Chapter 7
Surveying the Molecular Milky Way

> *Aren't the clouds beautiful? They look like big balls of cotton... I could just lie here all day, and watch them drift by... If you use your imagination, you can see lots of things in the cloud formations... What do you think you see, Linus?*
> *Charles M. Schulz, The Complete Peanuts, Vol. 5: 1959–1960*

Abstract After a brief review of the Galactic molecular surveys, we discuss the distinct types of Galactic clouds. We briefly describe the large GMCs and then turn our attention to the smaller objects, like dark clouds, but with an emphasis on the flotsam of the ISM, the small diffuse and translucent clouds. We also discuss how recent work on diffuse clouds is revising our ideas of this component of the ISM.

7.1 Introduction

Discussing the molecular component of the ISM is difficult because the term "molecular component" means different things to different people. The FUSE observations by Shull and co-workers show that very few sight lines are free of H_2 absorption. It is striking that at least some H_2 is detectable along nearly 90% of lines of sight at high Galactic latitude (e.g., Snow 2005; Wakker 2006). Of course, most of the directions have only trace amounts of H_2, with N(H_2) values of order 10^{14} cm^{-2}, six or more orders of magnitude below the atomic hydrogen column density. So, although molecular gas is present along these sight-lines, we will not consider them part of the molecular component of the ISM. For this chapter we define a *molecular* line of sight as one with an $n(H_2)/n(H_{total})$ ratio of at least a few percent. Gillmon and Shull (2006) used FUSE data to show that half of the sky at $|b| \geq 30°$ has sheetlike cirrus structures with molecular hydrogen fractions between 1%-30%. These clouds have been considered CNM and their molecular content was largely ignored. It is likely that some of this gas has been misidentified as "dark gas"; while not all of it may be traceable with CO(1-0) emission, there are other ways to trace it spectroscopically (see Sect. 8.4). Thus, diffuse molecular clouds can be mostly atomic and yet still be referred to as molecular clouds. Translucent clouds have higher fractions of molecular gas and are not usually considered part of the CNM (however, see Sect. 1.6). The two principal properties shared by diffuse and translucent clouds are turbulence as their principal structuring mechanism and lack

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of star formation. In these respects, these objects are very different from the dark molecular clouds or the envelopes of GMCs. Reviews of the molecular component of the ISM that do not focus primarily on the star-forming aspects of the molecular gas include those by Combes (1991) and Heyer and Dame (2015).

The CO(1-0) transition was the first systematic tracer of the molecular gas and so we begin with a discussion of what was revealed by the early CO surveys in the 1970s. We then discuss how the molecular gas is organized as "big clouds" and "little clouds", and the sometimes misleading terminology employed in the taxonomy of the latter objects. Given the excitation characteristics of CO(1-0), it is not suitable for detecting molecular gas where $N(H_2) \lesssim 10^{19}$ cm^{-2} (because the volume density in these regions is almost always significantly less than 10^2 cm^{-3}).[1] Nevertheless, most of our knowledge of molecular cloud comes from CO observations. We briefly review them in the next sections.

7.2 The CO Surveys Along the Galactic Plane

7.2.1 Early Results

The study of molecular clouds began in earnest with the detection of the lowest CO rotational transition at 115.271 GHz in 1970 by Wilson et al. (1970). Large-scale surveys of CO(1-0) emission are considered to be maps of the molecular gas distribution of the Galaxy with most of this gas contained in discrete, gravitationally bound entities knowns as molecular clouds (a counterpoint to this view is discussed at the end of this chapter). Most of our knowledge of molecular clouds has come from many extensive surveys conducted in the 1970s and 80s. Because the molecular gas is associated with the thin disk, all early CO surveys were made at relatively low Galactic latitudes. The early CO surveys (Burton et al. 1975; Scoville and Solomon 1975; Cohen and Thaddeus 1977; Burton and Gordon 1978; Stark 1979; Robinson et al. 1984; Israel et al. 1984; and Sanders et al. 1984) focused almost exclusively on latitudes within a few degrees of $\ell = 0°$. It was not until relatively recently that wide-latitude, fairly complete surveys of the Galactic molecular distribution became available (Dame et al. 1987, 2001). Interior to the Sun, the distribution of molecular gas defines a thin plane. However, beyond 12 kpc the midpoints of the molecular distribution deviate significantly from $\ell = 0°$ and mapping the molecular outer Galaxy was more problematic. Specific, targeted surveys (using IRAS sources to track the molecular gas) were carried out by Wouterloot and Brand (1989) and Wouterloot et al. (1990).

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[1] It is this diffuse molecular component that has recently caused much confusion about its quantity and importance in the ISM. The rise in popularity of the idea of a "dark" molecular component (in its original definition, a component of molecular gas that was spectroscopically undetectable, and, later, one that could not be traced by the CO(1-0) transition) will be examined in the next chapter.

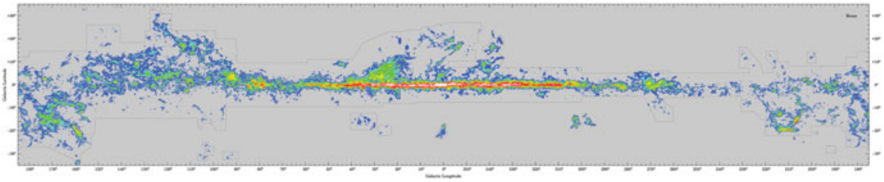

Fig. 7.1 The Dame et al. (2001) CO(1-0) map of the Galaxy made with the 1.2 m millimeter-wave telescopes at Cambridge, Massachusetts and Cerro Tololo, Chile. The color scale represents the log of the CO(1-0) velocity-integrated line emission from ~ 0 to 2.4. The angular resolution is $9'$ over most of the map, but lower ($15'$ or $30'$) over some regions. A large version of this map is available at https:///www.cfa.harvard.edu/mmw/MilkyWayinMolClouds.html Figure courtesy of Tom Dame

