Chapter 3

The Clouds

There is overwhelming evidence that stars are born inside clouds. Yet it was not always obvious that this had to be so. Stars could have been eternal beacons in a steady-state Universe. They could have come into existence in the early Universe, or simply built up through collisions and coagulation of clouds of atoms.

Although normal stars like our Sun consist of atoms and the gas from which they originate was also atomic, stars are born in molecular clouds. More precisely, all present day star formation takes place in molecular clouds. These protected environments also serve as the wombs and the nurseries for the young stars. It has thus become clear that the processes in molecular clouds hold the key to understanding star formation. Without this intermediate molecular stage, galaxies would be very different.

Most of a cloud consists of hydrogen molecules, \( \text{H}_2 \). To observe it, however, we require a surrogate since the \( \text{H}_2 \) is simply too cool to be excited and so virtually inaccessible to direct observation. We now have the technology to detect the emission of many trace molecules and to penetrate deep into the clouds. The detection of interstellar ammonia in 1968 indicated the existence of very dense clouds. We can now even map the distributions of various molecules and distinguish collapsing molecular cores.

What we have discovered has drastically altered our view of star formation. We shall show that clouds are much younger than previously thought. Secondly, many clouds and clumps are a figment of observations with limited dynamic range combined with the human tendency to split complex patterns into recognisable units. The apparent structures often represent a convenient means of categorisation rather than real entities. First, we need to assimilate the fundamental evidence relating to cloud origin, age and internal structure.
3.1 Phases of the Interstellar Medium

How much material do we have available and in what form? Molecules and molecular clouds form out of an expansive reservoir which occupies over 99% of the volume. This is the atomic interstellar medium. The gas is atomic because the ultraviolet light from massive stars dissociates any molecules much faster than they can reform (as discussed in §2.4.3). Only where material is protected from the UV can molecular clouds, and ultimately stars, form.

We recognise four atomic components, two of which are largely ionised gas and two neutral, as listed in Table 3.1. First, there is a hot ionised component. Although hot and buoyant, its low density and pressure stops it from blasting away the entire interstellar medium. Related hotter gas, termed coronal gas, with temperatures of millions of Kelvin and particle densities under $0.01\,\text{cm}^{-3}$ is observed in soft X-rays. It is heated by blast waves from supernovae and violent stellar winds. This gas escapes, often diverted into chimneys which funnel it out of the galactic plane.

The second component is a warm ionised medium of lower temperature and higher density, but still very diffuse. The electron fraction is close to unity. The ionised components together could occupy up to about 80% of the interstellar volume, although these numbers are very uncertain.

One neutral component consists of warm gas with temperature $\sim 8000\,\text{K}$ and density $\sim 0.3\,\text{cm}^{-3}$. It is composed largely of neutral hydrogen (i.e. H I, so observable in the 21 cm line) with about 2–20% of ionized gas, including electrons (so observable as free-free in the radio continuum, see §2.3.1). It probably fills about 20% of the volume in the disk of the Galaxy. The stability of this phase is maintained by photoelectric heating and by Ly$\alpha$ and recombination cooling, which together act as a thermostatic regulator.

Finally, there is a cold atomic medium with temperature under 100 K, density $30$–$50\,\text{cm}^{-3}$ and a very low ion fraction (under 0.1%). Photoelectric heating is balanced here by C II and O I cooling in the fine-structure lines (see §2.3.2).

The densest parts of the ISM are observed as molecular clouds. These are just parts of dense condensations within the atomic phases. Apparent sharp boundaries are exactly that: apparent. The boundaries are not necessarily edges in density. Instead, they are boundaries in the phase, with extended envelopes of atomic gas around the clouds.

The phase transition takes place where the ultraviolet radiation flux has reached the limits of its penetration into the accumulated gas. The ability
to penetrate is measured by the column of shielding gas. When sufficient, this is like a thick skin to the cloud, the degree of penetration being given by the column density of the absorbing dust in the skin.

The clouds are classified, according to their opacity, into diffuse, translucent and dark clouds; and by size, into Giant Molecular Clouds (GMCs), clumps and cores (see Table 3.2). Translucent clouds are those in which their opacity (the optical depth from the edge to the centre) is of order of one to a few at visual wavelengths. They have drawn particular attention since the physical processes and interaction with external radiation are spread out over large distances. We can thus conveniently measure variations of quantities with distance into the cloud and so test our models.

The total molecular mass in our Galaxy of $3 \times 10^9 \, M_\odot$ is as large as the atomic mass. It is not distributed evenly but 90% is closer to the centre of the Galaxy than the Sun (inside the ‘solar circle’), in comparison to only 30% of the atomic gas. Note that almost all the mass of gas is cold and occupies a small volume.

