating UV. Given the effectiveness of photodesorption processes, dust surfaces in diffuse clouds are regarded as essentially clean of molecular species for most of the cloud's diffuse lifetime.

1.3 Molecular Clouds

About 80 per cent of the molecular hydrogen in our Galaxy exists, however, in the much denser conditions of GMCs, each with masses commonly over 10^6 $M_\odot$. These enormous self-gravitating reservoirs of molecular gas and dust are where stars in the Milky Way exclusively form, although at a gas conversion efficiency rate of only ~5 per cent due to the multiple complex internal shock, turbulence, and radiation dynamics arising from star formation (particularly HMSF) that disrupt the localised continuity of gravitational collapse and gas coalescence. In classifying what we will find in our case studies to be far from homogenous molecular cloud conditions, we can generalise to the extent of noting that GMC column densities do average over 10^{22} H-nuclei cm^{-2} and show visual extinctions up to A_v ~8 magnitude. Remember, these are broad averages, and we will be identifying much higher-density locations within GMCs in some of the case studies that follow.

As in the diffuse cloud case, the thermal balance within a GMC determines its stability, and we will look at this in a little more detail in Chapter 6. Photoelectric effects dominate in the outer regions, while cosmic ray heating and local turbulence are most significant in the inner regions . However, dense

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molecular clouds are typically cold (~10 K). This is because the gas is predominantly molecular and, with the exception of H_2 (which has no dipole moment), molecules typically have many available rotational levels through which collisional energies are radiated. The kinetic energy of molecular gas is therefore efficiently reduced in comparison with an atom-dominated cloud. Balancing abundance against cooling efficiency, ^{12}CO offers the greatest cooling contribution in lower-density molecular conditions ($<10^3$ cm^{-3}). At higher densities, the ^{12}CO transitions become optically thick and the cooling efficiency of the less common isotopologue, ^{13}CO, can compete, as can that of certain molecular ions and neutral hydrides, including H_2O.

Where FUV photons penetrate molecular clouds, they ionise, dissociate, and heat the gas. Atomic H ionising photons are absorbed in a thin transition zone (column density ~10^{19} cm^{-2}) in which almost fully ionised atomic gas becomes almost fully neutral. FUV photons with energies <13.6 eV dissociate H_2 but ionise C, so an HI/CII region forms the next 'layer'. In dense photodissociation regions (PDRs), dust at visual extinction A_v ~4 magnitudes marks the H_2 front, and beyond that come C/CO zones. This is a simplification of reality, as the case studies in Chapters 14 and 15 will show. However, where dust grains within GMCs are protected from externally impinging FUV, here the gas and dust temperatures drop, and gas-phase chemistry is now driven, as we noted, by cosmic ray ionisation that initiates complex ion–molecule reaction networks. Within such a dark cloud, the dust-grain surfaces become the sites of migration and reaction between atoms and radicals, with gas–grain exchange through accretion and desorption. With progressive cooling during cloud collapse, ice layers accumulate as storehouses of the gas–grain molecular products, many of which are saturated and/or complex, only to be released if and when the gas and dust are subsequently warmed by star formation activity.

1.4 Dense Prestellar Cores

Against the gravitational forces within a cooling dense molecular cloud, turbulent motions from a variety of processes both disrupt and amplify existing inhomogeneities in gas and dust distribution, resulting in the formation of extra-dense filaments. The densest of these (on a scale ~0.1 pc) may collapse under their own gravity, forming a central nascent protostar with an accretion disk (radius ~ ten thousand AU). The disk actually expands over time, with magnetic braking working against the conservation of angular momentum while continuing accretion onto the central protostar is enabled through

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an energy balance maintained by jets and outflows (disk winds) emerging from the central object perpendicular to the disk plane.

Prior to any appearance of a nascent protostar within a central density peak, the initial dense , cold core has a typical gas-phase particle density of 10^6–10^7 cm^{-3} and temperature ~10 K. In Chapter 3 we will meet the many cores of the Ophiuchus molecular cloud with characteristic sizes of several thousand AU. At this point, on a scale at which the current generation of interferometers has really come into its own, we might ask what is it that is so valuable that is gleaned from the higher resolution of the molecular composition of accretion disks and their associated winds? After all, could any of these molecular species survive the disruption, dispersal, and material aggregations that follow stellar ignition? We must look to the outer reaches of protoplanetary disks and later in their evolutionary development for circumstances favourable to molecular formation chemistries that might produce the molecular species we currently observe in the fleeting passage of outer Solar system objects close to Earth. However, in the early stages of star formation, in trying to understand the multiple steps associated with that formation process, molecular emission tells us much about the physical conditions of each stage, all of which will become clearer through the case study examples to follow.