The principal results from the early CO(1-0) surveys are the following: (1) Surveys in the CO(1-0) line are effectively surveys of H_2. (2) The bulk of the molecular gas is distributed in the inner Galaxy along the Galactic plane. The mass surface density peaks at the Galactic Center (GC) and then decreases rapidly between 1–3 kpc from the GC. There is a strong concentration between 3–6 kpc known as the "Molecular Ring",[2] and then a gradual falloff to the Solar Circle and beyond. See, for example, the radial CO distribution in Clemens et al. (1988). (3) Individual contiguous objects exist and are more clearly delineated when velocity information is used in addition to the two-dimensional spatial data. The bulk of the molecular gas along the plane is tied up in large entities known as Giant Molecular Clouds (GMCs). These objects are tens of pc in size and 10^3-10^6 $M_\odot$ in total mass. Their properties make them among the largest entities in the Milky Way. (4) The average gas number density, $n(H_{total})$, inside the Solar Circle is of order 1 cm^{-3}, while the average density in GMCs is about 10^2 cm^{-3}, so that the volume filling factor of GMCs along the Galactic Plane is $\sim 1\%$. (5) Most of the star formation in the Galaxy is in GMCs.

Figure 7.1 shows the Galactic CO(1-0) emission from the most recently published survey by Dame, Hartmann, and Thaddeus based on over 270,000 CO spectra. Several characteristics of the molecular distribution are readily apparent: the most intense CO(1-0) emission is located at the Galactic center and in the inner Galaxy (significantly different from the HI distribution that has 70% of its mass outside the Solar Circle—e.g., Dickey and Lockman 1990). The strong CO emission is confined to low latitude, although regions known to contain dark clouds such as the Taurus-Auriga or ρ Ophiuchi cloud complexes lie at higher latitudes and, consequently, must be fairly nearby.

Even a perfunctory glance at Fig. 7.1 indicates that the molecular emission regions at the higher latitudes have lower surface brightness than regions towards the Galactic center or along the plane in the Inner Galaxy. The higher latitude

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[2] These values are for a Solar Circle at 8 kpc; using the originally accepted value of 10 kpc would increase the galactocentric locations by 20%.

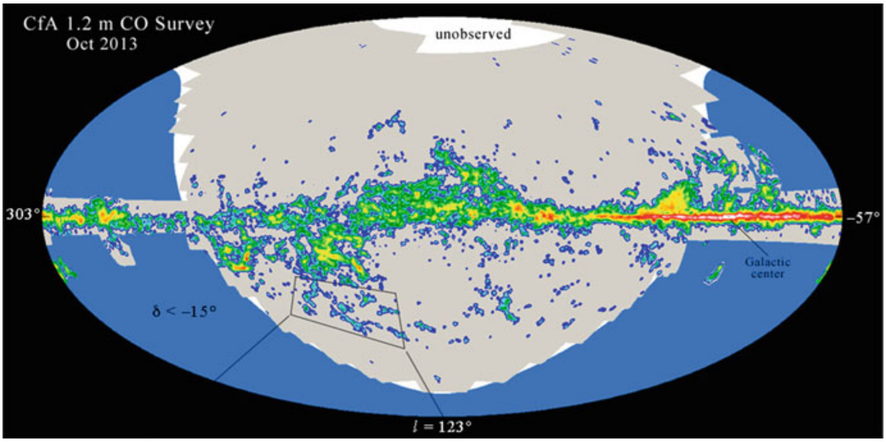

Fig. 7.2 The most recent CO map of the Galaxy from Thaddeus and Dame that extends the map in Fig. 7.1 to higher Galactic latitudes. See https://www.cfa.harvard.edu/mmw/ for more details and progress reports. The Aitoff projection of the CO data is centered at $\ell = 123°$ to show the high-latitude molecular clouds more prominently. Figure courtesy of Tom Dame

CO-emitting regions in the figure (note that the latitude extent of the map ranges from +32.5° to −32.5°) are relatively nearby (a few hundred parsecs) and, with the exception of the Orion molecular clouds, are composed of smaller molecular clouds whose basic properties are discussed below.

7.2.2 *Recent Surveys*

Most of the Galactic plane CO surveys were completed by the late 1980s, and only a few have been made in recent years from ground-based mm-telescopes. The emphasis in mm-wave radio astronomy has shifted to studies of individual clouds or star-forming regions, and, most notably, to external galaxies. However, the Thaddeus/Dame mm-wave group at the Harvard-Smithsonian Center for Astrophysics continues their systematic survey of the CO(1-0) line in the Galaxy and as of 2013 their mapped area had extended over a significant portion of the high-latitude sky (see Fig. 7.2).[3]

In the late 90's the Five College Radio Astronomy Observatory's (FCRAO) 14-m mm-wave telescope was used to map a substantial portion of the Outer Galaxy between 102.49°–141.54° in Galactic longitude and −3.03° to +5.41° in latitude. With a spacing of 50″ (about the beam size at 115 GHz), this survey includes nearly

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[3] As of the summer of 2016, the Harvard-Smithsonian mm-wave group had completely mapped the Northern Galactic Hemisphere in the CO(1-0) line.

1.7 million spectra and represents perhaps the best combination of coverage and angular resolution over a wide area. Heyer et al. (1998) described the initial results. Voids are present in the molecular distribution possibly from the action of UV radiation fields and stellar winds. Radial profiles of the mass surface density and variations of the midplane and scale height of the molecular distribution in the outer Galaxy are presented completing the picture of the distribution of GMCs begun with the early surveys. Most surprisingly, a great deal of low surface brightness, low mass surface density molecular gas is present in the spiral arms of the Galaxy and in the vicinity of GMCs. Blitz and Williams (1999) refer to this gas as "the chaff" and link it with the smaller, lower extinction molecular clouds discussed below. This raises the question of what fraction of the overall molecular gas is contained in these smaller objects. Regarding the molecular gas, the early surveys implied that 90% of the H_2 mass is tied up in GMCs, but the results from the more sensitive, better sampled FCRAO survey indicate that up to 50% of the CO *intensity* may be contained in this low surface brightness gas surrounding the dense cores of a GMC (Carpenter et al. 1995).