Table 3.1 Phases of the interstellar medium. These phases may not be in equilibrium but dynamic and short-lived at any particular location.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Temperature K</th>
<th>Density cm$^{-3}$</th>
<th>Fraction of Volume</th>
<th>Mass in $10^9 M_\odot$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot ionised medium</td>
<td>$3–20 \times 10^5$</td>
<td>$3 \times 10^{-3}$</td>
<td>0.4–0.7</td>
<td>0.003</td>
</tr>
<tr>
<td>Warm ionised medium</td>
<td>10,000</td>
<td>$3 \times 10^{-1}$</td>
<td>0.15–0.4</td>
<td>0.05</td>
</tr>
<tr>
<td>Warm neutral medium</td>
<td>8000</td>
<td>$4 \times 10^{-1}$</td>
<td>0.2–0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Cold neutral medium</td>
<td>40–100</td>
<td>$6 \times 10^1$</td>
<td>0.01–0.04</td>
<td>3</td>
</tr>
<tr>
<td>Molecular Clouds</td>
<td>$3–20$</td>
<td>$3 \times 10^2$</td>
<td>0.01</td>
<td>3</td>
</tr>
</tbody>
</table>

3.2 Weighing up Molecular Clouds

Dense cool gas in molecular form occupies just 2–4% of the interstellar volume. It is mainly contained within giant molecular clouds (GMCs), typically tens of parsecs in size and containing up to a million solar masses. In fact, for some unknown reason, there appears to be a limit to a cloud mass of six million solar masses. The properties listed in Table 3.2 are broad estimates.
Table 3.2  Estimated properties of individual molecular aggregates in the Galaxy.

<table>
<thead>
<tr>
<th>Phase</th>
<th>GMCs</th>
<th>Clumps/Globules</th>
<th>Cores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (M⊙)</td>
<td>$6 \times 10^4–2 \times 10^6$</td>
<td>$10^2$</td>
<td>1–10</td>
</tr>
<tr>
<td>Size (parsecs)</td>
<td>20–100</td>
<td>0.2–4</td>
<td>0.1–0.4</td>
</tr>
<tr>
<td>Density (cm$^{-3}$)</td>
<td>100–300</td>
<td>$10^3–10^4$</td>
<td>$10^4–10^5$</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>15–40</td>
<td>7–15</td>
<td>10</td>
</tr>
<tr>
<td>Magnetic Field (µG)</td>
<td>1–10</td>
<td>3–30</td>
<td>10–50</td>
</tr>
<tr>
<td>Line width (km s$^{-1}$)</td>
<td>6–15</td>
<td>0.5–4</td>
<td>0.2–0.4</td>
</tr>
<tr>
<td>Dynamical life (years)$^a$</td>
<td>$3 \times 10^6$</td>
<td>$10^6$</td>
<td>$6 \times 10^5$</td>
</tr>
</tbody>
</table>

$^a$ Note: dynamical life defined as Size/(Line Width), true lifetimes would be considerably longer if clouds were static.

There are many sources of inaccuracy in the parameters of individual clouds. The mass, temperature and internal motions (velocity dispersion) rely on an interpretation of molecular line observations. The size depends on the measured angular size and a distance estimate. However, the cloud distances are only approximate and even the nearby examples may be 20% closer or further away than assumed.

Accurate distances are required to derive accurate sizes, luminosities and masses of both clouds and young stars. We can classify the methods employed to estimate cloud distances but remark that all three classes are indirect: the distance to stars is actually determined.

The classical methods employ the obscuration of the cloud to distinguish background stars, foreground stars and associated stars (e.g. as reflection nebulae). If we knew the distances to these stars, then we could place the cloud. We achieve this with spectroscopic observations of the individual stars to determine their spectral type. Once certain types of stars are classified, we know their absolute luminosity and so can determine their distances. Finally, knowing their distance and whether they are foreground or background is sufficient to restrict the cloud distance.

Astrometric methods are now capable of determining distances to bright young stars associated with the molecular clouds. The Hipparcos satellite used its orbit around the Sun to determine distances by the method of parallax (the apparent motion of nearby objects relative to distant objects). However, milliarcsecond accuracy is not sufficient to obtain a precise distance even to the nearest star formation regions.
The third class of methods employs independent determinations of speed. Given an angular speed and a true speed, we can obtain a distance. The angular speed can be derived from an observed motion of an object or shock wave in the sky (proper motion) or the rotation period of spots on the surface of a young star. The true speed can be derived from modelling the broadening of emission lines in terms of Doppler shifts. These methods require some geometrical or statistical assumption to relate the two speeds and extract the distance.

Molecular clouds are routinely mapped and weighed in the CO rotational transition at 2.6 mm (since the H$_2$ is not detectable). Empirical relations have been deduced to relate CO and H$_2$ including one for the H$_2$ surface density $\Sigma$(H$_2$) in terms of the CO J=1–0 intensity, I(CO): $\Sigma$(H$_2$) = $5\pm3$ I(CO) $M_\odot$ pc$^{-2}$. The derived quantity is the surface or column density i.e. the total H$_2$ through the cloud along the line of sight. The CO line is usually optically thick and observers often resort to mapping weaker emission from optically-thin isotopes. In all cases, an abundance for the trace isotope must be justified. Cloud masses are then estimated by integrating the column of gas over the cloud extent. Finally, the cloud density is estimated after assuming a reasonable size for the cloud along the line of sight.

Dense cores have been mapped in other molecules such as NH$_3$ or HCN. Occasionally, we can estimate a gas density with this approach since different molecules and different energy levels within a molecule require particular critical densities for excitation (§2.3.2).

Dust emission can also be used to determine cloud masses although the dust emissivity and temperature need to be specified. In the millimetre or submillimetre continuum the dust emission is typically optically thin and the emission from thermal dust is given in the simple low-frequency Rayleigh-Jeans limit (see §6.1). This method is commonly employed to determine masses of dense cores since tracing molecules become unreliable as they are heavily depleted from the gas phase into the dust itself. In turn, this alters the dust emissivity and this must be taken into account (see §6.1). Thus, while a single mass determination method relies on several assumptions, one can build confidence through a broad corroborating approach.