Along with the many smaller molecular species observed in the gas phase of cold, dense prestellar cores, there are complex carbon molecules offering direct evidence for active microscopic dust grain surface chemistries. Also evident is deuterium fractionation , and these observations collectively give distinctive clues as to core conditions of temperature, density, and radiation flux. Ices are also widely observed in absorption towards many reddened background stars, having accumulated on the surface of dust grains. H_2O ices are known to begin accumulating at densities ~10^3 cm^{-3} and temperatures ~15 K. Other ices, such as CH_4, NH_3, and some CO_2, also start to freeze out under these conditions with rapid increases as the core collapses and particle densities increase. Alternative routes for these simple saturated molecules to form in the gas in the quantities observed are woefully inefficient. Rather, the molecules are undoubtedly forming on grain surfaces through elemental reactions, including ubiquitous successive hydrogenation.

By the time the collapsing core reaches a gas-phase density ~10^5 cm^{-3}, the dominant volatile carbon species, CO, is undergoing rapid depletion onto the grains. This abrupt large-scale freeze-out of CO produces a distinct H_2O-poor (apolar) ice phase which has been observed directly as well as re-created in laboratory analogues. This CO-rich ice reacts with, among other species, atomic H to form H_2CO and CH_3OH – molecules we shall meet repeatedly in the case studies to follow, along with even more carbon-based complex organic molecules (COMs). We can reiterate that these species are certainly not made efficiently through collisional gas-phase reactions alone. However, this is cold carbon-chain chemistry, not to be confused with a warm carbon-chain chemistry (WCCC) that we will also find associated with low-mass protostars at a later stage of their evolution. For theorists and modellers, a major puzzle of recent years has been by what process or processes the COMs observed in the gas phase are actually desorbed from grain ices. The dust temperatures are deemed too low for thermal desorption, yet non-thermal processes such as photodesorption, cosmic-ray-induced spot heating, or localised exothermic reaction desorption give unsatisfactory results in any but species-specific cases. This is where current laboratory research into ice analogues will prove of crucial interest.

To pick up on the deuterium fractionation evidence, it is characteristic of cold prestellar cores that they have a high abundance of deuterated molecules such as DCO^+, DCN, and HDCO, with ratios to their undeuterated counterparts at least three orders of magnitude higher than the overall [D]/[H] ratio (which is $\sim 2 \times 10^{-5}$ in the ISM). Even doubly and triply deuterated species have been observed. The reasons for their abundance are that their formation reactions are exothermic and therefore efficient in such cold conditions, while the dominant destruction pathway for H_3^+ and H_2D^+, the principal initiators of fractionation, involves CO which by this stage, as we said, is quickly freezing out. Chapter 3 will reconsider deuteration in more detail. Chemical modelling suggests a lifetime for the cold, dense prestellar freeze-out phase of about 10^5 years before we next identify distinctive protostellar characteristics. For those unfamiliar with the many molecular species introduced throughout the following chapters, Appendix A directs the reader to some conveniently tabulated data.

1.5 Cold Protostellar Envelopes

Prestellar cores emit at infrared and longer wavelengths. Collapse of the core progresses, with the gravitational free-fall time extended perhaps by ambipolar diffusion and turbulence from within, irrespective of possible external influences such as shocks from neighbouring stellar activity. Once a central hydrostatic object coalesces within the core, we can say we have a protostar, and it will grow with accretion of surrounding envelope material from the engendered circumstellar disk. We will see in the LMSF chapters that protostellar envelopes are detected through millimetre-wave dust continuum emission, luminosities being roughly proportional to the total mass of dust in the envelope. Centimetre-wave radio continuum detections arise from accretion shocks at the protostellar surface, this luminosity being proportional to the total luminosity of the star, and envelope and protostellar masses can then be deduced from these luminosities. High ratios of millimetre-wave luminosity to total luminosity also show just how much the envelope mass may exceed that of the central protostar, through an accretion phase we expect to last up to 10^5 years. Infall motions themselves can be traced through molecular and molecular ion rotational lines, and both red and blue shifts are observed along the line of sight resulting from the large-scale rotation of the envelope gas around the protostar.