Galactic CO emission peaks in the Molecular Ring at 3–6 kpc, and molecular gas dominates over atomic gas inside the Solar Circle (see figure 6 by Scoville and Sanders 1987). Beyond the Solar Circle, the molecular gas peters out rather rapidly and hydrogen in atomic form overwhelmingly dominates. Despite this, there are molecular clouds, even GMCs, beyond the Perseus arm (at around 11 kpc from the Galactic Center). Surveys by Kutner and Mead (1981),[4] Mead and Kutner (1988), Wouterloot and Brand (1989), Digel et al. (1994), and Heyer et al. (1998), established that molecular gas can be found out to 20 kpc, albeit in the form of isolated clouds. However, beyond a galactocentric radius of 16 kpc, the molecular mass surface density has dropped to $0.095\ M_\odot\ pc^{-2}$ compared to $0.5\ M_\odot\ pc^{-2}$ at the Solar Circle. The *Planck* survey, discussed in Chap. 5, in the 100 μm band offers a complementary view of the molecular gas distribution in the Galaxy, and Fig. 7.3 shows an early release of the *Planck* 100 GHz data for the whole sky showing emission from the CO(1-0) line since ^{13}CO and CMB contributions have been removed.

Early results on the Galactic CO emission detected by Planck were reported by the Planck Collaboration, Planck 2013 results, paper XIII (2014). The CO(1-0), (2-1), and (3-2) rotational transitions contribute significantly to the signal in the Planck 100, 217, and 353 GHz HFI channels. Preliminary extraction of the signals were compared to existing CO maps of the sky and give excellent results. However, it is important to point out that the Planck satellite produced imaging data. The 100 GHz survey is virtually useless for studying GMCs throughout the Galactic plane because of the lack of kinematic information. The *Planck* survey is likely to be more useful at high Galactic latitudes where the molecular clouds are isolated both spatially and in velocity.

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[4] Some of the detections of the initial paper were disputed by Solomon et al. (1983).

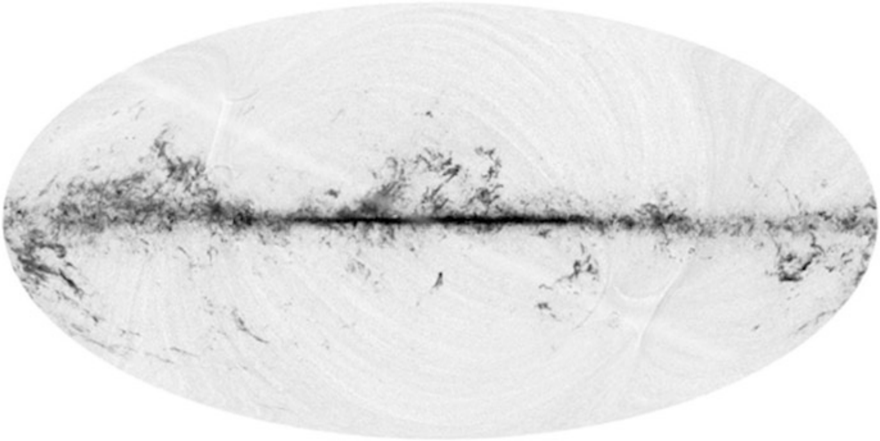

Fig. 7.3 The *Planck* CO(1-0) map of the entire sky based on imaging data in the 100 GHz channel. The contributions from ^{13}CO and the CMB have been removed. The molecular cloud distribution along the Galactic plane arises primarily from GMCs. CO emission away from the plane (i.e., at $|b| \geq 20°$) is relatively nearby, in the solar neighborhood. Compare this map with the CO(1-0) maps made with the Harvard-Smithsonian CfA 1.2 m telescope (see Figs. 7.1 and 7.2). Image credits: ESA/Planck Collaboration

7.3 Giant Molecular Clouds

The building blocks of the CO emission in Figs. 7.1 and 7.3 are enormous concentrations of molecular gas known as Giant Molecular Clouds or GMCs. They are among the largest individual entities in the Galaxy with masses ranging from 10^3 to 10^6 $M_\odot$, dimensions of up to 100 pc, temperatures around 10 K (at least away from star forming regions) and volume averaged densities of order 10^2 cm^{-3} (Blitz 1979; Sanders et al. 1985). By the end of the 1980s, large CO surveys of the Galactic plane had shown that nearly 90% of the H_2 in the Galaxy contains about 5000 GMCs with masses greater than 10^5 $M_\odot$ and of which about 1000 clouds with sizes greater than 50 pc and masses greater than 10^6 $M_\odot$ containing about half of the total H_2 mass (see, however, Sect. 7.4.3). More importantly, for Galactic evolution, virtually all of the most massive stars and most of the lower mass stars form in these structures. GMCs nearly always have clusters of OB stars associated with them and many of their names are identical to the accompanying OB association (e.g., Cep OB3, Ser OB1, Cyg OB1, *etc.*). The connection between GMCs and OB associations is so marked that the lower limit to the mass range for GMCs shows that clouds smaller than 10^3 $M_\odot$ cannot produce OB associations. In light of these considerations, in order to understand the stellar content of a galaxy and the overall life-cycle of stars, GMCs must be studied thoroughly.