An alternative technique has been successfully pioneered which employs dust extinction. We can now measure the extinction to up to thousands of stars behind a cloud due to the recent deployment of large and sensitive infrared array detectors. The extinction can then be scaled to a column
density. Working in the infrared, we are able to detect sufficient stars in the background even where there are 25 magnitudes of visual extinction. As a result, we can also map out how the dust is distributed.

One can also calculate a cloud mass, $M_{\text{vir}}$, by assuming virialisation or virial equilibrium instead of assuming an abundance. This requires knowledge of the internal motions. The basic argument is that if the motions in a cloud were not precariously held in equilibrium by gravity then the cloud would either disperse or collapse in a brief time. We begin by observing an emission line and fitting a Gaussian line shape to its profile of the form

$$I(v) \propto \exp \left[ -\frac{v^2}{2\sigma_v^2} \right]$$

(3.1)

to determine the velocity dispersion, $\sigma_v$. The classical formula for the escape speed $v_{\text{esc}}$ from the surface of a spherical cloud, planet or star of mass $M$ and radius $R$ is

$$v_{\text{esc}} = \sqrt{\frac{2GM}{R}}.$$  

(3.2)

A virialised cloud, in which the kinetic energy of cloud motions is not sufficient for material to escape yet enough to stabilise against collapse, is the most likely condition for observation. The virial theorem will be discussed in §4.3.1. Here, we do not actually require a static equilibrium but, at least, temporary energy equipartition. Whether true or not, we can still calculate a theoretical ‘virial mass’ for any cloud, given an observed velocity dispersion (i.e. from the motions along our line of sight). For a uniform cloud of radius $R_c$, we find a velocity dispersion

$$\sigma_v(0) = \sqrt{\frac{GM_{\text{vir}}}{5R_c}},$$

(3.3)

significantly lower than the surface escape speed. Reversing, we derive the virial mass given the velocity dispersion:

$$M_{\text{vir}} = 1160 \left( \frac{R_c}{1 \text{ pc}} \right) \left( \frac{\sigma_v}{1 \text{ km s}^{-1}} \right)^2 M_\odot.$$  

(3.4)

Clouds may develop evolved cores in which the gas density rises steeply towards the centre. Given a spherical cloud with a density structure

$$\rho = \rho_o \left( \frac{R}{R_c} \right)^\alpha,$$

(3.5)
it can be shown that the velocity dispersion increases by a factor

\[ \sigma_v(\alpha) = \sqrt{\frac{5 (3 + \alpha)}{3 (5 + 2\alpha)}} \sigma_v(0), \]  

quite close to unity even in the least uniform cores with \( \alpha = -2 \).

In practice, it is straightforward to measure the full line width at half the peak intensity, \( \Delta v \), and then apply the formula for the Gaussian distribution to obtain \( \sigma_v = 0.426 \Delta v \).

The virial method, however, can be very misleading because clouds are, in general, not bound. The evidence will be given in §3.4.

### 3.3 Molecular Clouds

#### 3.3.1 Breeding grounds for high-mass stars

Molecular clouds are found throughout our Galaxy, including the Galactic centre and at quite high latitudes from the Galactic plane. They are, however, very strongly associated with the Galactic plane and preferentially associated with the spiral arms. The locations of major regions are indicated in Fig. 3.1.

Millimeter wavelength CO maps show the typical structure of a cloud: inhomogeneous, elongated and containing dense clumps and filaments. The dense clumps are very closely related to regions of on-going star formation.

One major debate is whether star formation occurs spontaneously or whether it is triggered. We first demonstrate with some examples that the formation of high-mass stars is initiated by various external influences due to neighbouring active phenomena such as shock waves from supernova remnants, expansion of \( \text{H II} \) regions, and UV radiation from other massive stars.

#### 3.3.2 Orion

Messier 42, also known as the Great Orion Nebula, is perhaps the most well-known and well-studied star-forming region. It extends \( 15^\circ \) across the sky and lies conspicuously well below the Galactic plane. As shown in Fig. 3.2, the Orion Molecular Cloud (OMC) complex, at a distance of roughly 450 pc, is about 120 pc long. The total mass of gas is estimated to be a few \( 10^5 \, M_\odot \). It can be divided into three clouds, Orion A, Orion B (containing NGC 2024) and Mon R2, each consisting of a few thousand solar masses.
Fig. 3.1 Molecular clouds in the Milky Way: a composite picture from a CO survey of the Galaxy. In galactic coordinates, the (1) Galactic centre lies near $0^\circ$ longitude. Also marked are (2) Orion, (3) Taurus, (4) Ophiuchus, (5) Polaris Flare, (6) Aquilla Rift and (7) Chamaeleon (Credit: T. M. Dame and P. Thaddeus, Harvard-Smithsonian Center for Astrophysics).
The clouds appear connected to the Galactic plane by two remarkably long slender filaments.

The evolution of star formation in large clouds is exemplified by the Orion complex. Massive stars, with the spectral classes O and B assigned to them, have been forming here within four distinct groups called OB associations. These contain extremely bright and hot stars with mass exceeding about $10 M_\odot$.