Within an opaque protostellar envelope, very close to a low-mass protostar, small (<100 AU), warm, dense regions have been discovered in recent years, designated ‘hot corinos’, the prototypical example being that associated with IRAS 16293-2422 which we will examine in Chapter 3. This gas is rich in complex organic molecules (COMs) – those with at least six atoms – with line profiles suggesting the emission arises from the inner surface of the accretion disk. However, while the disks themselves can have lifetimes of several million years, hot corino observations seem limited to the earliest stages of accretion disk evolution, and it seems likely that the complex organics are quite quickly degraded to CO in the warm gas as the protostar evolves.

1.6 Jets and Disk Winds

Along with the accretion disk itself, protostellar systems typically show outflow activity in which some of the accretion energy converts to kinetic energy in a collimated bipolar jet or disk wind. The nearby Perseus molecular cloud, for example, which we will meet in Chapter 4, shows hundreds of jets associated with embedded protostars, which we can trace in rotationally excited H_2 as well as emission lines from SiO, SO, and CO. These outflows generate turbulence in the surrounding envelope, driving their dispersal, and effectively limiting the available accretion mass. Equally, outflows can drive shocks that may well trigger star formation in neighbouring clouds and, especially in the high-mass case, account for the tendency for stars to form in clusters. Wherever the velocity of ejected material exceeds the sound speed, the surrounding gas and dust cannot respond dynamically until the material arrives. When that happens, the shocked gas is compressed, heated, and accelerated before subsequently cooling through line emission, and these changes in conditions are reflected in observable changes directly to the gas phase and to its composition resulting from the sputtering of ices. While H_2 and CO, as so often, are the dominant coolants, the common shock indicators in molecular clouds close to emerging stars are H_2O, SiO, SO, and SO_2, which we will meet particularly in the HMSF sources.

1.7 Protoplanetary Disks

As we will see when we look at specific examples, the impinging FUV (Far Ultraviolet), EUV (Extreme Ultraviolet), and X-ray stellar radiation emerging from the protostar creates dense photodissociation conditions at a disk's inner surface. Deeper into the disk, the magnetised gas is turbulent and grain collisions promote growth into larger aggregates, which is how planet formation begins. Accretion continues, jet and disk outflows drive strong shock waves into the disk and envelope, small shock-heated knots called Herbig–Haro (HH) objects appear where jets impact surroundings, and broad, diffuse lobes of high-velocity ambient gas are swept up and accelerated to high velocities. With the dispersal of the envelope cloud, the protostar and disk become visible, and we have what are called T Tauri stars ($<2\ M_\odot$) or Herbig AeBe stars if larger ($2–8\ M_\odot$). Total accretion timescales are ~2 Myr, while disk dissipation takes ~3 Myr. With a variety of evolutionary stages, the timescale for low- and intermediate-mass stars to reach the main sequence is of order 10–100 Myr respectively.

Observations of the transition from accretion disk to protoplanetary disk have begun to be made possible by the latest high-resolution instrumentation. Close to a star, densities and temperatures are high and chemical equilibrium conditions rapidly attained. Further out from the star, differing conditions engender zones of particular molecular mixes before freeze-out onto cold grains at the outer margins. While gas–grain interactions dominate in the icy mid-plane, there is turbulent diffusion mixing material vertically and radial transport moving material laterally in the longer term. Dust grains will collide, stick, and potentially grow into aggregates. In several case studies we will look at key micro-chemical gas–grain processes occurring in the various molecular zones that undoubtedly do precede any aggregation of dust that might initiate planetesimal formation. Any subsequent evolution towards larger aggregations having a gravitational impact sufficient to engender, say, kilometre-size planetesimals that precede the formation of those planets that we now see associated with at least five thousand stars in our own Galaxy is a question for study elsewhere. The schematic of Figure 1.1 summarises the stages of low-mass star formation, giving spatial and temporal estimates.