The GMCs differ somewhat in their general properties depending on their location in the Galaxy. The overwhelming majority of molecular gas is inside the Solar Circle.[5] In general, local GMCs are the best-studied and their general properties are summarized in several review articles (e.g., Scoville and Sanders 1987; Solomon and Rivolo 1987; Friberg and Hjalmarson; Blitz 1991*a*,*b*; Combes 1991; Williams et al. 1999; Blitz and Williams 1999; Heyer and Dame 2015). GMCs are internally highly structured with the denser clumps occupying a small fraction of their total cloud volume ($\sim$10% - Lada 1990). Both the GMC as a whole and its constituent dense clumps are gravitationally bound with masses a factor of ten greater than a Jeans mass (see Chap. 11). The formation of O and B stars wreaks havoc within the GMCs and they do not appear capable of surviving more than a few generations of massive star formation (Franco et al. 1994). Cloud dispersal times are then 10^6–10^7 years after star formation begins.

The broad scenarios for molecular cloud formation have been widely discussed: (1) collisional agglomeration from smaller clouds (e.g. Kwan 1979; Scoville and Hersh 1979; Stark 1979); (2) a gravi-thermal instability in the Galactic plane (e.g. Parker 1966; Mouschovias et al. 1974; Elmegreen 1982a,b); and (3) formation in shock fronts (e.g. Woodward 1976). While much work has been done in this area (see review by Elmegreen 1990; Elmegreen and Palous 2006), a definitive answer still eludes us. The relatively short lifetime of GMCs compared to the Galactic rotation period implies that they are for the most part confined in or near the spiral arms of the Galaxy. This enables astronomers to trace the structure of the Galactic spiral arms using the global distribution of CO emission (Liszt 1984; Dame et al. 1986; Clemens et al. 1988).

Although we know how GMCs are destroyed, the support mechanisms before the onset of star formation for both the large and small molecular clouds are not fully understood. Self-gravity considerations imply that these objects should collapse on a few times the free-fall time scale [$t_{\rm ff} \sim (3G\rho)^{-0.5}$; less than a few times 10^6 years—see Genzel 1991 for a discussion of the energy balance of molecular clouds]. Recent work indicates that turbulence (either externally or internally driven) may be the principal supporting mechanism for molecular clouds (LaRosa et al. 1999, and references therein; Hennebelle and Falgarone 2012).

An important uncertainty for GMCs concerns their lifespan. Early estimates based on the fraction of H_2 compared to total nucleons in the ISM favored very long lifetimes ($\sim 10^9$ years). The idea is based on mass conservation arguments or continuity of the hydrogen mass between the various ISM phases (in this case, atomic, molecular, and ionized). It seems plausible that the mass flux from one phase to another should be balanced (see Scoville and Hersh 1979). Scoville (2014) then writes the mass flux equality as:

$$\dot{M}_{H_2 \rightarrow HI+HII} \;(\equiv M_{H_2}/\tau_{H_2}) = \dot{M}_{HI+HII \rightarrow H_2} \;(\equiv M_{HI+HII}/\tau_{HI+HII}) \qquad (7.1)$$

Since in the inner Galaxy, most of the hydrogen nucleons are sequestered in H_2, the lifetime of the molecular gas is significantly longer than the HI, which is thought

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[5] The distribution of molecular gas with respect to Galactic radius can be seen in Fig. 8.1.

to be 10^8 yr based on their dynamical time scale or orbital passage between the spiral arms. However, the recognition that dynamical processes were critical to the formation and destruction of these objects led to estimates more in the 10^7–10^8 year range (e.g., Blitz and Shu 1980). By the late 1980s, almost everyone in the field agreed that GMC lifetimes depended on how quickly star formation begins, in the sense that the onset of star formation would destroy the cloud in 10^6–10^7 years. Methods to determine their ages have employed (1) determining the HI/H_2 ratio, (2) ^{13}CO depletion on dust grains, (3) the deuterium fractionation of N_2H^+, and (4) ratio of ortho-H_2D^+ to para-H^2D^+. The first method basically assumes that the formation of GMCs occurs within large atomic regions, so that the H_2/H ratio is small at first and then increases so that by the time star formation begins the clouds is almost entirely molecular. To exploit this idea, Goldsmith and Li (2005) proposed to obtain cloud ages using the abundance of HI Narrow Self-Absorption (HINSA) lines in clouds. These absorption lines are due to the presence of atomic hydrogen within the molecular cloud. The strength of the HINSA features decreases as the cloud ages and becomes progressively more molecular until an equilibrium is reached between the formation of H_2 and its destruction by cosmic rays.

Without question, the study of GMCs dominates observational molecular astrophysics. However, the nearest GMC to the Sun is the Orion molecular cloud system, about half a kiloparsec away. There are molecular clouds closer to the Sun than that, but they are much smaller than GMCs. Although GMCs contain very dense clumps, their envelope and interclump medium share some of the properties of the diffuse molecular gas discussed in this book. We will now focus on the smaller clouds and, in particular, the diffuse and translucent molecular clouds which are clearly part of the gas inventory of the *diffuse* ISM.

7.4 The Smaller Molecular Clouds

Historically, small molecular clouds ($\lesssim 10^3$ $M_\odot$) were divided into diffuse molecular clouds studied primarily by optical and ultraviolet absorption lines against the background continuum of early type stars, and dark clouds, so named because their large column density of dust obscured background starlight.

An important development occurred in the late 1980s, when John Black and Ewine van Dishoeck proposed a quantitative distinction, dividing the small clouds into three broad categories defined by visual extinction: diffuse ($A_V < 1$ mag), translucent (1 mag $\leq A_V \leq$ 5 mag), and dark ($A_V >$ 5 mag) (Van Dishoeck and Black 1988). This was not a mere taxonomic exercise. These cloud types represent different physical and chemical states of molecular gas. The astrochemistry of diffuse clouds is regulated primarily by photoprocesses and molecular abundances tend to be low. Before 2000, they had been studied mainly by optical astronomers using a limited set of absorption lines. In contrast, dark cloud chemistry is dominated by collisional processes and typically leads to higher abundances of most molecular species. Consequently, the column densities of many species suffice for radio spectroscopic studies. Because the diffuse and dark clouds were studied primarily by different techniques and communities in the late 20^{th} century, the literature on these objects did not overlap significantly (notable exceptions include the work of Steve Federman, Robert Willson, Ken Lang, Harvey Liszt, and Robert Dickman), especially throughout the 1970's and early 80's, when millimeter receiver technology was in its infancy. The transition objects, the translucent clouds, could be studied by both techniques and represent an astrochemical regime where both photoprocesses and collisional reactions are important. Moreover, for the most important tracer of molecular gas, CO, the translucent clouds represent the regime where the CO abundance with respect to H_2 rises precipitously from less than 10^{-6} to $\sim 10^{-4}$ and the carbon content changes from atomic form to mostly CO over an increase of an order of magnitude in $N(H_{total})$ (Van Dishoeck and Black 1988). Another significant difference between dark molecular clouds and the translucent ones is that the former, for the most part, are gravitationally bound while the latter are not. Below, we will take a closer look at each type of object.