One generation of massive stars in region 1a formed 12 Myr ago. The parental cloud is absent, having been completely disrupted or transformed into stars. The stars are now free from molecular material and not obscured. Although still clustered, they slowly drift apart. A second generation of
stars has been forming for about 7 Myr just on the right edge of the cloud, region 1b, sweeping up and disrupting the cloud in the process. Some stars are now visible while others remain embedded. The latest generation only began about 3 Myr in location 1c. All these objects are still embedded and star formation is ongoing. Indeed, there are many cores which appear to be just on the verge of collapse. This region contains strings of many very young protostars which react with the cloud through powerful jets and winds of gas, driving shock waves and inflating lobes of fast-outflowing molecular gas.

Massive bright stars are forming in the south, in the Trapezium region, appropriately called because of the placement of the four brightest young stars. The bright stars light up the cloud material nearby producing the magnificent Orion Nebula which we see in reflected light. In addition, molecular gas is photo-dissociated by the far-ultraviolet radiation from the OB stars, producing very strong infrared emission in the fine-structure lines of oxygen and carbon. Although the massive stars are prominent and appear to re-structure the complex, giving it the V-shape, lower mass stars are present in great numbers throughout the clouds.

Just behind the Orion Nebula H II region lies the Orion-KL region which contains the densest core in the cloud and a cluster of luminous infrared stars with a total luminosity of $10^5 \, L_\odot$. The core mass is $200 \, M_\odot$ contained within just 0.1 pc. Consequently, this very young region has been the focus of many studies.

Other regions in which stars of high mass are forming are nearby to Orion: the Rosetta Cloud and Gem OB1 complexes. As noted above, however, most of the molecular gas lies in the inner Galaxy. The Sagittarius B2 cloud is massive, $3 \times 10^6 \, M_\odot$, and just 200 pc away from the Galactic centre. It contains small-scale structure, hot cores and outflows. Extending away from the Galactic centre is a thin intense ridge of CO emission. This is associated with a so-called molecular ring, probably consisting of several spiral arms, located a few parsecs from the Galactic centre.

3.3.3 The Eagle

The Eagle Nebula shown in Fig. 2.2 is a very young star formation region containing dark columns of cold molecular gas and dust dubbed the ‘Pillars of Creation’ or ‘elephant trunks’. Many thousands of deeply-embedded young stellar objects are detected in near-infrared images. In addition, 73 small evaporating gaseous globules (EGGs) have been detected on the
surface of the pillars. Two of the pillars have relatively massive young stars in their tips. However, most of the EGGs appear to be empty: about 15% show evidence for young low-mass stars or brown dwarfs. There are also a large number of X-ray sources. These are more evolved young stars not associated with the evaporating gaseous globules (EGGs) as will be discussed in §9.7. They suggest that star formation has been proceeding for millions of years.

It appears that this structure was formed by the interaction of interstellar clouds with multiple supernova explosions and stellar winds from massive stars near the Galactic plane. These act to compress the clumps which become exposed, thus triggering star formation. Although the Orion Nebula and the Eagle Nebula appear disimilar, this is largely attributed to the orientation: we observe the Orion Nebula face on and so observe through it (see Fig. 7.2 whereas the Eagle Nebula is clealy edge on to our line of sight.

### 3.3.4 Breeding grounds for low-mass stars

The Taurus-Auriga-Perseus Cloud Complex is the most intensively studied star-forming region containing only low mass stars. It is a dark, quiescent complex located towards the Galactic anti-centre. In contrast to the regions described above, the cloud complex has long been regarded as a site where star formation occurs spontaneously. The total complex mass is \( \sim 2 \times 10^5 \, M_\odot \). Estimated masses of fragments cover a wide range with clumps embedded in more massive envelopes, all the way down to a few solar masses. The Perseus molecular cloud is located at a distance estimated to range from 200 to 350 pc and has a projected area of dimension 10 pc \( \times \) 30 pc with an estimated mass of \( 10^4 \, M_\odot \).

The Taurus Cloud (TMC) itself (Fig. 3.3) lies relatively close-by, at a distance of 130–160 pc. Its gas mass is \( \sim 3 \times 10^4 \, M_\odot \) and size 30 pc. The most striking aspect is its striated morphology, displayed in Fig. 3.3. About 150 young stars, mainly T Tauri stars, are in the T association (§12.4) weakly clustered within individual clumps embedded in the striations.

There is evidence that each star in the TMC has developed in an isolated environment. Firstly, the potential trigger in the vicinity, the Cas-Tau OB association, is already old (25 Myr) and the stars are widely dispersed. Secondly, the number density of the young stellar objects (YSOs) in the TMC is quite low, 10–20 stars pc\(^{-3}\), implying that neighbouring systems do not generally gravitationally interact with each other during star formation.
On the other hand, some evidence for a more systematic star formation mechanism is derived from a chemical analysis. The TMC-1 component is a prominent example of chemical inhomogeneity. The south-eastern part of the cloud is abundant in ‘carbon-chain’ molecules such as CCS and cyanopolynes (CPs), while the north-western part is abundant in molecules such as NH$_3$ and N$_2$H$^+$. Since carbon-chain molecules are considered to be abundant in the early stage of chemical evolution and the abundances of NH$_3$ and N$_2$H$^+$ are enhanced in the later stage, this separation has been interpreted to be consequence of sequential chemical evolution along the cloud.

More evidence is derived from the numbers and ages of the T Tauri stars and the lack of post T Tauri stars. This implies that, in the past, star formation proceeded at a low rate until about $4 \times 10^6$ yr ago. There
then followed a rapid rise toward the present epoch. This could not have plausibly occurred spontaneously over 30 pc but, instead indicates that a triggering wave crossed the cloud at a speed of $\sim 10 \text{ km s}^{-1}$.