7.4.1 Dark Clouds

The small, dark clouds tend to be local objects because at low Galactic latitudes and distances much greater than a kiloparsec their modest CO emission tends to blend with that of the background GMCs. Thus, only the nearer objects or those at high latitudes are seen without confusion. Examples of isolated small clouds are Lynds 134 and Barnard 68 (see Figs. 7.4 and 1.7, respectively), while some dark cloud complexes include the Taurus-Auriga-Perseus dark clouds and the ρ Ophiuchi clouds (see Astronomy Picture of the Day—http://apod.nasa.gov.apod—for 2009 July 8). Isolated clouds tend to be a few parsecs or less in size while dark cloud complexes made up of many dozens of small clouds can stretch for tens of parsecs (e.g., the Taurus-Aurigae dark cloud complex; Ungerechts and Thaddeus 1987). At the smallest extreme are the Bok globules (Bok et al. 1971; Bok 1977) which are compact, spherical entities of size a few tenths of a parsec and mass $\sim 10\ M_{\odot}$. Dark clouds were recently reviewed by Bergin and Tafalla (2007) with emphasis on their star-forming capabilities.

One of the earliest systematic searches for obscured regions or dark nebulae in the Galaxy was conducted by Barnard (1919) and included a catalog of 182 such objects. Interestingly, in that work, Barnard left open the possibility that some of these regions were not dark nebulae but could be produced by "vacancies" in the stellar distribution. Later, Barnard (1927) published a photographic study of dark nebulae distributed along the Galactic plane; only 3 of 50 photographic plates were at Galactic latitudes (old Galactic coordinates) $|b^I| \geq 20°$, and there were none above $|b^I| = 25°$. This attests to the difficulty of detecting obscured areas at high Galactic latitudes where the stellar density decreases rapidly and fluctuations below the mean in the number of stars over a small region can mimic obscuration by dust.

Fig. 7.4 Three-color SDSS2 image (blue, red, infrared—York et al. 2000) of the dark molecular cloud Lynds 134 (also known as MBM 36). The image size is 1.5°× 1.5° centered at (RA, Dec 2000.0) = (238.40°, −4.59°). The most obscure regions of this cloud have $A_V > 6$ mag. Consequently, no stars beyond the cloud are visible through the opaque central regions; any stars projected there are in the foreground. However, note that a diffuse or translucent envelope surrounds the cloud

Contemporaneously, P.J. Melotte and K. Lundmark conducted a whole-sky search for dark nebulae which was reported by Lundmark (1926). Melotte and Lundmark used photographic plates taken during the Franklin-Adams 1911 sky survey that have an approximate limiting photographic (blue) magnitude, m_{pg}, of 15. Melotte and Lundmark attributed any five-fold or greater decrease in stellar surface density over an area of more than a few square degrees to the presence of a "dark" nebula. In this manner, they identified 1550 dark nebulae in the regions covered by the Franklin-Adams plates, with many of the regions occurring at high Galactic latitudes (see Fig. 7.5).

In the years that followed, Khavtassi (1955), Roschkovsky (1955), and Schoenberg (1964) compiled lists of dark nebulae mostly confined to the Galactic plane with few objects at $|b| \geq 20°$, but only the work of Beverly Lynds in 1962 produced a complete survey of all dark nebulae visible from the northern hemisphere. In her work, 879 fields photographed on red- and blue-sensitive photographic plates with the Palomar Observatory 48-inch Schmidt were examined for the presence of obscuration (Lynds 1962, 1968). The resulting 1801 objects (many of which are spatially related to each other) represent all the easily discernible dark clouds at $\delta > -33°$. Recent surveys of dark clouds were reviewed by Dutra and Bica (2002).

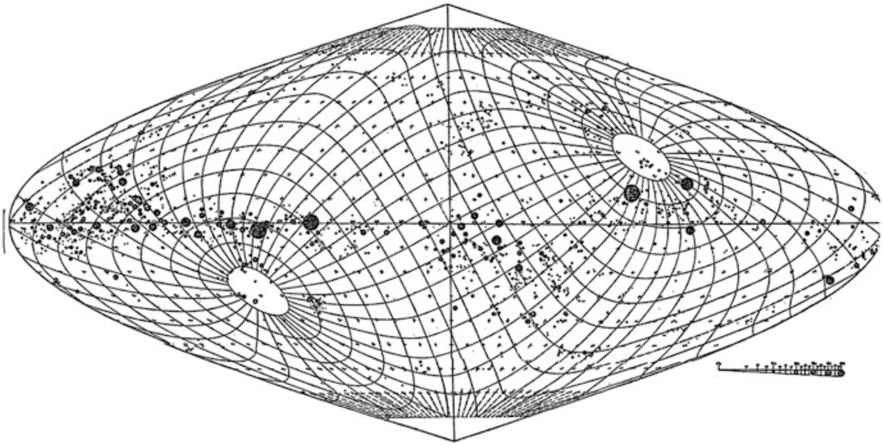

Fig. 7.5 The Melotte and Lundmark dark clouds from a paper by Lundmark (1926). The *dark clouds* denoted on map by *black circles* are based on regions of decreased stellar density identified from photographic plates taken during the Franklin-Adams 1911 sky survey. The map is centered at old Galactic coordinates (ℓ^I, b^I) = (180.0°, 0.0°) and the superimposed equatorial coordinate grid is epoch 1900. The wedge at lower right displays the size of the obscured region from 1° to 5°

Of particular note are the studies by Feitzinger and Stüwe (1984) and Hartley et al. (1986), both based on looking for obscuration on the ESO/SERC plates, and that of Clemens and Barvainis (1988) using the Palomar Sky Survey prints.