Lupus and $\rho$ Ophiuchus contain similar clouds to the TMC. They are situated above the plane towards the Galactic centre. The $\rho$ Ophiuchus cloud at a distance of 160 pc contains a total mass of molecular gas of $\sim 3 \times 10^3 M_\odot$. It contains a much denser concentration of gas, the L1688 cloud, which has allowed a detailed study of the distribution of gas and embedded protostars. Visually, it is a cobweb: the cloud filaments resemble strands in a spider’s web. Physically, several structures possess head-tail or cometary morphologies, as though blown and shaped by the impact of a wind. The filamentary tails can be either cold un-shocked ambient material or material streaming away from cores. There is ample evidence, including spatial variations in the chemistry, that the star formation has been triggered by winds and supernova blast waves arriving from the nearby Sco OB2 association as well as nearby expanding H II regions.

### 3.3.5 Isolated clouds

Bok globules were discovered as small isolated clouds. They were not identified through emission but as dark patches on the background curtain of stars which covers the Milky Way. At visible wavelengths, these patches are caused by the presence of a high column of obscuring dust. They are examples of ‘Dark Clouds’ which can also appear as dark patches superimposed on bright nebula (Fig. 3.4). With their discovery, Bart Bok suspected that these were sites where we might uncover the first signs of star formation. Indeed, this has proven correct with over half of them possessing protostars or young stars. While most are low mass, containing a few solar masses of cloud material, others contain several hundred solar masses and may form generations of stars over a few million years.

Considerable attention is now being given to the globules since we hope to isolate the formation mechanism in the absence of external triggers. They are typically 0.1–1 pc in size with quite rough distorted shapes.

An example of a quiescent Bok globule is B 68 shown in Fig. 3.4. There is no evidence for associated protostars or for collapse towards a protostar. It possesses a small mass and a radial density distribution consistent with a static and constant temperature cloud (i.e. resembling a Bonnor-Ebert sphere as described in §4.3.3). It is, however, far from spherical and contains peculiar chemical distributions and internal motions not consistent with a
static configuration.

Other Bok globules such as B335 and CB 34 are actively forming stars. The CB 34 globule is observable in emission at submillimetre wavelengths, where the central region is found to be clumped. The clumps contain protostars, observed in the near-infrared. The protostars drive gas outflows in the form of bipolar outflows and chains of bullet-like knots. Spreading out from the clumps are young stars which suggest that the globule is in an advanced stage but still only a few million years old.

Not all clouds will form stars. Examples are High Latitude Clouds (HLCs) and Chaff. The HLCs are molecular, and, as their name suggests, not found in the Galactic plane. They possess high turbulent pressure but are of too low a mass to be self-gravitating. Chaff is the name given to the equivalent of HLCs but in the Galactic plane. These consists of low column density material detected in the vicinity of GMCs and the spiral arms with masses under 1000 M_☉. The total mass in Chaff in our Galaxy is estimated to be 7.5–15 × 10^7 M_☉.

### 3.4 The Internal Dynamics and Structure of Clouds

The masses of the stars which eventually form could be pre-set by the masses of the clumps and cores. Therefore, astronomers have been very
creative in their attempts to characterise cloud structure. Probability distribution functions (PDFs) for density or velocity provide a robust basis for the analysis of cloud structure. There are various more sophisticated techniques to describe the volume distribution, the sky distribution and the velocity distribution. The latter requires spectroscopic methods. That is, we obtain images of the cloud in specific narrow wavelength channels, which correspond to channels in radial velocity (the velocity component in the line-of-sight). This is called a clump decomposition technique, which uses the relative shift in radial velocity to distinguish cloud components superimposed on the sky. We can then derive some information in the third spatial dimension.

The results are crucial to how a cloud evolves into stars, how much of a cloud evolves into stars and their distribution in space and in mass. The observed masses of clouds generally follow a power-law distribution with the number of clouds per unit interval in mass given by \( \frac{dN_{\text{cloud}}}{dM} \sim M^{\alpha_i} \). It is convenient to employ a mass-weighted distribution:

\[
M \frac{dN_c}{dM} = \frac{dN_c}{d\log M} \propto M^{\alpha_c} \quad (3.7)
\]

since then a positive index \( \alpha_c \) means that most clouds are massive and a negative index means that most clouds are low mass.

We actually find that most clouds are low mass with the index almost invariably in the range \( \alpha_c = -0.6 \pm 0.2 \). For a large sample of clouds in the inner Galaxy \( \alpha_c = -0.6 \), and in the Perseus Arm \( \alpha_c = -0.75 \). The power-law holds over a wide range of masses from GMCs down to the high-latitude clouds with mass \( 10^{-4} M_\odot \).

It is highly significant that most of the clouds are small but most of the mass is contained in the most massive clouds (since \( 1 + \alpha_c \) is positive). It is equally important that we do not observe any giant molecular clouds in our Galaxy above a certain limit. In fact, the power-law possesses a sharp cut-off at \( 6 \times 10^6 M_\odot \). Writing the number distribution of clouds within the solar circle in the form

\[
M \frac{dN_c}{dM} = 63 \left( \frac{M}{6 \times 10^6 M_\odot} \right)^{-0.6}, \quad (3.8)
\]

one can immediately see that the cut-off is very sharp – we would expect about 100 extreme GMCs above the break if we extrapolate the power law. Instead, there are actually none.