These studies identified dark clouds by their obscuration of background stars. The visual extinction through the most opaque regions of a dark cloud is typically more than five magnitudes and the dust responsible for the obscuration is typical of regions where hydrogen column densities are greater than 10^{21} cm^{-2}. The overwhelming fraction of their gas is in molecular form and their masses range from a few tenths to hundreds of solar masses. Like GMCs, dark clouds are distributed mainly along the Galactic plane, although they have a wider latitude distribution than the GMCs. When interstellar radio emission lines were discovered in the 1960s, dark clouds were among the first objects studied (*e.g.*, Heiles 1968; Palmer et al. 1969; Penzias et al. 1972).[6]

Initial surveys of the more important astrophysical molecular species in dark clouds included OH by Cudaback and Heiles (1969) and Crutcher (1973); H_2CO by Dieter (1973); and CO by Dickman (1975). Others, for example, Snell (1979), studied the molecular properties of a limited sample of dark clouds. In all these studies, the Lynds list provided the sources which the various observers studied. It soon became apparent that all dark clouds with extinction greater than a few

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[6] The drop in HI column density as determined from the 21 cm line in the direction of dark clouds (as compared to their surroundings) implied that the gas thought to be present in the dark cloud was most likely molecular in form.

magnitudes showed molecular emission or absorption lines. In particular, Dickman (1975) reported observations of CO(1-0) emission from 63 of the 64 Lynds dark clouds he surveyed, including all four sources at $|b| \geq 25°$. By the late 1970s it was widely held that if an interstellar cloud had $A_V > 2$ magnitudes, it was almost certain that at least emission from CO and OH would be present. Moreover, the relationship between CO and extinction is quite linear with the ^{13}CO(1-0) transition being the species of choice because of its low optical depth in all but the densest cloud cores (Dickman 1978). The dust obscuration in dark clouds implies significant column densities of gas as is confirmed by observations of various molecular species. With core densities of 10^4 cm^{-3}, dark clouds were associated with sites of low mass star formation, especially T Tauri stars. Some dark clouds, such as TMC-1 are among the principal regions for the discovery of new molecules and, like GMCs, dark clouds comprise the dense component of the ISM.

7.4.2 Translucent Molecular Clouds

According to the van Dishoeck and Black hierarchy, interstellar clouds with extinctions between 1 and 5 magnitudes are called "translucent" molecular clouds. This category is not based only on extinction; from the chemical point of view it is in this regime where the bulk of the carbon changes from C^+ to CO. This drives the CO/H_2 abundance from $\sim 10^{-6}$ to 10^{-4}. Effectively, this meant that the CO column density in these types of clouds was high enough to allow detection as mm-wave receivers improved in the early 1980s. Some of the Lynds "dark" clouds actually have peak extinctions *less than* 5 magnitudes (e.g., L1642—see extinction map by Sandell et al. 1981) so that, technically, they are likely translucents. However, the first real systematic study of translucent clouds came as a by-product of the discovery of the high-latitude molecular clouds (see Chap. 9). Most of these have $A_V < 5$ mag and so can be considered translucent or diffuse molecular clouds. The high-latitude molecular surveys by Magnani et al. (1985) revealed another distinction between dark and translucent clouds. The latter are not gravitationally bound and consequently are dissipating on the sound-crossing time scale of 10^6 yr. For instance, comparing the SDSS red/blue/infrared image of L134 (coincidentally also a high-latitude molecular cloud with a Galactic latitude of +36°) shown in Fig. 7.4 with a typical translucent high-latitude cloud, MBM 54 (see Fig. 7.6), one can easily see the different dynamics at work in both types of cloud. L134 is compact and dense, while MBM 54 is less dense (you can see more stars through it) and more ragged in morphology.

One of the problems in mapping translucent high-latitude clouds is their proximity to us. Although not significantly larger than dark clouds, their average distance tends to be a few hundred pc or less so that they often subtend several square degrees in the sky. Thus, a fully-sampled map of a translucent cloud such as MBM 16 can take nearly 10^4 spectra even at the relatively low spatial resolution of $8'$ (see Fig. 5.2). Despite the large time investment, several complete maps

Fig. 7.6 Same type image as Fig. 7.4, but of the high-latitude molecular cloud MBM 54 from the SDSS2 survey. This is a translucent cloud in contrast to dark cloud in Fig. 7.4; note both the filamentarity of MBM 54 and that stars are clearly visible through the structure The image is 1.5° by 1.5° centered at (RA, Dec 2000.0) = (347.32°, 18.48°). The large spiral galaxy in the background is NGC 7497

of translucent clouds over very large regions have been made (e.g., Pound and Goodman 1997; Yamamoto et al. 2003; Shore et al. 2003, 2005). These maps show that the translucent clouds have clumpy structure like dark clouds, but with generally lower column densities ($\sim 10^{20}$ cm^{-3} vs. $\geq 10^{21}$ cm^{-3}).