In 1981, Larson brought together several significant results which have
remained essentially unchallenged. He uncovered correlations between the cloud densities, cloud sizes and the internal velocities within a cloud. It first became clear that the motions could only be described by supersonic turbulence. The line widths were non-thermal, far exceeding the thermal velocity dispersion $v_{th}$ which is the line widening attributable to the gas temperature $T$. The sound speed in an isothermal cloud would be

$$c_s = 0.44 \mu_m^{-1} \left( \frac{T}{10K} \right)^{1/2} \text{km s}^{-1} = 0.19 \left( \frac{T}{10K} \right)^{1/2} \text{km s}^{-1}, \quad (3.9)$$

where $\mu_m$ is the mean molecular weight. This is equivalent to the thermal velocity dispersion. The bulk of the clouds may often be treated as isothermal, exhibiting only small temperature variations. In contrast to the low sound speed, observed velocity dispersions are large, regularly exceeding 1 km s$^{-1}$.

Furthermore, for many clouds, the velocity dispersion (or line width $\Delta v = 2.355 \sigma_v$) is related to the cloud size expressed in parsecs by

$$\sigma_v = (0.72 \pm 0.07) R_{pc}^{0.5 \pm 0.05} \text{km s}^{-1}. \quad (3.10)$$

There are numerous exceptions reported, but it is probably safe at present to expect indices in the range $0.5 \pm 0.2$. This cornerstone relationship holds from cloud to cloud as well as within individual clouds.

A similar relationship exists for low-mass cores. For high-mass cores, however, the relationship for non-turbulent motions is significantly shallower:

$$\sigma_{nt} \approx 0.77 \ R_{pc}^{0.21} \text{km s}^{-1}, \quad (3.11)$$

suggesting some support or feedback from stars forming within.

The second major result is that the density is related to the cloud size by $\rho \propto R_c^{-1.1}$. For GMCs inside the solar circle this can be more accurately expressed in terms of the average column of hydrogen nuclei, $N(H)$,

$$\frac{N(H)}{10^{22} \text{cm}^{-2}} = (1.5 \pm 0.3) \ R_{pc}^{0.0 \pm 0.1}, \quad (3.12)$$

which is the product of the average density and the cloud depth. When written in terms of cloud mass, we find $M \propto R^2$ as a rough guide. This was initially taken as strong evidence that the clouds are stable and in virial equilibrium since the above relations yield $\sigma_v^2 R/M$ to be a constant, on putting $M \propto N(H) R^2$, which satisfies the virial formula, Equation 3.3.
The above relationship, however, does not extend to low mass clouds and clumps for which $M_c \propto R_c^{1.8}$ is more appropriate, giving

$$\frac{N(H)}{10^{22} \text{ cm}^{-2}} = (1.5 \pm 0.3) \, R_{pc}^{-0.2 \pm 0.1}. \quad (3.13)$$

To determine if a cloud could be bound we evaluate the virial parameter $\alpha$:

$$\alpha = \frac{5\sigma^2 R_c}{G M_c}. \quad (3.14)$$

Putting the formula to define virial mass (Eq. 3.4) in the form

$$M_{\text{vir}} = 209 \left( \frac{R_c}{1 \text{ pc}} \right) \left( \frac{\Delta v}{\text{km s}^{-1}} \right)^2 M_\odot \quad (3.15)$$

and determining the cloud mass $M_c$ from CO observations, yields power-law fits

$$\frac{M_{\text{vir}}}{M_c} = 0.85 \left( \frac{M_c}{10^4 M_\odot} \right)^{-0.38 \pm 0.03} \quad (3.16)$$

for the Cepheus-Cassiopeia region and similar relationships for other regions.

The result is that we find most GMCs are indeed gravitationally bound with $\alpha \sim 1$. The virial formula applies accurately for $M_c > 10^4 \odot$ but similar scaling relations are also now extended to include gravitationally unbound lower mass clumps in many regions, such as the Gemini-Auriga, Cepheus-Cassiopeia and Cygnus complexes. A lot of the lower mass clouds are unbound with $\alpha$ typically $\sim 5$. Also, many clumps, such as those in the Rosetta cloud, are not gravitationally bound. The typical value for the clumps in $\rho$ Ophiuchus is $\alpha \sim 10$. These clumps must be either confined by an external pressure or in the process of expanding. On the other hand, dense cores are necessarily bound and could well go on to form single stars or small systems such as binaries.

The lack of observed clouds or sub-components with $\alpha << 1$ is of great significance. Such clouds would be unstable and collapse abruptly in the absence of any other support mechanism. This indicates that there is indeed no other support mechanism, such as the pressure of a the magnetic field, which could become totally in command.

The $\sigma$–$R$ law and the lack of virial equilibrium could be the consequences of turbulence. A turbulent energy cascade, if it were to follow a Kolmogorov-type law for incompressible gas, would predict $\sigma \propto R^{1/3}$,
slightly shallower than observed. The origin of this expression can be seen from a dimensional analysis of a turbulent cascade. In what is termed the ‘inertial range’ of scales $L$ and velocity amplitude $U$, the rate at which turbulent energy is transferred to smaller scales is proportional to the energy $MU^2/2$ and the inverse time scale $U/L$. Hence, in a steady energy cascade we find the rate of flow of energy $MU^3/L$ is a constant. Therefore, $U \propto L^{1/3}$ could be expected. This scenario is fully explored in §4.4.