Comprehensive searches for star-formation in translucents with peak $A_V \leq 3$ mag have not yielded any viable candidates (McGehee 2008). However, some researchers claim that signs of star forming activity are present. For example, Kun (1992) found Hα emitting stars projected on or near known translucent clouds, but it should be noted that not all such objects are T Tauri stars or pre-main sequences stars. Li et al. (2000) found three x-ray emitting stars near MBM clouds using the ROSAT point source catalog, but the follow-up work to determine whether these are or pre-main sequence objects has not yet been done. For the moment, no unambiguous sign of star formation has been found in any translucent cloud with A_V less than 3 magnitudes in its most obscured region. The cloud known as Lynds 1453/4/7/8 or MBM 12 does have significant star formation, actually harboring a small T-association (Luhman 2001), but extinction measurements for this region reveal a maximum value of 6.8 mag (Schlegel et al. 1998). According to the van Dishoeck and Black criterion this is a dark cloud, so its harboring a T-association is not so surprising. Figure 7.7 makes clear that there is a clear separation between

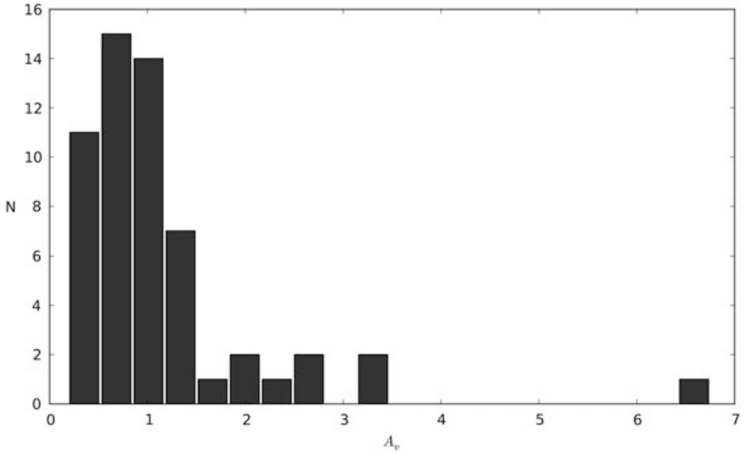

Fig. 7.7 Histogram of the high-latitude molecular clouds from the MBM catalog as a function of A_V. The peak extinction is derived from E(B-V) from the Schlegel et al. (1998) dust maps using R = 3.1. The cloud at the far right of the histogram with the greatest A_V value is MBM 12 which harbors a small T association (Luhman 2001) and is also a Lynds (1962) dark cloud complex (L1453-4, L1457-8)

MBM 12 and the other MBM clouds as far as peak extinction. L1642 or MBM 20 has two binary T Tauri stars in its core region (Sandell et al. 1987). Schlegel, Finkbeiner, and Davis determine a peak A_V of only 2.2 mag, but the actual peak extinction is likely significantly higher (see Sandell et al. 1981). A thorough review of the star-formation situation at high Galactic latitude is available in McGehee 2008.

That the translucent clouds would not be star-forming sites might have been inferred from their dynamic status. Virial analyses of the high-latitude cloud showed from the beginning that many of these clouds were not gravitationally bound (e.g., Blitz et al. 1984). Exceptions such as L1642 that are gravitationally bound (Liljestrom 1991) are also forming stars. However, aside from a few objects, the bulk of the known translucent clouds are not forming stars and have dynamics dominated by turbulence. The issue of turbulence in these clouds will be discussed further in Chap. 11.

In some respects, the distinction between translucents and diffuse clouds is academic. The classification is based on the maximum extinction in the cloud, but it ignores the filling factor for regions at that maximum extinction. A translucent core region has a diffuse molecular envelope—in all cases, and this envelope often contains a considerable amount of matter, sometimes rivaling the mass of the core region (e.g., Cotten and Magnani 2013). Dark clouds and GMCs also have diffuse molecular envelopes, something that is often ignored in discussion of these objects. We will examine this question in detail in Chap. 8.

7.4.3 Diffuse Molecular Clouds

Diffuse molecular clouds are hard to characterize because throughout the latter part of the 20^{th} century they could only be probed in absorption along the infinitesimally small solid angle to the background continuum source, almost always a star but sometimes an extragalactic source. Based on studies of color excess over large areas (*e.g.*, Knude 1979) diffuse clouds are thought to be a few pc in size. Originally, they were considered to have extinctions less than 1 or 2 visual magnitudes and were thought to range in physical properties from what is sometimes referred to as a "standard cloud" (Spitzer 1978), to objects with significantly more extinction and column density. Spitzer characterized standard clouds statistically as having $N_H \sim 3 \times 10^{20}$ cm^{-2} and an interception rate in the disk of 6.2 clouds per kiloparsec (Spitzer 1985). Many of the sightlines typical of a standard cloud show molecular absorption lines even if the bulk of the gas is atomic. Spitzer also described a "large cloud" which has a visual extinction of nearly 1 magnitude and an interception rate of 0.8 per kiloparsec. Given current astrochemical models, these objects have a significant portion of their gas content in molecular form. With densities of order 1 cm^{-3} (Spitzer 1978) for standard clouds and perhaps an order of magnitude more for Spitzer's large clouds, these objects have masses in the 0.01–10^1 $M_\odot$ range.

In 1965, Beverly Lynds compiled a catalog of reflection or emission areas as determined from the blue and red POSS plates (Lynds 1965).[7] There are many more of these Lynds Bright Nebulae (LBN) at high Galactic latitude than there are Lynds dark nebulae. Both van den Bergh (1966) and Sandage (1976) remarked that some of the bright nebulae at high latitudes could be dust clouds reflecting the integrated star light of the Galactic plane below them. Because these clouds are rich in dust, it is likely that they contain significant atomic hydrogen and, possibly, molecular hydrogen. The area studied by Sandage comprises one of the richer regions of high-latitude molecular gas, the Ursa Major cloud complex (mapped in part by Pound and Goodman 1997). Although it is certain that some of the emission nebulosity coming from regions containing high-latitude molecular clouds is due to reflected star light, there are also indications that some of the red emission may be produced by luminescence in very small hydrogenated carbon grains (Szomoru and Guhathakurta 1998—see §3.5.4).