The $\rho$ Ophiuchi molecular complex yields distinct properties with $\alpha_c = -1.1$ and $N(H) \propto R^{1}$ for the clumps with masses between 3 and 300 $M_\odot$. The latter implies that the density and size are uncorrelated. Virial equilibrium does not apply with $\sigma_v$ nearly independent of $R$; the low-mass clumps deviate most from virial equilibrium.

We note here that pre-stellar cores, which are dense cores thought to be on the verge of collapse, have also been analysed in $\rho$ Ophiuchus (see §6.2). These display a number distribution with $\alpha_c = -1.5$ below $\sim 0.5 M_\odot$, steepening to $\alpha_c = -2.5$ above. This, as we shall see, is reminiscent of the Initial Mass Function of the stars, suggesting a direct evolution of these discrete cores into stars.

### 3.5 Rotation Trends

Not much has been known about cloud rotation apart from the fact that they don’t rotate much. This requires explanation since rotation at high speed is expected according to the principle of angular momentum conservation. Clouds should spin up as they contract (see §7.6).

As an indicator of spin, we can measure the spatial variation of the radial component of velocity across a cloud. As a tracer, we employ the CO molecular lines at millimetric wavelengths. A velocity gradient is then interpreted as rotation although that may not always be the case. For example, dynamical shearing between a cloud and the ambient medium, chance superposition, wind impacts from supernova and outflows from young stars may all lead to radial velocity gradients. Systematic extended gradients are, however, attributed to rotation and these require explanation. In particular, a linear shift of velocity in a spectral line with a spatial coordinate is predicted for a cloud uniformly rotating.

The first result is that the spin axes are not randomly orientated on the largest cloud scales. Systematic gradients in velocity extend in some cases over tens of parsecs. If clouds in our Galaxy derive their spin directly from
the shear on galactic scales, then we would expect the spin axes to be aligned with that of the Galaxy. This is, in fact, what is found with approximately equal numbers orientated towards the north and south galactic poles.

The smaller clouds and cores, however, do not follow the trend, consistent with random orientations over all directions. This indicates that they do not derive their present angular momentum from the galactic shear but turbulent processes or interactions between fragments are responsible. A further highly relevant fact is that the directions of cloud rotation and elongation are not statistically related.

The rate of rotation in radians per second, $\Omega$, is correlated with the cloud size, $R$. Smaller clouds rotate faster, in general. In theory, conservation of cloud angular momentum, $J_c$, for a cloud of mass $M_c$, size $R_c$ and rotation speed $v_{rot}$ would predict that the product of rotation speed and radius remain constant:

$$J_c \propto M_c v_{rot} R_c \propto M_c \Omega R_c^2.$$  (3.17)

This implies $\Omega \propto R_c^{-2}$. The observed trend, however, is remarkably shallower with $\Omega \propto R_c^{-0.6}$:

$$\frac{\Omega}{10^{-14} \text{s}^{-1}} = 10^{0.34} \left( \frac{R}{1 \text{ pc}} \right)^{-0.56}.$$  (3.18)

Hence, although smaller clouds rotate faster, the increase is not consistent with angular momentum conservation.

This is succinctly expressed in terms of the angular momentum per unit mass, $J/M$, called the specific angular momentum. For any individual core, the radial velocity gradient may not be a good indicator of its specific angular momentum. However, the distribution of deduced angular momenta from a large sample of cores with different random velocity fields is close to the distribution of actual angular momenta of these model cores if one assumes $J/M = p \Omega R^2$. For centrally condensed cores, the standard value of $p = 0.4$ overestimates the mean intrinsic angular momentum by a factor of 3. On measuring according to $J/M = 0.4 \Omega R^2$, we find that $J/M \propto R^{1.4}$. This suggests that, in most scenarios, the smallest clouds and condensations have lost their angular momentum during their contraction. Much research has been expended in deriving explanations for this fact with the process of magnetic braking being best explored (see §7.6).

The tightest correlation is between $J$ and $M$. This is, in part, because both these quantities have been determined over many orders of magnitude. Cloud masses range from 0.1 to 10,000 $M_\odot$ and angular momentum from
$10^{-4}$ to $10^6$ in the units of $M_{\odot}$ km s$^{-1}$ pc (see Table 3.5). The relationship in this measurement unit takes the form

$$J = 10^{-2.22} \left( \frac{M}{M_{\odot}} \right)^{1.68}.$$ \hspace{1cm} (3.19)

This is fully consistent with the above formula for $J/M$ combined with $M \propto R^2$, as shown above from Eq. 3.12. The tightness of this correlation, however, implies that the loss of angular momentum is related closer to the decrease in mass rather than the contraction. This is thought to be indicative of the physical mechanism.

Since we expect the specific angular momentum to be conserved during a contraction, it is useful to tabulate the typical values for $J$ and $J/M$. It is then immediately clear from the final columns of Table 3.5 that angular momentum is not just sub-divided into the fragments but is transferred around, being extracted from the smaller scale structures. In fact, in the absence of this extraction, the centrifugal force would soon prohibit the contraction (see §7.6).

Table 3.3 A summary of the rotational properties of star formation structures and objects. Note that the angular momentum per unit mass $J/M$ decreases by many magnitudes as the scale decreases.