It is difficult to determine when exactly a diffuse cloud stops being "molecular" and is, instead, an atomic cloud with some trace amount of molecules. So where do we draw the line between diffuse molecular and atomic clouds? As discussed earlier in this Chapter, we subjectively choose a cutoff for a diffuse molecular cloud of $n(H_2)/n(H_{total}) \sim$ a few percent. Our definition differs from that of, e.g., Liszt et al. (2010) who identify diffuse clouds as having at least 25% of the hydrogen in molecular form. Our more liberal definition allows us to consider as diffuse molecular clouds those objects with $N(H_2)$ as low as a few $\times\ 10^{19}$ cm^{-2}. Here,

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[7] Lynds dark cloud from the 1962 catalog are denoted as L followed by their numerical designation. However, the SIMBAD database refers to them as LDN followed by a number.

detection of molecular lines by radio spectroscopy is still possible and their physical characteristics can be determined over more than an infinitesimal line of sight.

Although normally studied by optical and UV absorption lines towards background stars, it became clear even in the 1980s that some diffuse lines of sight had sufficient CO column densities for detection in emission via the CO(1-0) line at 115 GHz. About half of the MBM high-latitude clouds turn out to have peak A_V less than 1 mag (see Fig. 7.7), but, for more than 20 years they were classified by nearly everyone as translucent clouds. However, in a series of brilliant papers, Liszt, Lucas and coworkers have recently studied the molecular properties of diffuse clouds and have come to some startling conclusions.

Liszt and Wilson (1993) and Liszt (1994) began by identifying about two dozen lines of sight towards background millimeter-wave sources where CO(1-0) absorption was detectable by synthesis instruments. In a series of papers, they systematically studied the molecular properties of these diffuse lines of sight using both absorption and emission lines. The formation, fractionation, and excitation of CO in diffuse clouds was treated at length by Liszt (2007). Other species studied include HCO^+ and HCN (Lucas and Liszt 1994; Liszt and Lucas 1994); H_2CO (Liszt and Lucas 1995); OH (Liszt and Lucas 1996); C_2H and C_3H_2 (Lucas and Liszt 2000); CH (Liszt and Lucas 2002).

In addition to studying the chemistry of diffuse clouds, Liszt et al. (2010) and Liszt and Pety (2012) identified a set of diffuse clouds with very strong CO(1-0) lines (antenna temperatures as high as 10 K) but with CO column densities $\lesssim 10^{16}$ cm^{-2}. Clouds with these properties do not fit the diffuse/translucent/dark categorization. Such strong CO emission and relatively modest abundances are not plausible in the traditional scheme. Liszt, Lucas, and Pety conclude that CO(1-0) emission does not trace well the molecular distribution of diffuse clouds because the molecule represents a small fraction of the carbon in the gas phase. Instead, it highlights where the CO chemistry is converting the carbon primarily into CO rather than C^+ or C^0. In addition, radiative transfer effects can produce abnormally strong CO(1-0). Line formation effects in low density regions can cause strong emission lines if the gas is subthermally excited; the low densities allow radiative processes to dominate over collisional de-excitation so the photons scatter about in the gas until they escape. This picture effectively changes the conventional wisdom that the CO(1-0) line traces almost exclusively the dense cold gas in the Galaxy (i.e., primarily the dark clouds and GMCs). Instead, strong CO(1-0) lines may arise in what is clearly diffuse molecular gas. Besides diffuse molecular clouds, the envelopes of GMCs and dark clouds are warmer, lower in pressure, and may occupy a larger fraction of the volume than the denser, colder gas. These envelopes are well traced by mid-IR emission (see Chap. 6), but not always by CO(1-0) (see Sect. 8.4). Thus, Liszt et al. (2010) conclude that a CO(1-0) map is really a map of CO abundance and chemistry, and only secondarily a map of the dense gas (and hence the mass). In their words, "The CO sky is mostly an image of the CO chemistry."

Liszt et al. (2010) find that the CO-H_2 conversion factor (see Chap. 8) is similar in diffuse and dark clouds because in diffuse clouds, a drop in the CO/H_2 abundance is compensated by an increase in the CO line intensity per CO molecule because of chemistry and radiative transfer considerations. The findings of Liszt, Lucas, and coworkers highlight the complexity of interpreting CO observations in diffuse and translucent regions. While further, in-depth, study of molecular clouds with A_V less than 1 magnitude is needed, it may be that the diffuse/translucent/dark paradigm for categorizing small clouds is just too approximate.

7.5 What Is a Molecular Cloud?

If GMCs and dark clouds were the only types, one could attempt to define a molecular cloud as a self-gravitating entities, isolated both spatially and kinematically from the column of hydrogen in their direction. The contrast in density between the molecular entity and the surrounding medium is between 10^2 and 10^3, nearly that of a baseball plowing through air. But, even in these cases, the cloud construct is too simplistic. GMCs have diffuse molecular and atomic envelopes which are sometimes filamentary, and they are not disconnected from the surrounding CNM. With the exception of Bok globules, dark clouds also have envelopes and filaments that seem to blend into the background medium. Suddenly, the analogy to a baseball moving through air becomes more complicated. And this does not even consider the role of the magnetic field in linking these structures to their environs.

The situation is even worse if one tries to include translucent and diffuse clouds within the definition. For one thing, self-gravity is often unimportant in structuring these objects. Instead, turbulence seems to dominate in their structure and dynamics. Diffuse and translucent clouds are much more filamentary than dark clouds or GMCs (compare Figs. 7.4 with 7.6). Moreover the density contrast between the molecular gas and the surrounding atomic medium is at least one order of magnitude lower than for GMCs and dark clouds. Diffuse and translucent clouds are not so much baseballs as they are the denser, colder portions of large-scale atomic flows. Given their relatively short lifetimes (10^6 yr), they are transient structures, forming and dissipating more like smoke than baseballs. To make progress in understanding the relationship between dark cloud and GMCs versus diffuse and translucent clouds, the role of turbulence in these objects must be addressed. We will revisit the question of what is a molecular cloud after we discuss turbulence in Chap. 11.

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