<table>
<thead>
<tr>
<th>Structure</th>
<th>$\Omega$ s$^{-1}$</th>
<th>$J$ (M$_{\odot}$ cm$^2$ s$^{-1}$)</th>
<th>$J/M$ (cm$^2$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Giant MC</td>
<td>$3 \times 10^{-15}$</td>
<td>$3 \times 10^{29}$</td>
<td>$3 \times 10^{25}$</td>
</tr>
<tr>
<td>Molecular clump/cloud</td>
<td>$0.3-3 \times 10^{-14}$</td>
<td>$10^{22}-10^{27}$</td>
<td>$10^{23}$</td>
</tr>
<tr>
<td>Molecular core</td>
<td>$1-10 \times 10^{-13}$</td>
<td>$3 \times 10^{21}$</td>
<td>$0.4-30 \times 10^{21}$</td>
</tr>
<tr>
<td>Wide Binary$^a$</td>
<td>$2 \times 10^{-11}$</td>
<td>$10^{21}$</td>
<td>$10^{21}$</td>
</tr>
<tr>
<td>Circumstellar disk $^c$</td>
<td>$2 \times 10^{-10}$</td>
<td>$5 \times 10^{18}$</td>
<td>$5 \times 10^{20}$</td>
</tr>
<tr>
<td>Planet (Jupiter orbit)</td>
<td>$2 \times 10^{-8}$</td>
<td>$10^{17}$</td>
<td>$10^{20}$</td>
</tr>
<tr>
<td>Close Binary$^b$</td>
<td>$6 \times 10^{-6}$</td>
<td>$10^{19}$</td>
<td>$10^{19}$</td>
</tr>
<tr>
<td>T Tauri star</td>
<td>$2 \times 10^{-5}$</td>
<td>$5 \times 10^{17}$</td>
<td>$5 \times 10^{17}$</td>
</tr>
<tr>
<td>Present Sun</td>
<td>$2 \times 10^{-6}$</td>
<td>$10^{15}$</td>
<td>$10^{15}$</td>
</tr>
</tbody>
</table>

$^a$ 10$^4$ year period

$^b$ 10 day period

$^c$ 100 AU, 0.01 M$_{\odot}$ disk
3.6 Structural Analysis: Fractals and Filaments

The GMCs and large clouds are highly clumped, as evident from the CO maps. To quantify this, we combine an observed GMC mass and a typical extinction-derived column density into the predicted mean density:

\[
\begin{align*}
n(H) &= 84 \left( \frac{M}{10^6 M_\odot} \right)^{0.5} \left( \frac{N(H)}{1.5 \times 10^{22} \text{cm}^{-2}} \right)^{-3/2} \text{cm}^{-3},
\end{align*}
\] (3.20)

In contrast, we infer densities exceeding 1000 cm\(^{-3}\) from the column densities of the defined clouds and clumps. Hence, volume filling factors are typically under ten per cent. Surprisingly, we still have little knowledge of the inter-clump medium in a molecular cloud which could be atomic or molecular.

A fractal or hierarchical description of clouds is suggested by the lack of a scale in the power-law mass distributions of clumps. We have seen that the gas is indeed highly textured. The ‘self-similarity’ is present on scales stretching from hundreds of parsecs down to a tenth of a parsec, from spiral arms down to molecular clumps. Furthermore, cloud boundaries show a complex structure and have highly irregular shapes that do not correspond to equilibrium configurations. Rather, they resemble the amorphous terrestrial clouds, which are known to be transient dispersing structures.

The fractal dimension of a cloud perimeter, \(D\), is found by relating the perimeter length to the cloud area, \(P \propto A^{D/2}\), so that simple, rounded shapes correspond to \(D = 1\). Analysis of observed clouds yields a projected fractal dimension \(D = 1.3 \pm 0.3\) in several cases. This value is intriguingly similar to fractal dimensions measured in turbulent flows.

It is not yet clear how much interstellar structure is fractal. Quite commonly observed regular features are filaments and shells, detected in dust and molecular tracers. Filaments can extend several parsecs and are marked by a string of embedded starless and protostellar cores. These elongated structures are not generally aligned with rotation or magnetic field axes. Filaments can be remarkably straight, but there are also examples of curved and wavy forms. Spectacular long, twisted structures were observed by the Hubble Space Telescope in the Lagoon nebula. Elsewhere, a system of helix-like, interwoven dark filaments were found in the Rosetta nebula.
3.7 Summary: Invisible Clouds

We have recorded many correlations between cloud properties which need explaining. All this knowledge arises from the clouds we observe. Are these the clouds which actually form the stars or are they the clouds which, in this state, make themselves obvious? In our snapshot of the Universe, clouds which have a fleeting existence would not be fairly represented. Yet, we cannot sweep search a volume of our Galaxy. We could also be overlooking a population of invisible clouds, too cold to detect in molecular emission lines or dust emission. There may also be a population of clouds too diffuse to distinguish from the background. To the opposite extreme, a large collection of compact clouds of high density and very low mass have also been proposed as a means to hide dark matter within the interstellar medium.

Such claims are not easy to confirm or dismiss until decisive observations are made. Nevertheless, we proceed in the knowledge that the molecular clouds we observe contain protostars and are surrounded by young stars. We also note that the young stars we observe are almost exclusively associated with molecular clouds. Exceptionally, we detect young stars without any obvious parent cloud and we then speculate that the star has been orphaned either by rapid cloud dispersal or as a runaway.